Modelling and Analysis of A 3-Dof Triglide Parallel Manipulator with Extensible Links for Angular Drilling Operations

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***Abstract*: -The papers presents an approach for increasing the work volume of 3-DOF triglide parallel manipulator by providing extensible links and apply the manipulator for performing inclined drilling operation. The modeling and analysis of triglide type parallel manipulator with extensible links, actuated by screw pairs and spherical pairs are carried out and presented. The working model of the fabricated angular drilling machine is analyzed for practical applicability. The models 3-dof glide type manipulator have been designed and constructed. Experimental analysis is carried out to find the angular tilt of moving platform. An algorithm is used to find the displacement of the nuts. Further validation of the model is done by software package ADAMS simulation. Force analysis is carried out to verify the practicability of the drilling machine.**

The results obtained from experimental and simulation methods are verified and found to be closer. There has not been any considerable effort made to apply robots for machining operations. The current interest of authors is to modify and use the manipulator for angular drilling operations. With the conventional machines, drilling an angular hole requires special fixtures for each specific angle. This parallel mechanism can automate the operation, which is the original idea of the authors.

Key Words: Parallel Manipulator, triglide, Degrees of freedom, Simulation, ADAMS, MATLAB, angular drilling, and force analysis.

1. INTRODUCTION

1.1 CONSTRUCTION OF 3-DOF TRIGLIDE MANIPULATOR WITHOUT EXTENSIBLE LINKS

The various parts of the 3-DOF triglide manipulator that are designed are screws, links and spherical joints as in Fig.1. The manipulator has been designed to carry a maximum load of 300 N under equilibrium condition and 200 N in tilted positions of the platform with factor of safety [1]. Three stepper motors are used to actuate the screw pairs and hence the manipulator's movable platform through spherical pairs. The tilt of the moving platform will be in either x or y directions or it can be a combination of x and y or y and z or x and z directions [2].

2. KINEMATICS OF PARALLEL MANIPULATOR

The manipulation tasks in the inverse position kinematics are given as a set of positions in world co-ordinate system of the end-effectors [3]. A base Cartesian coordinate frame XYZ is fixed at the center of the base platform with the Z-axis pointing vertically upward and the X-axis pointing towards the screw pair P_1 [4]. Similarly, a coordinate frame xyz is assigned to the center of the upper platform, with the z-axis normal to the platform and the x-axis pointing towards the ball joint1 (b_1) as shown in schematic Fig.2.

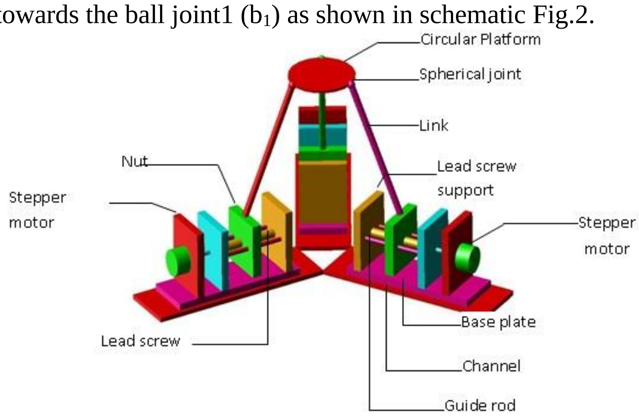


Fig.1 Various parts of the 3-DOF triglide manipulator

The coordinates of the ball joints in xyz frame are

$$b_1 = \begin{pmatrix} r \\ 0 \\ 0 \end{pmatrix} \qquad b_2 = \begin{pmatrix} -\frac{r}{2} \\ \frac{r\sqrt{3}}{2} \\ 0 \end{pmatrix}$$

$$b_3 = \begin{pmatrix} -\frac{r}{2} \\ -\frac{r\sqrt{3}}{2} \\ 0 \end{pmatrix} \quad (2)$$

The co-ordinate frame xyz with respect to the fixed co-ordinate frame XYZ can be described by the homogeneous transformation [T] matrix,

$$T = \begin{pmatrix} r_{11} & r_{12} & r_{13} & x_c \\ r_{21} & r_{22} & r_{23} & y_c \\ r_{31} & r_{32} & r_{33} & z_c \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

