International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

High Precision Flexural Mechanisms for Scanning Applications: A Comprehensive Review

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DOI: https://doi.org/10.55248/gengpi.5.0224.0502

A B S T R A C T

Flexure mechanisms are a designer's delight; several mechanisms, including as piezo-based stages, spring-loaded systems, and ball screw mechanisms, have been developed to meet the needs of precision scanning applications. The importance of precision positioning stems from its critical role in accomplishing improved production and precise measurements. While rigid body mechanisms like spring-loaded and ball screw systems provide a wide range of motion, they run at slower speeds, have reduced positioning precision, and are prone to friction and backlash problems. On the other hand, piezo-based Nano positioning stages have a high operational speed and precision but a limited scanning range. In response to these issues, researchers are increasingly focusing on flexural processes. These mechanisms have fast speeds, large scanning ranges, and excellent positioning precision. Flexural mechanisms offer frictionless and backlash-free motion, allowing for high levels of repeatability and precision control. This article provides a detailed analysis of the development of flexural mechanisms, including planar and hinge varieties, by researchers throughout the world. The present level of research into creating flexural mechanisms for high-precision applications is also discussed. The study finishes by outlining the process of designing and implementing flexural mechanisms for a variety of applications.

Keywords: Flexural Mechanisms, Compliant Mechanism, Repeatability, Speed, backlash and Precision Control

Introduction

The accuracy of positioning is determined by the resolution of positioning sensors and precise actuators, both of which can be costly, elevating the overall cost of scanning systems. A multitude of procedures are utilized to ensure accurate positioning. While piezo-based nano positioning stages are quick and precise, they have a limited scanning range. Friction and backlash are common problems with rigid-body devices like ball screws and spring-loaded systems. Roller bearings, air bearings, and magnetic bearings can all cause nonlinear behavior [11-13]. As a result, these classic systems have several drawbacks, including a limited scanning range, poor accuracy, fixed degrees of freedom, and motion dependency as given in figure 1. In addition, an adequate control system must be developed and implemented to ensure precise control [14].

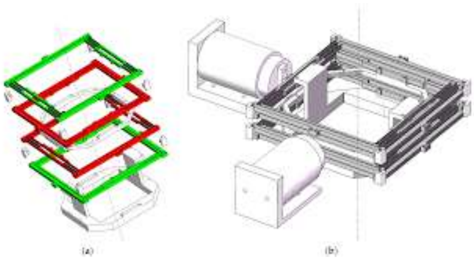

Figure 1: Flexure Mechanism with Actuator

A flexural mechanism is a one-piece flexible device that transmits force and motion by elastic deformation. Unlike ordinary rigid body joints, it derives mobility from the relative flexibility of its components. The study and design of generic platform-type parallel mechanisms with flexure joints were performed. This study addressed static performance indicators including task space rigidity and manipulability. Based on these performance measurements, a multi-objective optimization strategy was implemented. Initially, the Pareto border was identified. The pseudo-rigid body architecture was simplified using a lumped approximation of flexure joints as shown in figure 2. A key distinction between flexure mechanisms and parallel mechanisms with conventional joints was established: kinematic stability is no longer a design consideration. Instead, the critical design parameter is task space stiffness, which must be carefully designed to prevent undesired motion in the presence of external loads. [15-17].

