DOCTORAL THESIS PROPOSAL

Title: Analysis and Synthesis of Multiple Degree-of-Freedom Flexure Mechanisms
Candidate: Shorya Awtar
Advisor: Prof. Alexander Slocum

ABSTRACT

This thesis presents a new class of parallel-kinematics flexure mechanisms that have multiple degrees of freedom and substantially small parasitic error motions. These mechanisms are of importance to macro and micro scale precision positioning applications, including MEMS sensors and actuators, optics, and semiconductor fabrication. A systematic approach for the analysis and synthesis of these flexure mechanisms is presented. Synthesis rules are laid out based on insight gained from analytical findings. Constraint analysis, error motion analysis, and optimization for static and dynamic performance are some of the design tools that are developed for this specific class of flexures, and may be extended to other topologies as well.

BACKGROUND

Flexure mechanisms rely on material elasticity to produce motion and transmit forces. These mechanisms constitute a significant body of mechanical designs and find applications in conventional as well as emerging areas. The key advantage of flexure mechanisms lies in their simplicity and high precision in the absence of friction and backlash. There exits a considerable amount of design knowledge on flexures, which is derived from the experiences of numerous inventors and engineers [I, 1-8].

While a large part of flexure design is based on creative thinking and engineering intuition, analytical tools can significantly aid the design conception, evaluation and optimization process. Consequently, a systematic study and modeling of these devices has recently gained momentum in recent times. Clearly, flexures deviate from the classic linkage mechanisms with regard to the fact that they rely on elastic deformation for functionality. Hence any analysis of flexures requires a study of mechanics of deformable bodies, in additional to kinematics.

Some early work deals with precision mechanisms that use flexures as replacements for hinges thus eliminating friction and backlash [II, 1-2]. Unlike these cases where compliance in the system is localized, another interesting group of mechanisms that have now become more common are those in which compliance is distributed over the entire topology of the mechanism. These mechanisms offer a rich mine of innovative and elegant design solutions for a wide range of requirements. Many researchers have tackled the problem of analysis and synthesis of these mechanisms (II, 3-8). The biggest tradeoff in any analysis method is that between the generality of the theory, computational complexity involved, and scope of results. On one extreme is Finite Element Method that can be used for mechanisms of any shape and size, but is computationally intensive and provides no parametric information. On the other hand are simplified models, for example, pseudo-rigid-body models [II, 8] that involve less computational complexity and provide parametric performance information, but are limited in their range of application. Based on these various analytical methods, researchers have also explored topological and shape synthesis of mechanisms (II, 4-8). Significant advances have been made in the area of topological synthesis of flexure mechanisms by applying the principles of multi-objective structural optimization using numerical techniques (II, 6-7). Unfortunately, such computational synthesis methods limit the otherwise vast design space of flexures, which is what makes flexure design exciting in the first place. Some of the best designs come from pseudo-random thought processes that can rarely be captured by a computer-based optimization algorithm.

As an alternative to the above methods, it is desirable to develop analytical tools that aid the intuition of a design engineer - tools that can be used to quickly and accurately estimate the stiffness of a mechanism in various directions, that can help identify over-constraining arrangements, that can be used to estimate error motions in a mechanism and validate the role of symmetry in design. Symbolic mapping of system parameters to system performance, if obtained, can prove to be very powerful in this regard.

An important performance measure is degrees of freedom (DOF) and constraint. Due to the continuum nature of flexure mechanisms, it is a challenge to build a finite DOF model. While a rudimentary constraint analysis for flexures can be found in some texts [III, 1], fundamental work in this area has been done by researchers who developed a modified Grubler's criteria for compliant mechanisms [III, 2-4]. However, this existing research does not address complex mechanisms and over-constraint phenomena. Furthermore, this DOF criteria depends on prior knowledge of the what the mechanism does, rather than providing insight into what it is supposed to do.

Another performance measure is that of parasitic errors in flexure mechanism. For the sake of simplicity and compactness, flexure stages may be built on parallel kinematics rather than by stacking up multiple single DOF flexure stages. An inherent challenge with parallel-kinematics designs is that they are prone to parasitic error motions, i.e., there is a coupling between the various degrees of freedom and constraint. Little work exists in the literature that deals with the parallel kinematics of flexures and quantification of error motions. Designers strive to eliminate or minimize these errors by making insightful use of geometry and symmetry (IV, 1). It is desirable to develop a simple model for the parameterization of parasitic error motions in flexure mechanisms.