Where $(x_c, y_c, z_c)^T$ describes the position of the origin of the xyz frame and the orientation vectors $(r_{11},r_{21},r_{31})^T$,$(r_{12},r_{22},r_{32})^T$, and $(r_{13},r_{23},r_{33})^T$ are the directional cosines of the axes x, y, and z with respect to the base frame XYZ. After finding the P_1, P_2 and P_3 position by the above transformation matrix [5], the corresponding positions of the spherical joints b_1, b_2 and b_3 can be determined as the link lengths are constant and the positions P_1, P_2 and P_3 are constrained by the screw joint to move in the lines y = 0, y = -x √3 and y= + x √3 respectively.

The Cartesian position of the ball joints with respect to the fixed coordinate system can be expressed as

$$\begin{pmatrix} P_i \\ 1 \end{pmatrix}_{XYZ} = (T)\begin{pmatrix} b_i \\ 1 \end{pmatrix}_{xyz} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & x_c \\ r_{21} & r_{22} & r_{23} & y_c \\ r_{31} & r_{32} & r_{33} & z_c \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r & -\frac{r}{2} & -\frac{r}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 0 & 0 & 0 \\ 1 & 1 & 11 \end{pmatrix} \quad (4)$$

Where, the vectors b_i and P_i describe the position vectors of the i^{th} ball joint with respect to the movable frame xyz and fixed frame XYZ respectively. The difference between the previous positions and new calculated positions is determined and the corresponding pulses are given to each stepper motor to obtain the required manipulation of the moving frame [8]. The shape of the moving platform in a 3-dof parallel manipulator of glide type is shown in Fig.2.

Let 'r' be the radius of the moving platform

C is the center of the moving platform and

R- Radius of the fixed base

θ- Angle of tilt of moving platform

Φ- Angular position of the link at initial condition

α- Angular position of the link at the base when The nut moves 'X' distance apart

S_1, S_2 and S_3- The positions of the Spherical joints at J_1, J_2 and J_3 positions

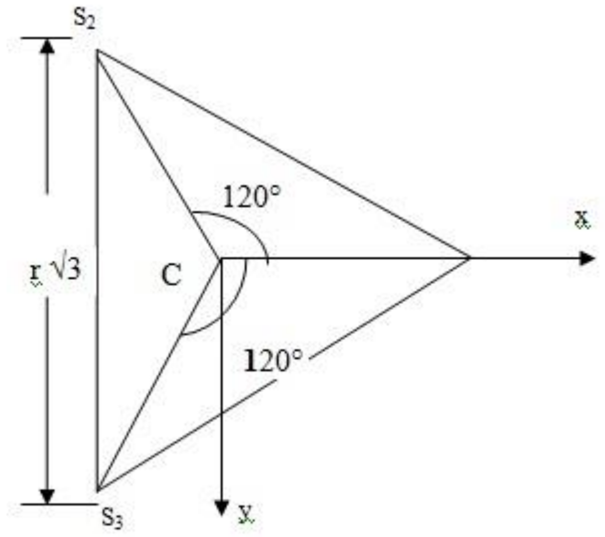


Fig.2 Shape of the moving platform

3. POSITION ANALYSIS OF ONE LINK MOVEMENT

Let 'd' be the diameter of the circular platform and 'θ' be the tilt of platform when the link is moved through a distance of 'X.

$$\sin\alpha = \frac{h - 1.5r\sin\theta}{l} \quad (3)$$

When a stepping motor is used, then the number of steps to be supplied is given by

No. of steps = No. of rotations of screw x No. of pulses per revolution.

When the Motor is of variable reluctance type, the number of pulses per revolution is 24, and then every step of rotor produces an angle of 15°.