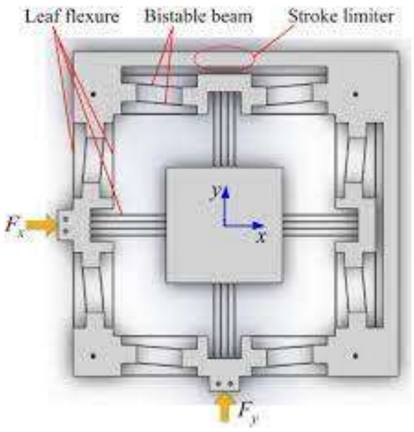

Figure 2: DFM with X & Y direction

This type of mechanism, which employs flexible segments, simplifies design by removing several stiff parts, pin joints, and additional springs. As a result, it typically saves space while also lowering component, material, and assembly work costs. Incorporating compliance (flexibility) into devices can lead to further advantages such as reduced weight, friction, noise, wear, backlash, and, most importantly, maintenance requirements. Designed and analysed a unique compliant flexure-based XY micropositioning stage that is totally decoupled. This stage is powered by electromagnetic actuators and has a basic design with double parallelogram flexures and four contactless electromagnetic force actuators. A matrix approach was used to analyse compliance and stiffness, and analytical models for electromagnetic forces were developed based on the mechanical system's kinematics and dynamic modelling. The mechanical structure and electromagnetic model were confirmed using finite element analysis (FEA) with ANSYS. The resultant stage has perfect XY decoupling, a basic symmetrical construction, an easily implementable control method, and a large range of motion. Kinematics and dynamics modelling of the mechanical structure were accomplished using compliance-based matrix techniques [18-21].

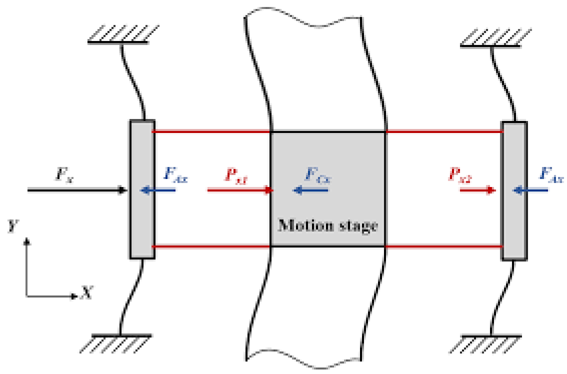

Figure 3: Large Stroke XY positioning

Flexural joints feature negligible friction losses and do not need lubrication due to their smooth operation as shown in figure 3. They produce continuous displacement without backlash. The engineering community recognizes the need of adequately constrained designs. The examination includes an analytical assessment of parasitic motion, cross-talk, lost motion, workspace, and resonant frequency. Mathematical models for the kinematics and dynamics of the XY stage are developed in closed-form, and their correctness is verified using finite element analysis (FEA) using pseudo rigid-body (PRB) simplification and lumped model approaches. Recognizing the limits of simple models for forecasting kinematic performance, a nonlinear kinematics model is developed based on the deformation of the complete manipulator. The efficiency of the nonlinear model is validated using finite element analysis and experimental experiments on a prototype. The findings of this validation illustrate the precise prediction of manipulator kinematics by the nonlinear model, and expose the reasons why simpler models fail [22-25]. An ideal limiting element, mechanism, or device tries to give infinite stiffness and zero displacements in specific directions while allowing infinite motion and zero stiffness elsewhere [26-29]. These restricted directions are known as Degrees of Constraint (DOC), whereas uncontrolled directions are known as Degrees of Freedom (DOF). This paper discusses the fundamental issues in creating a decoupled XY stage for micro/nano positioning and manipulation applications. The suggested XY stage generates motion using two piezoelectric actuators (PEAs), with cross-axis couplings reduced by statically indeterminate symmetric (SIS) structures. In static and dynamic modelling, the PEA is modelled as a force generator with an incorporated spring-damper component. When monitoring 1-degree-of-freedom (1-DOF) trajectories at low frequencies, the tracking error may be decreased to the noise level, according to experimental data. However, for 2-DOF trajectories, tracking error is determined by cross-axis couplings as well as axe-cooperative tracking [30-33]. When designing a machine or mechanism with appropriate limits, designers must choose among a number of restrictive characteristics. For example, ball bearings and flexures are both popular options. This work describes a unique piezo-driven, parallel-kinematic micropositioning XY stage. The monolithic design consists of parallelogram four-bar connections, flexure hinges, and piezoelectric actuators. Kinematic and dynamic studies show that the stage's mechanical construction provides a big workspace, high bandwidth, and good linearity. In open-loop mode, the stage system was tested for step and frequency response. Closed-loop mode investigations show outstanding linear and circular contouring performance, indicating strong scanning capability for parallel kinematic phases. The positional resolution, which is limited exclusively by the feedback sensors utilized, is around 20 nm [34-37]. Flexures, on the other hand, allow for extremely clean and precise movement. Flexure displacement is created by molecular-level deformations, therefore friction, stiction, and backlash are completely eliminated. The XY flexure mechanism offers a broad range of motion suitable for various applications, but ensuring accuracy and precision is paramount. Controlling motion effectively involves minimizing errors and backlash. This paper presents the design, development, and experimental analysis of a XY flexure mechanism. Initially, numerical analysis was conducted on the CAD model of the mechanism using ANSYS software. Subsequently, experimental measurements of deflection were obtained using a dial gauge setup, and these values were compared with the numerical results to validate the model [39-41].