Furthermore, flexural motion stages are used along with sensors, actuators and drive electronics for closed-loop operation. However, in most cases a flexure design is first conceived; sensors, actuators and controls are an afterthought. An integration of mechanics, systems and controls, and sensor/actuator selection through the process of design can lead to better overall flexure systems. This then requires design for dynamic performance in addition to the static performance measures mentioned above.

Technical literature presents many existing multi-DOF motion stage designs based on flexures [V, 1-16]. Designs that rely on serial-kinematics, [V, 3] for example, incorporate moving actuators and cables that limit the dynamic performance. Moving actuators and connections are also undesirable for flexure mechanisms used in MEMS applications. On the other hand, parallel-kinematics designs, [V, 1-2] for example, provide smaller range of motion and suffer from serious parasitic error motions. Hence, it is desirable to create compact multi-DOF motion stages that can generate precise and error-free motion over large ranges, and at the same time allow for ground-mounting of all actuators.

PROPOSED AREAS OF INVESTIGATION AND CONTRIBUTION

Static Performance: DOF Analysis and Quantification of Parasitic Errors

This work investigates simple methods based on kinematics and mechanics that can provide a basis for robust degree of freedom analysis for flexure mechanisms with distributed compliance. Certain simplifying, yet practical, assumptions need to be made to be able to capture the continuous media of flexures in a finite DOF model. Stiffness in various directions is easily quantified as a function of geometric and material parameters, as well as loading. These stiffness values are then non-dimensionalized to obtain a *stiffness number* that allows a comparison between the relative magnitudes of stiffness in various directions. The *stiffness number* can be used as a basis for defining degrees of freedom and constraint. Factors that cause over-constraint need to be identified and incorporated in the *stiffness number*.

A parasitic error may be identified as an undesired motion that is kinematically dependent on the degrees of freedom. These error motions are derived for simple flexure units and subsequently can be used for estimating errors in complex mechanism built from these. A parametric representation of errors is useful when trying to alleviate the coupling between the various degrees of freedom and constraint in a mechanism.

Analytical Aids for Topological Design

The stiffness properties and error motions of some simple flexures including the beam flexure, parallelogram flexure, and compound parallelogram flexure, have been thoroughly characterized. These simple flexure units can be arranged in various patterns to generate interesting flexure mechanisms with specific functionality. This thesis shall explore how the characteristics of the individual building units influence the performance of the overall flexure mechanism. Specifically,

- Estimate *stiffness numbers* and DOF of a flexure mechanism simply by considering the stiffness properties of its constituent building units
- Investigate how the error motions of the building units translate to the error motions in the resulting flexure mechanism
- Estimate the influence of motion in one direction on the stiffness in other directions, in a multi DOF flexure mechanism
- Define a Center of Stiffness (COS) concept for flexures and investigate how the COS shifts with motion in one or more directions
- Perform a Sensitivity Analysis to estimate performance sensitivity to manufacturing tolerances, thermal inputs and other system parameters
- Investigate the effect of symmetry in the topological layout of a flexure mechanism on the resulting performance measures

Based on the above considerations, this research shall attempt to obtain some simple rules of thumb for an optimal topological layout of flexure mechanisms, such that the undesirable aspects of the building units can be minimized, while the desirable aspects can be retained or enhanced. This shall be illustrated by means of examples. It should also be noted that the applicability of the above rules and analytical aids would be limited to a class of flexure mechanisms, and may not be useful for any generalized elastic body.

Topological Synthesis Rules and Novel Multi-DOF Flexure Mechanisms

Based on engineering intuition and the analytical aids mentioned above, this thesis presents topological layout guidelines for two or more axes flexure mechanisms with very low parasitic error motions. Some exemplary designs that have been invented are shown in Figures 1 and 2. Salient features of these designs are:

- Employ parallel-kinematics to achieve multiple degrees of freedom: no moving actuators or cables
- Single plane design, compact in Z-direction: no stacking of stages
- Six actuation forces produce five degrees of freedom
- Twist in Z-direction is completely eliminated
- Symmetry in design improves performance measures
- Appropriate location of actuation forces minimizes parasitic errors and coupling between the five degrees of freedoms
- Theoretically zero parasitic errors and coupling has been predicted for the design illustrated in Fig. 2.

Dynamic Performance

Often flexure stages are operated in a closed-loop configuration, and therefore it is necessary to consider all aspects of the system, including mechanics, controls, electronics, and sensor/actuator selection, while developing and detailing the flexure design. Dynamic performance measures like system bandwidth, steady-state errors, dynamic stiffness, and settling time can be improved only by paying careful attention to each the above-mentioned aspects. Damping analysis is critical in the evaluation of dynamic performance measures. This research attempts to illustrate the process of deterministic mechatronic design in the development of multiple DOF flexure stages for micro and macro scale applications.

