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Research Article

Design and Analysis of a 3-DOF Rigid Motion Stage

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ABSTRACT

In this paper, a rigid motion stage having three degrees of freedom (DOF) translation along the X and Y axes and rotation about the Z axis is investigated. The configuration of the motion stage is 2PPR (Prismatic-Prismatic-Revolute) 1PRR (Prismatic- Revolute-Revolute). In this work, workspace of motion was determined using finite element analysis (FEA) carried out in ANSYS Workbench. The workspace of the proposed motion stage was calculated as 127.59 mm in the X direction and 46.18 mm in the Y direction. The first six mode shapes and their respective frequencies were obtained through dynamic analysis, which is another aspect of this study. The first natural frequency of 156.43 Hz, which is relatively high for a wide-range mechanism, was observed in order to ensure operational stability. The findings demonstrate the design's structural stability and potential applications in precision manufacturing, robotics, optics, and micromanipulation. This approach is innovative because it provides a comprehensive view of the motion stage's performance by integrating workspace analysis with dynamic behaviour assessment.

Keywords: Planar Parallel Manipulator, Motion Stage, Voice Coil Motor.

Introduction

Motion stages are essential components in precision engineering, enabling controlled movement along defined degrees of freedom. A three-degree-of-freedom rigid motion stage with two translational motions along the X and Y axes and one rotational motion about the Z axis is a flexible platform for applications needing both planar displacement and angular orientation, among other combinations. These systems are commonly used in industries where precise positioning and manipulation are essential, like robotics, microfabrication, and optical instrumentation. This study uses ANSYS Workbench's finite element analysis to examine a 3DOF stiff motion stage. The planar parallel manipulator is set up as 2PPR 1PRP. In order to describe the system's performance, the study incorporates both workspace appraisal and dynamic behavior assessment. The workspace, defined by the stage's translational and rotational limits, directly influences its adaptability across various applications. The proposed motion stage design achieved a translational range of 127.59 mm along the X-axis and 46.18 mm along the Y-axis, confirming its suitability for high-precision tasks. Workspace optimization and actuation techniques for planar parallel robotic stages have been studied in the past. Singh et al.[1] demonstrated enhanced motion accuracy and simplified mechanical design by introducing a smart-actuated planar parallel stage and using FEA to examine its workspace. Building on this, Singh et al.[2] improved flexibility and efficiency in a U-shaped 3-DOF stage by using SMART linear actuators based on shape memory alloys. Zhai et al.[3] highlighted the accuracy and compactness of their 3-DOF stage while concentrating on micropositioning technologies. In order to improve precision and workspace efficiency for nanomanipulation activities, Ding and Li.[4] created a two-layered 3-RRR micro/nano manipulation stage. A PPR-configured micro-positioning system with a 2.4° rotating capacity and ±2.5 mm translational range was examined by Ammar et al.[5] Zhang and Xu.[6] proposed a symmetrical 3-DOF stage with extended stroke length, maintaining high accuracy through a novel structural design. Nie et al.[7] introduced control algorithms for a nanopositioning stage aimed at improving stability and precision. Lai et al.[8] designed an out-ofplane micro-positioning mechanism with advanced actuation techniques for multi-axis control. Saurabh and Singh.[9] demonstrated the effectiveness of NiTi SMA-based compliant actuators in achieving precise motion with minimal mechanical complexity. Choudhury and Singh.[10,11] conducted comprehensive studies on planar parallel manipulators, addressing kinematic, dynamic, and control challenges, and identifying key limitations in workspace and stability optimization. In the family of U-shaped base planar parallel robotic manipulators, the PPRPRP-PRR manipulator had the largest experimental workspace among the several configurations.[12]

Despite extensive research, challenges persist in simultaneously optimizing translational and rotational degrees of freedom within a unified framework. Moreover, the impact of environmental factors—such as thermal fluctuations and external vibrations on workspace dynamics remains insufficiently explored. This study aims to address these gaps by providing a detailed analysis of a 3-DOF rigid motion stage, emphasizing its workspace capabilities and operational reliability.

Mechanism Design

Design of Proposed Motion stage

The rigid motion stage was designed with three DOF having translation along the X and Y axes and rotation about the Z axis. The design includes a rigid platform supported by precision actuators capable of linear and rotational movements.