4. TRIGLIDE WITH EXTENSIBLE LINKS

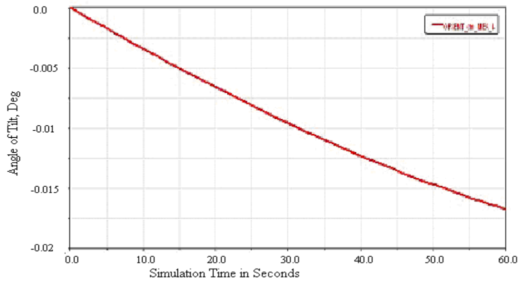
The 3-dof manipulator has been modified with extensible links and fabricated. Pneumatic cylinders are used as extensible links for increasing the angular tilt of moving platform and hence the work volume [11]. The kinematic analysis has been carried out by experiment and ADAMS and is shown in Table 1.

5. MODELLING THE EXTENSIBLE LINK TRIGLIDE BY ADAMS

The model of the triglide with extensible links is as in Fig.1. It been constructed in the ADAMS by building the parts in the mechanical systems and simulated by actuating the pneumatic links individually or simultaneously as shown in Fig.2. For the displacement of 35 mm of the nut, the angle of rotation of the moving platform about x axis and y axis are obtained as shown in Fig.3.

Table: 1 Comparison of Results by Experiment and ADAMS

Actuation Link no.	Angle of tilt of Moving Platform, degrees				Displacement of nut (mm)	Number of Rotations of screw
	Experiment		ADAMS			
	About X-axis (α)	About Y-axis (β)	About X-axis (α)	About Y-axis (β)		
1	-0.0819	9.0903	-0.0167	8.9493	50	10
2	-6.3287	9.2498	-6.3953	9.3657	50	10
3	8.7548	8.4685	8.927	8.5196	50	10



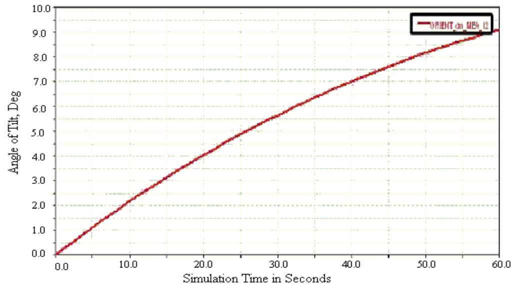


Fig.3 Simulation of parallel manipulator by actuating a link after actuation

6. CONSTRUCTION AND ANALYSIS OF ANGULAR DRILLING MACHINE

The angular drilling machine arrangement uses the movable platform along with the three extensible links of the 3-dof triglide parallel manipulator as work table to obtain the required tilt of work piece [17]. Three suitable pneumatic cylinders are used as extensible links and a screw actuated flat vice to grip the work piece.

The required angular tilt is obtained by actuating the lead screw. The photograph of the angular drilling machine is shown in Fig. 4.

Fig.4 Angular drilling machine with triglide mechanism

7. FORCE ANALYSIS

For drilling operation, the major forces acting on the platform are torque and thrust. The thrust force acts perpendicular to the axis of the hole. Excessive thrust will cause the drill to bend if not dislocate the work piece in the fixture [15]. The Thrust force can be as high as 100kN for high strength materials.

The thrust and torque values are calculated by using the following formulae.

$$\text{Torque (M)} = 0.6 \times F_c \times D \qquad (4)$$

$$\text{Thrust (F)} = 5 \times F_T \times \sin \beta \qquad (5)$$

Where F_c is cutting force, F_T is thrust force,

β is half point angle, and D is diameter of the work piece = 20mm

Considering wooden work piece Shear strength =400N/mm^2

Speed of the drill = 240 R.P.M and

Feed = 0.25mm/rev, then

torque and thrust values are (F) = 1500 N and (M) = 18200 N-mm.

Using these value simulations is carried out in ADAMS [19]. The forces acting on the three spherical joints when two links are actuated simultaneously are shown in Fig.5 (a). The forces acting on the three spherical joints when two links actuated simultaneously are shown in Fig.5 (b). From this the maximum and minimum stresses are found and are given in Table 2 to 5.