Design Optimization

Having obtained static and dynamic performance measures, size and shape optimization of a given flexure mechanism topology can be performed using one of the well-established optimization techniques - variational principles, Linear and Quadratic Programming, Genetic Algorithms etc. These optimization methods can be used to possibly generate variable cross-section beams to yield better overall performance.

Fabrication and Testing of ‘Pentaflex’, a 5 DOF Flexure Motion Stage

The contributions of this doctoral work shall also include the detailed design, fabrication and testing of a multi DOF flexure motion stage for the specimen mounting stage of a High Precision Microscope (HPM) that is currently being developed at the MIT Precision Engineering Research Group, for conducting single molecule experiments such as, observation of proteins binding to a single DNA strand. The design tools and methodology developed above shall be used in the analysis and optimization of this design. Experimental characterization shall be performed to validate the predictions of the classical as well as FEM analyses.

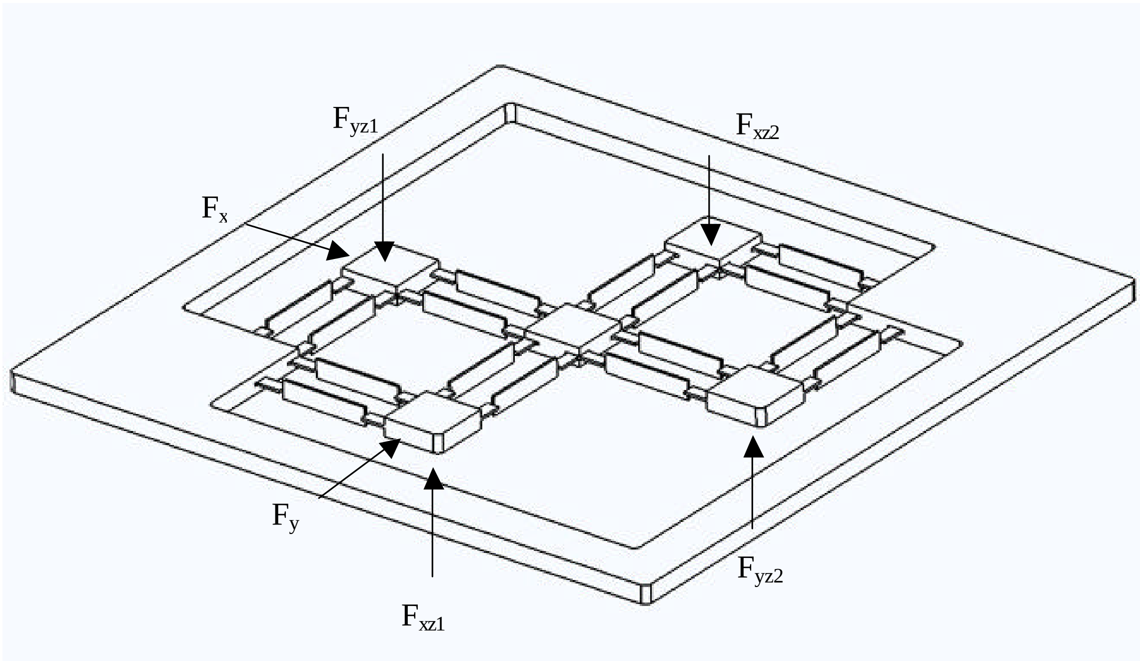

Figure 1. Pentaflex (Version 1)