Literature Survey

Hao Yun, Manabu Aoyagi, et al., conducted a study focusing on the construction and testing of a piezoelectric-type mechanism for dynamic analysis. Experimental tests were carried out on models to estimate performance in both the X and Y directions. The resulting actuator demonstrated a wide working velocity range, zero backlash, and precise positioning in the nanometer scale. Experimental validation of the fabricated actuator confirmed its reliability. The actuator exhibited a stroke length ranging from 325 to 725 nm with repeatability within ±25 to ±50 nm. Opportunities exist for further enhancement of the actuator's dynamic performance. This work describes an approach for doing accurate and economical finite element method (FEM) simulations of planar compliant mechanisms with flexure hinges. The method includes modelling one-eighth of a single hinge to determine its genuine stress and stiffness properties utilizing symmetry/antisymmetry boundary conditions and 3D components as shown in figure 4. Furthermore, a set of fictional beams with identical properties is generated to model the hinges, which are then coupled with additional beams representing reasonably stiff linkages to build an analogous model of the complete mechanism made entirely of beam components. The study shows that the static and dynamic properties of the entire 3RRR mechanism may be precisely recreated using a model with a low number of degrees of freedom (DOF). The Equivalent Beam Model (EBM) is highly efficient in numerical simulations, making it suitable for a wide range of applications, including mathematical optimization, simulating complicated dynamic reactions, and even real-time control and handling of compliant devices [1,42-43].