Table: 2 Force during Actuation of First Link

	Force (N)		Stress (MPa)		Strain (10^{-5})	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**
Link 1	Max. 626.83	Min. 532.65	Max. 0.499	Min. 0.424	0.238	0.202
Link 2	Min. 588.15	Max. 611.1	Min.0.468	Max.0.487	0.223	0.232
Link 3	Min. 510	Max. 518.89	Min. 0.406	Max.0.413	0.193	0.197

Table: 3 Force during Actuation of Second Link

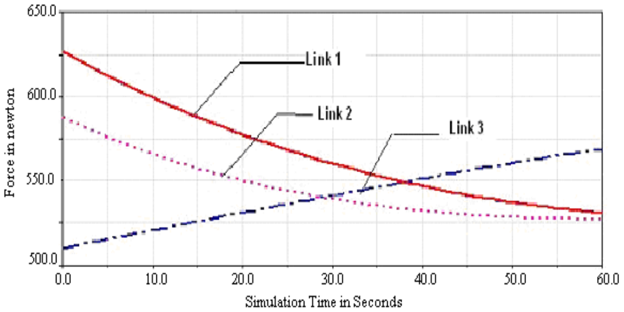
	Force (N)		Stress (MPa)		STRAIN (10^{-5})	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**
Link 1	Min.626.83	Max.654.03	Min.0.499	Max.0.521	0.238	0.248
Link 2	Max.588.15	Min.498.65	Max.0.468	Min.0.397	0.223	0.189
Link 3	Min.510.00	Max.532.67	Min.0.406	Max.0.424	0.193	0.202

Table: 4 Force during Actuation of Third Link

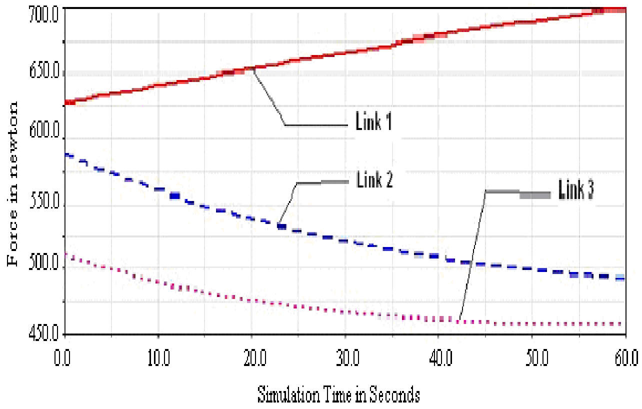
	Force (N)		Stress (MPa)		Strain (10^{-5})	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**
Link 1	Min.626.83	Max.641.44	Min.0.499	Max.0.511	0.238	0.243
Link 2	Min.588.15	Max.606.83	Min.0.468	Max.0.483	0.223	0.230
Link 3	Max.510.00	Min.423.88	Max.0.406	Min.0.337	0.193	0.160

Table: 5 Force during the Combined Actuation of Links 1 and 2

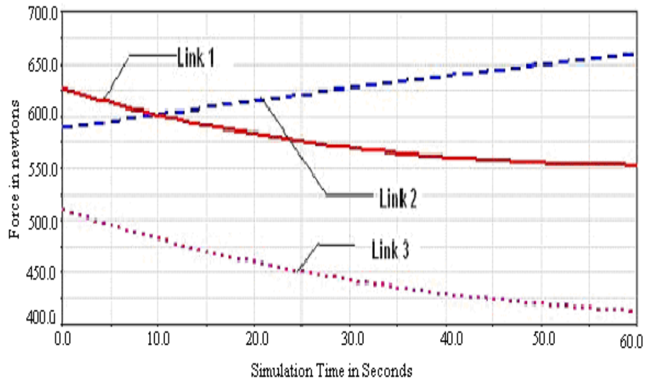
	Force (N)		Stress (MPa)		Strain (10^{-5})	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**
Link 1	Max.626.83	Min.530.75	Max.0.499	Min.0.423	0.238	0.201
Link 2	Max.588.15	Min.527.19	Max.0.468	Min.0.420	0.223	0.2
Link 3	Min.510.00	Max.568.9	Min.0.406	Max.0.453	0.193	0.216