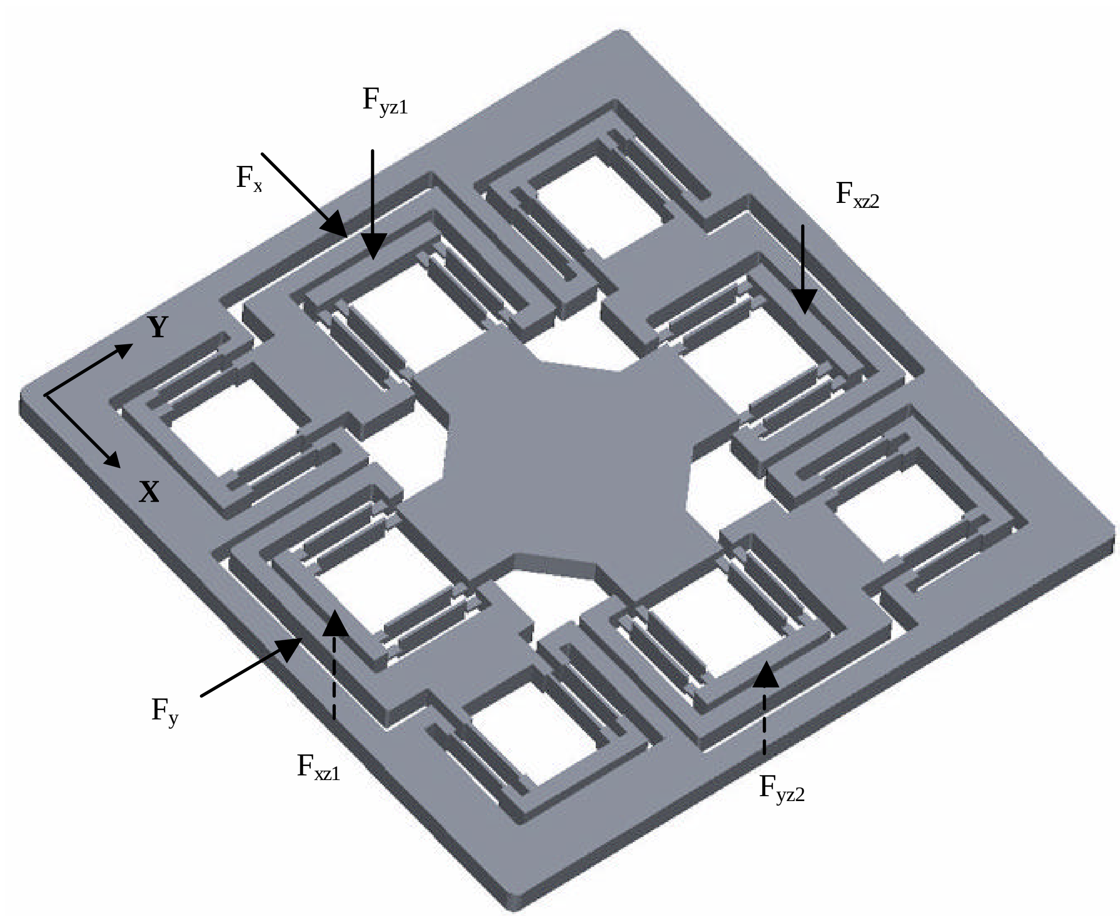

Figure 2. Pentaflex (Version 2)

POTENTIAL AREAS OF APPLICATION

- Precision motion stages for macro, meso and micro scale applications
- Specimen Panning/Scanning/Tilting stage for optical microscopes
- MEMS actuators, e.g., for micromanipulation
- MEMS sensors, e.g., multiple axis accelerometers
- Precision robotics , e.g., for robotic surgery
- Any application where single-plane high-precision XY motion is required: optical alignment, beam steering, optical fiber alignment, scanning microscopy, semiconductor test equipment, precision mask and wafer alignment, scanning interferometry, imaging, surface structure analysis, AFM control, surface structure analysis

BACKGROUND SEARCH

I. Texts on Flexures

1. R.V. Jones, "Instruments and Experiences - Papers on Measurement and Instrument Design", John Wiley & Sons, 1998
2. R.N. Motsinger, "Flexural Devices in Measurement Systems", Chapter 11 in *Measurement Engineering*, by P.K. Stein, Stein Engineering Services, 1964
3. S.T. Smith and D.G.Chetwynd, "Ultra-Precision Mechanism Design", Gordon and Breach Science Publishers, 1992
4. S.T. Smith, "Flexure- Elements of Elastic Mechanisms", Gordon and Breach Science Publishers, 2000
5. Blanding, "Exact Constraint: Machine Design Using Kinematic Principles", ASME Press, 1999
6. L.L. Howell, "Compliant Mechanisms", John Wiley & Sons, 2001
7. A.H. Slocum, "Precision Machine Design", SME, 1992
8. A. Midha, "Elastic Mechanisms", Chapter 9 in *Modern Kinematics – The developments in the Last Forty Years*, John Wiley & Sons, 1993