A schematic diagram of a planar parallel manipulator with three actuators and linear guides is shown in the figure 1. The motion stage comprises three actuators labelled as VCM 1, VCM 2, and VCM 3, which stand for Voice Coil Motors, a type of linear actuator. Each actuator is responsible for moving a corresponding slider along a linear guide. The linear guides named as Slider 1, Slider 2, and Slider 3, provide the linear movement of the sliders when VCM actuated. The mobile platform is in form of a triangular structure at the centre of the setup. The motion stage configurations explored in this study demonstrate a progression in mechanical complexity and functional capability across three distinct setups. In Setup 1, A linear slider enables translational motion. A box mounted above it via a revolute joint allows rotation, while a cylindrical rod inserted into the box adds an additional linear degree of freedom forming a hybrid linear-rotational mechanism. In Setup 2, Retains the slider-driven translation and box rotation via a revolute joint. The rod translates within the box, simplifying the mechanism while maintaining effective motion control. In Setup 3, The slider provides translation; the box above it is fixed and imparts rotational motion through a rod connected at one end to the box and at the other via a revolute joint.

The advances to a planar parallel manipulator with a 2PRP–1PRR joint configuration, actuated by voice coil motors. In this arrangement, three sliders move along linear guides, and their coordinated motion drives a central mobile platform, enabling two translational degrees of freedom (X and Y axes) and one rotational degree of freedom (about the Z axis). The integration of prismatic and revolute joints in this setup allows for precise planar manipulation, making it highly suitable for applications in micromanipulation, robotics, and precision manufacturing.

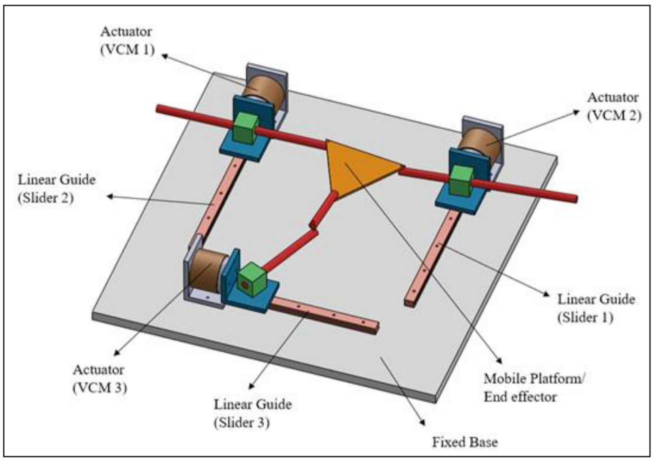

Figure 1.The VCM based proposed motion stage

Kinematic Modelling Of The 2Prp 1Prr:

The kinematic arrangement of the planar parallel manipulator with 3-DOF, which includes translational motion in the X and Y axes and rotation about the Z axis. The manipulator consists of three legs with different configurations. The forward and inverse kinematics equations for this manipulator is derived using the lengths of the legs and angle of the revolute joints.

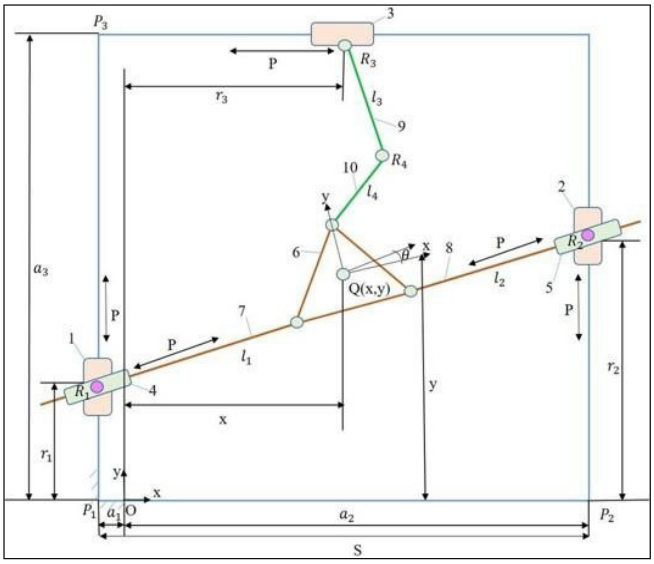

Figure 2.Kinematic arrangement of the 1PRR 2PRP manipulator

Forward Kinematics

With the given the prismatic joint lengths (P1, P2, and P3) and the revolute joint angles as shown in figure 2, the forward kinematics equations established for the location and orientation of the end-effector.

$$x = r_1 - \frac{2h}{3} cos\left(90 - \left(\frac{r_3 - r_2}{S}\right)\right) - l_2 cos\theta_2 + l_1 cos\theta_1 \quad (1)$$

$$y = r_2 - \frac{2h}{3} sin\left(30 - \left(\frac{r_3 - r_2}{S}\right)\right) - \left(r_1 - \frac{2h}{3} cos\left(90 - \left(\frac{r_3 - r_2}{S}\right)\right) - l_2 cos\theta_2 + l_1 cos\theta_1\right) \times \left(\frac{r_3 - r_2}{S}\right) \quad (2)$$