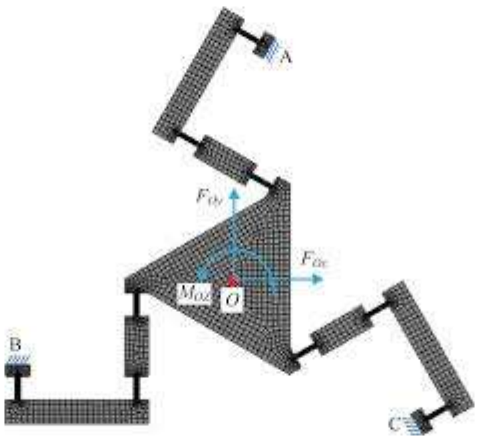

Figure 4: Axis Symmetry 3D Mesh Component

M. Verotti, S. Serafino, et al., conducted an evaluation of the rotational performance of planar flexures. They examined various criteria for uniform and cross-axis flexural pivots, as outlined in previous literature, and established relationships between them. Specifically, they applied the pole of the finite displacement criteria to the design of high-accuracy cross-axis pivots with initial curvature [2, 44]. Haiyang Li, Yijie Liu, et al., introduced the concept of constraint flow and mathematical expressions for synthesizing decoupled XYθ-CPMs (Cross-Platform Modules). This design was both analytically modeled and experimentally tested. They proposed up to 6859 constraint combinations for potential synthesis schemes. Two case studies were presented to demonstrate and verify the constraint-flow based synthesis method. The analytical model results showed less than a 6.45% difference compared to Finite Element Analysis (FEA) results. Both the motion and actuation couplings of the XYθ-CPM were less than 2.4% within the motion ranges. Experimental results showed high motion resolutions of 5 nm for translations along the X- and Y-axes and 50 n rad for rotation about the Z-axis. However, for the prototype, motion and actuation couplings were less than 3.9% within the motion ranges, higher than FEA results due to fabrication and measurement errors. The concept of constraint flow can be extended to the synthesis of other compliant mechanisms, and future studies may focus on nonlinear dynamic characteristics and parameter optimization. The mechanical design and dynamics of a flexure-based parallel mechanism with three degrees of freedom (3-DOF) were described. Three piezoelectric actuators powered the mechanism's active linkages. Flexure hinges were reduced to perfect revolute joints with constant torsional stiffness in order to determine the mechanism's inverse dynamics. The performance of the proposed 3-DOF flexure-based parallel mechanism was confirmed by finite element analysis. Extensive research into the interaction between the actuators and the flexure-based mechanism was carried out using the developed model. Experimental experiments were carried out to confirm the dynamic performance of the 3-DOF flexure-based mechanism [3,45]. Lijian Li, Dan Zhang, et al., presented two generalized models for designing numerous new types of multiple-axis flexure hinges. They formulated closed-form equations of compliance and precision for multiple-axis flexure hinges, including symmetric and hybrid types under small-deflection conditions. Dividing notch contours into segments and solving closed-form compliances and precisions of multiple-axis flexure hinges were transformed into several definite integrals associated with the notch shape functions of designated base segments and matrix operations. The presented models were verified by FEA results and existing equations, offering assistance in improving the performance of spatial compliant mechanisms. Compliant mechanisms are paving the way for micropositioning stages, providing several benefits. However, their design frequently entails trade-offs between motion range, precision, and design space, favouring mechanisms with dispersed compliance.Thus, this study describes a high-precision compliant XY micropositioning stage with flexure hinges capable of attaining a 10 mm motion range along both axes. The monolithic XY stage synthesis requires replacing all revolute joints in the rigid-body model with flexure hinges that use optimised power function notch shapes. The emphasis is on stage embodiment design and actuator integration to reduce potential error causes. Finally, the quasi-static behaviour of the compliant stage is characterised by simulation with a 3D finite element model and experimental testing of a prototype [4,47-48]. Dong, G., Sun, S., et al., developed a flexible micro-positioning platform to maximize the utilization of the high amplification ratio of the bridge-type mechanism for ceramic material testing. This platform utilized a laminated piezoelectric ceramic driver and bridge-type amplifier mechanism as the driving devices, allowing for 3DOF (Degree of Freedom) fretting with minimal motion loss and high transmission efficiency as shown in figure 5. Principles of material mechanics, the Lagrange equation, and elastic beam theory were applied to derive natural frequency and magnification expressions of the positioning platform. The results of magnification and natural frequency were simulated by FEA and compared with theoretical results [5].