II. Analysis and Design Methodology, Synthesis Techniques including Numerical Optimization

1. J. M. Paros, L. Weisbord, "How to Design Flexure Hinges", Machine Design, 1965
2. F.S. Eastman, "The Design of Flexural Pivots", Journal of Aerospace Science, Vol. 5, Nov. 1937
3. J.V. Ejik, "On the Design of Plate Spring Mechanism", Ph.D. thesis, Delft University of Technology, Delft, The Netherlands, 1985
4. R. H. Burns, "The kinetostatic synthesis of flexible link mechanisms", Ph.D. Thesis, Yale University, New Haven, CT, 1964
5. I. Her, " Methodology for Compliant Mechanisms Design," Ph.D. Thesis, Purdue University, West Lafayette, 1986
6. G. K. Ananthasuresh, "A new design paradigm in microelectromechanical systems and investigations on compliant mechanisms", Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1994
7. G.K. Ananthasuresh, S. Kota, Y. Gianchandani, " A Methodical Approach to design of compliant Micromechanisms", Solid State Sensor and Actuator Workshop, Hilton Head Island, SC, pp 189-192, 1994
8. B.D. Jensen, L.L. Howell et al, "The design and analysis of Compliant MEMS Using the Pseudo-rigid-body Model," Microelectromechanical Systems, at the ASME International Mechanical Engineering Congress and Exposition, Vol 62, pp119-126, 1997

III. Degree of Freedom and Constraint Analysis

1. Blanding, "Exact Constraint: Machine Design Using Kinematic Principles", 1999
2. I. Her and A. Midha, " A Compliance Number Concept for Compliant Mechanisms, and Type Synthesis", ASME Journal of Mechanisms, Transmission, and Automation in Design, Vol. 109, No.3, pp 348-355, 1987

3. G.K. Ananthasuresh, L.L. Howell, “Case Studies and a Note on the Degree-of-Freedom in Compliant Mechanism”, Proc. of 1996 ASME Design Engineering Technical Conferences, 96-DETC/MECH-1217
4. M. D. Murphy, A. Midha, L. L. Howell, “On the Mobility of Compliant Mechanism”, Proc. of the 1994 ASME Mechanisms Conference, DE-Vol.71, pp. 475-479
5. S. Ball, “Treatise on the Theory of Screws,” Cambridge Press, 1900

IV. Error Motion Modeling, Quantification and Alleviation

1. RV Jones, “Some parasitic Spring Deflexions in parallel spring movements”, Journal of Scientific Instruments, Vol.33, pp. 11-15, Jan 1956

V. Multi DOF Flexures and Micropositioners

1. Single-Module, XY Piezo Flexure NanoPositioner and Scanner, P-733, Physik Instrumente Product Catalog, 2002
2. T.B. Eom and J.Y. Kim, “Long Range Stage for the Metrological Atomic Force Microscope”, Proceedings of ASPE 2001 Annual Meeting, Pg. 156-159
2. B. Jokiel, G.L. Benavides, L.F. Bieg, J.A. Allen, “ Planer and Spatial Three Degree of Freedom Micro Stages in Silicon MEMS”, Proceedings of ASPE 2001 Annual Meeting, Pg. 32-35
3. N.G. Dagalakis, J.A. Kramer, E. Amatucci, R.Bunch, “Kinematic Modelling and Analysis of Planer Micro-positioner”, Proceedings of ASPE 2001 Annual Meeting, Pg. 135-138
4. US Patent 4520570, “Piezo Electric XY Positioner”, IBM Corp., 1985
5. US Patent 6414785, “Precision Positioner for Optical Elements”, Agilent Technologies Inc., 2002
6. US Patent 5808435, “Micropositioning Device for Disk Head Testing System”, KMY Instruments, 1998
7. USPatent 5623853, “Precision Motion Stage with Single Guiding Beam and Follower Stage”, Nikon Precision Inc., 1997
8. US Patent 4575942, “Ultra-Precision Two-Dimensional Moving Apparatus”, Hitachi Ltd., 1986
9. US Patent 5059090, “Two-Dimensional Positioning Apparatus”, IBM Corp., 1991
10. US Patent 5559915, “Apparatuses and Methods for Alighning and Optical Fiber Array with an Optical Integrated Circuit Assembly”, Lucent Technologies Inc., 1996
11. US Patent 6282066, “MicroActuator Suspension with Multiple Narrow Beams”, Seagate Technologies LLC, 2001
12. US Patents 5303035, “ Precision Micropositioners”, New Focus Inc., 1994
13. US Patent 5812310, “Orthogonal High Accuracy Microscope Stage”, Applied Precision Inc., 1998
14. Kanai et al, “An Elastic Fine Positioning Mechanism Applied to Contactless X-Y Table”, Bulletin of JSPE, Vol 17, No. 4, pp. 265-266, 1983
15. Layton, “X-Y Flexure”,
16. Six-Axis Parallel Kinematic Positioning System F-206, Physik Instrumente Product Catalog, 2002