(a) Links 1 and 2 are actuated



(b) Links 2 and 3 are actuated



(c) Links 1 and 3 are actuated

Fig.5 Force acting during combined actuation of links

8. RESULTS AND DISCUSSION

8.1 THREE DOF TRIGLIDE MANIPULATOR.

Position Kinematics: From the experiment the angle of tilt of moving platform is found to be 3.952° for 70 mm displacement of the nut connected to link one for 14 rotations of the screw having 5mm pitch. For 3.952° angle of tilt as input, the analytical result is 69.352mm displacement for 13.870 rotations of the screw. The error of 0.648 mm in the displacement of the nut is due to the mechanical inaccuracies at joints and links. For the same displacement of nut and number of rotations of screw for the other two links it is supposed to get equal angles of tilt of moving platform.

Synthesis : By increasing the link length from 310mm to 387.5 mm and 465mm the angle of tilt obtained is decreased from 8.84° to 6.92° and 5.70° respectively for the same numbers of rotations of the lead screw having the radius of moving platform of 85mm. Similarly by decreasing the link length from 310mm to 232.5mm and 155mm for the same number of rotations of the lead screw the angle of tilt obtained is increased from 8.84° to 12.44° and 23.71° respectively. By increasing the radius of the moving platform from 85mm to 106.25mm and 127.5mm, the angle of tilt of moving platform decreases from 8.84° to 5.67°and 3.60° respectively for the same numbers of rotations of the lead screw (10) having the link length of 310mm. By decreasing the radius of the moving platform from 85mm to63.75mm and 42.5mm, the angle of tilt increases from 8.84° to 14.19° and 24.86° respectively. The results reveal that the link length and angle of tilt are inversely proportional in the triglide type of manipulator.

8 .2 ANGULAR DRILLING MACHINE

Position analysis: The kinematic analysis is carried out by experiment and 'ADAMS'. The experimental results show that for 10 rotations of the lead screw (pitch-5mm), the moving platform tilts to an angle of 9.0903° about y-axis and 0.0819° about x-axis for the first link actuation. By actuating link 1, the rotation about the x-axis should be equal to 0° since x-axis passes through the link 1 and there is rotation about y-axis only. Similarly by actuating the other two links, for the same number of rotations of the screw, the angle of tilt about x-axis and y-axis are obtained. The simulation results by actuating the links are obtained from ADAMS. The rotation about x-axis is found to be 0.016725° and about y-axis it is 8.9493° by actuating the link 1 for the same displacement of nut. The small variation in the angle of tilt of moving platform between ADAMS and Experiment results is due to arresting the motion of other two links while simulating the model. The velocity and acceleration values of the moving platform are also obtained from ADAMS.

Force Analysis: The simulation graphs reveal that the forces and stresses acting on the links 2 and 3 are found to be more than link, 1 while actuating the link one. This is true because while actuating the link1, the load on platform will be acting on other two links than the previous one. The forces acting on the spherical joints for the combined actuation of two pneumatic links (i.e. two links actuated simultaneously) are studied for maximum and minimum stresses.

9. CONCLUSION

- The position analysis carried out for link actuation individually shows that the experiment values are approximately closer with the Analytical and ADAMS results.
- The kinematic synthesis of triglide shows that the link length and radius of moving platform have influence on angle of tilt of moving platform. If the link lengths and the radius of platform are increased then the angle of rotation of moving platform is decreased and vice versa.
- The accuracy of movement of platform is found to be better since for one pitch movement of the link makes 0.282 ° angle of the moving platform.
- The angular drilling operation is made easy with the help of triglide mechanism. The model can also find its applications in cockpit simulations and hypersonic plane simulations in wind tunnels by providing the rolling motion.
- The lesser strain values from the dynamic analysis indicate that the links have good stiffness constant payload capacity. From the force values it is observed that the load is approximately distributed on all the links. Hence the manipulator could be used as a machine tool table for drilling inclined holes on components and contour milling using end-milling cutters. The manipulator design could be made simple by using planar motors instead of stepper motors. Dynamic analysis could also be carried out using ANSYS package and the results of ADAMS and ANSYS can be correlated and this research work could very well be extended for any degrees of freedom parallel manipulator either in regular fashion or in inverted fashion.

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