Inverse Kinematics

The inverse kinematics equations for the proposed platform is given in the equations (3-6). Inverse kinematics equations are utilized to determine the necessary prismatic joint lengths and revolute joint angles in order to achieve the desired end-effector position and orientation. In the motion step, inverse kinematics computations establish the slider locations along the linear guides to accomplish the desired mobile platform motion and alignment.

$$r_1 = x + \frac{2h}{3} sin\theta + l_2 cos\theta_2 - l_1 cos\theta_1 \quad (3)$$

$$\theta_2 = sin^{-1}\left\{\frac{y - \frac{2h}{3} cos\theta - l_1 sin\theta_1}{l_2}\right\} \quad (4)$$

$$r_2 = y + \frac{2h}{3} \sin(30 - \theta) - tan\theta\left\{x - \frac{2h}{3} \cos(30 - \theta)\right\} \quad (5)$$

$$r_3 = y + \frac{2h}{3} \sin(30 - \theta) - tan\theta\left\{s - x - \frac{2h}{3} \cos(30 - \theta)\right\} \quad (6)$$

These equations are derived based on the geometric constraints imposed by the lengths of the connecting rods and the positions of the sliders on the linear guides.

Analysis Of Planar Parallel Motion Stage

ANSYS Workbench was utilized to simulate the motion stage and to determine its workspace. Initially, a 3D model of the motion stage was created, incorporating all mechanical components and constraints. Structural steel was chosen for the platform and actuators, with material properties including a Young's modulus of 200 GPa and a Poisson's ratio of 0.3. Constraints were applied to replicate real-world conditions, ensuring realistic simulation results. Translational forces were applied to evaluate the stage's range of motion. A fine mesh was generated to ensure accuracy in the simulation results. Finally, static structural analysis was performed to determine deformation and stress under various loading conditions (Figure 3). The positions of the end effector are summarized in Table 1, and the final position of the end effector is presented in Table 2.

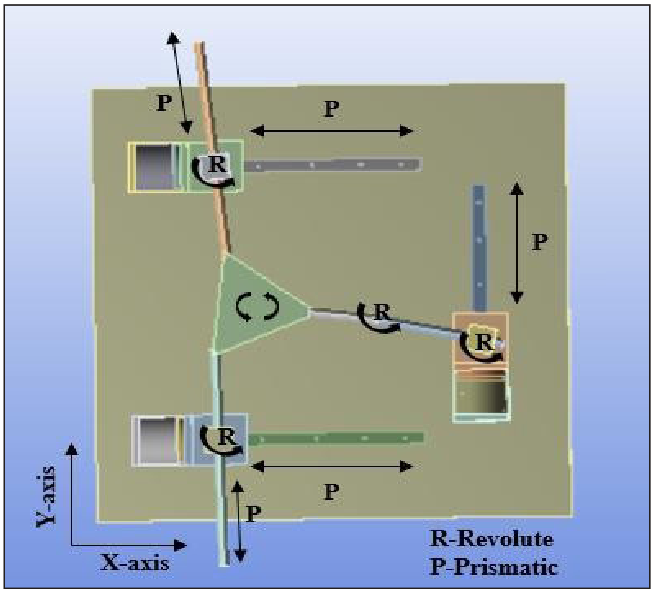

Figure 3.Analysis of 1PRR 2PRP motion stage

Table 1: Positions of the end effector

Set of VCM actuator conditions	Positions	End effector positions	
		X	Y
VCM 1	Initial Positon	226.72	425.04
	Final Position	264.36	443.61
VCM 2	Initial Positon	226.72	425.04
	Final Position	304.58	454.03
VCM 3	Initial Positon	226.72	425.04
	Final Position	261.58	423.00
VCM 1 and VCM 2	Initial Positon	226.72	425.04

	Final Position	310.23	469.18
VCM 1 and VCM 3	Initial Positon	226.72	425.04
	Final Position	301.08	436.72
VCM 2 and VCM 3	Initial Positon	226.72	425.04
	Final Position	354.31	454.53
VCM 1, VCM 2 and VCM 3	Initial Positon	226.72	425.04
	Final Positon	354.17	464.73

Table 2: Final position of the end effector

Final Position	Position (X) [mm]	Position (Y) [mm]
	354.31	469.18
Initial Position	226.72	423.00
Total Displacement	127.59	46.18

Workspace of Planar parallel Motion Stage

The workspace was determined by analyzing the displacement and rotation results from the FEA simulations. The range of motion along the X and Y axes and the maximum rotational angle about the Z axis were quantified. The proposed motion covers 127.59 mm in X direction and 46.18 mm in Y direction (figure 4).