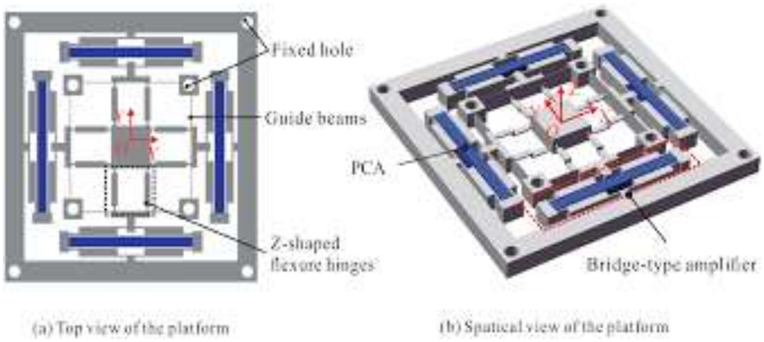

Figure 5: 3DOF Bidirectional Motion platform

Zhichao Shi, Xiaoquan Li, et al., proposed a four-layer structure composed of L-shaped spatial double parallelogram flexure mechanisms for a magnetic stage to address existing design challenges of 2-degree-of-freedom guiding mechanisms. This mechanism was modeled using the compliance matrix method. An electromagnetic model for the Voice Coil Motors (VCMs) and the equivalent magnetic network method were combined for an electromagnetic-mechanical coupling optimization method with multiple constraints, aiming to achieve millimeter-range motion with a maximized natural frequency. The optimized prototype was tested with a stroke of ±3.41 mm and ±3.08 mm for the X-axis and Y-axis, respectively, a closed-loop resolution of 100 nm for the X-axis and 150 nm for the Y-axis, and a resonant frequency of 11.75 Hz for both axes. The tracking of a 0.1 Hz spiral of Archimedes achieved a maximum tracking error of 2.9% [6,49]. Pratik M. Waghmare, Shrishail B. Sollapur, et al., presented a review focusing on the design and analysis of flexure mechanisms. They suggested the use of Finite Element Method (FEM) simulations for the validation of planar compliant mechanisms with flexure hinges. Future work could involve creating an algorithm to aid in determining design parameters of a mechanism given specific constraints [7]. Pietro Bilancia, Giovanni Berselli, compared the capabilities of computationally efficient modeling techniques, including 1D Finite Element Analysis (FEA), PRB method, and chained-beam constraint model, focusing on their applicability in nonstandard planar problems. Cross-axis flexural pivots were highlighted as important in research due to their highly configurable behavior and wide range of applications. MATLAB and CAD CAE packages were found to provide an easy-to-use environment for compliant mechanism (CM) analysis and design. A summary table was provided for the selection of an appropriate technique and software framework, and two design examples were examined to configure nonstandard beam-based CMs with prescribed behavior [8]. Stefan Henning, Lena Zentner, presented a Graphical User Interface (GUI) for accelerated analysis and synthesis of compliant mechanisms. This interface allowed for fast and accurate analysis of planar compliant mechanisms, considering bending, shear, and lateral contraction for large deflections. The tool facilitated parametric studies to optimize given geometries for specific motion tasks [9]. Qiang, Huaibo, Qiang Huang, et al., presented a motion screw model of a parallelogram guide mechanism compliant mechanism to meet the precision requirements of a translational guidance precision probe. The flexibility analysis method was used to study the motion screw of the flexible guiding units and the compliant guiding mechanism. FEA simulation results showed a maximum relative error of 6.33% with the matrix model. The motion screw method offered a novel approach for studying the motion characteristics of flexible mechanisms [10,50].

A current demand in precision scanning applications is the development of a low-cost flexural mechanism and control system that offers high precision positioning accuracy. Researchers worldwide have tackled this challenge by exploring monolithic designs of flexural mechanisms and incorporating high-resolution position sensors, such as optical encoders or piezo-based sensors. These sensors serve as crucial feedback elements for achieving precise scanning capabilities.

Conclusion

This paper presents unique designs that use existing flexural units and novel geometric symmetries to decrease or eliminate cross-sensitivity among actuators and parasitic coupling across axes. Future study will focus on establishing an efficient synthesis method for determining design characteristics that match particular limitations. The suggested technique incorporates accurate and efficient finite element simulations of planar compliant mechanisms with flexure hinges, which are validated using finite element analysis as described in the current literature. To meet the requirement for accurate scanning applications, several mechanisms have been developed, including piezo-based stages, spring-loaded systems, and ball screw mechanisms. Flexural mechanisms are becoming increasingly popular among researchers due to their benefits, which include rapid speed, a wide scanning range, and greater positioning precision. Flexural mechanisms provide frictionless, backlash-free motion, resulting in great reproducibility and precision control. This article examines the present level of research in creating flexural mechanisms for high-precision applications, as well as the prospective scope for their design and development across a wide range of applications.

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