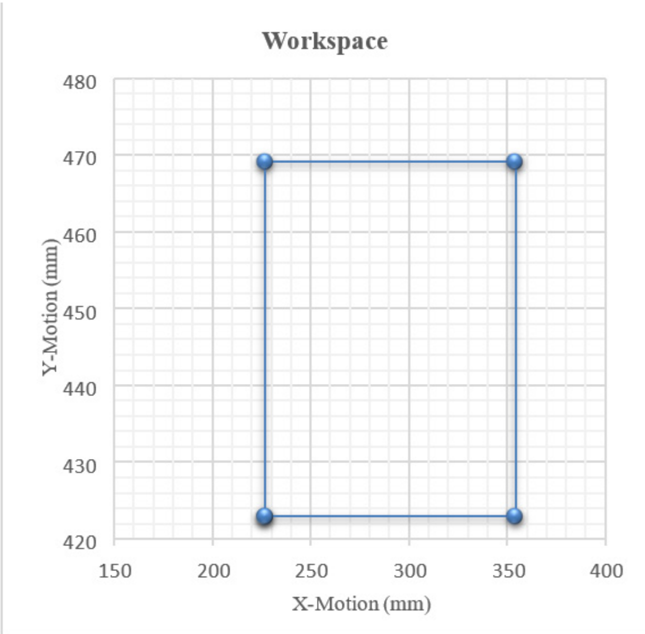

Figure 4.Workspace of the proposed motion stage

Dynamic Analysis

Using modal analysis, the suggested mechanism's dynamic behaviour was examined. The figures 5 show the first six mode forms and the frequencies that correlate to them. Translation in the y-direction is represented by the first mode, and translation in the x-direction by the second mode. Rotation inside the plane is represented by the third mode. Out-of-plane translation is represented by the fourth mode. In-plane parasitic rotation is represented by the fifth and sixth modes. 156.43 Hz is the initial natural frequency, which is high for a wide-range mechanism.

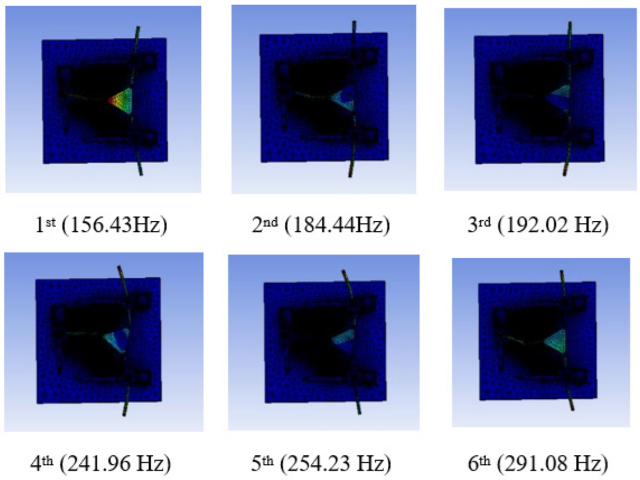

Figure 5.First six mode forms and their frequencies

Result And Discussion

The results of this study confirm the effectiveness of the proposed planar motion stages with configuration 2PPR 1PRP in achieving a versatile and compact workspace. The translational range of proposed motion stage is 127.59 mm in the X axis and 46.18 mm in the Y axis, provides a broad operational capability for applications in precision engineering. The proposed motion stage also gives the rotational range of ±5°that enhances the flexibility of the motion stage. The rotational motion making the motion stage suitable for the tasks requiring angular adjustments. The workspace of the motion stage was visualized using the plots, illustrating the displacement and rotation capabilities within the specified range. Dynamic analysis revealed the high natural frequency of the motion stage, which ensures operational stability and resistance to external vibrations. The results also highlight the structural integrity of the design, with stress distribution and deformation remaining within acceptable limits. These findings validate the use of ANSYS Workbench as an effective tool for workspace determination, structural analysis, and dynamic behaviour assessment of motion stages. However, the study also highlights certain limitations, particularly the need to account for thermal and dynamic effects, which were not included in the present analysis. Future studies should focus on incorporating these factors to enhance the reliability and performance of planar motion stages in various operational environments.

Conclusion

This paper presented the investigation of rigid motion stage with 3-DOF using Ansys Workbench. In this study design, kinematic analysis, workspace and dynamic behaviour of a rigid motion having 3-DOF. The configuration of the proposed motion stage is 2PPR and 1PRP. The workspace analysis results showed that the proposed motion stage was capable of cover 127.59 mm in X direction and 46.18 mm in the Y direction. From the results of dynamic analysis, stability in motion of stage is ensured by the 1st natural frequency of 156.43 Hz. The proposed motion stage can be used in manufacturing, micromanipulation, robotics and optics.

The results highlight the design's feasibility and possible uses in manufacturing, robotics, micromanipulation, and optics. Future studies should focus on reducing heat impacts, utilizing adaptive control systems to mitigate dynamic effects, and enhancing the robustness of the stage.

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