

Multiple degree of freedom compliant mechanism possessing nearly uncoupled dynamics: experimental findings

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ABSTRACT

Micromanipulation has enabled numerous technological breakthroughs in recent years, from advances in biotechnology to micro-component assembly. Micromanipulators commonly use piezoelectric actuators (PZT) and a compliant mechanism to provide fine motions with position resolution in the nanometre or even sub-nanometre range. Parallel compliant mechanisms are used to provide motion with multiple degrees-of-freedom (DOF) as parallel mechanisms provide greater rigidity and positioning accuracy than serial mechanisms. However, parallel mechanisms with multiple DOF often have dynamic behavior that is coupled, non-linear and highly complex. This leads to difficulties in modeling and controller design, often requiring sophisticated control techniques such as model-based or neural networks to provide fast, accurate control.

This paper presents the findings of an experimental study into the dynamics of a particular 3 DOF compliant mechanism, specifically considering actuator-space coupling at a range of frequencies and poses. It was expected that the dynamics would be coupled as a dynamic model developed for this mechanism suggested this to be the case. However the experimental results reveal the surprising and useful finding that this mechanism possesses almost completely uncoupled dynamics for the operating bandwidth of the manipulator. This result simplifies the problem of controller design and suggests that the micromanipulator could be effectively controlled using simple independent joint control without requiring development of a decoupling controller.

Keywords: Micromanipulation, compliant mechanism, multiple degree-of-freedom, parallel mechanism, dynamics, coupling

1. INTRODUCTION

During the past two decades considerable research has been conducted to develop micromanipulators to be used for purposes, such as biological cell manipulation in biotechnology or micro-component assembly in micro-technology. The majority of these micromanipulators are based on the use of the piezo-ceramic actuator (PZT) and the compliant mechanism. PZT actuators can provide near linear motion with resolution of nanometers or sub-nanometers. Compliant mechanisms, which move solely through deformation of flexures instead of bearings, provide smooth motion with no backlash or Coulomb friction. As there are no hard non-linearities in the compliant mechanism behavior there are no physical limitations on the resolution of position control. Therefore a manipulator based on these components is able to provide ultra-high precision positioning.

Parallel micromanipulators are commonly used in micromanipulation [1-9] due to the advantage of greater rigidity, which allows for more accurate motion and faster response. These attributes are particularly beneficial for ultra high precision positioning. In addition the actuators can be located in the base of the manipulator so that the link masses can be reduced.

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The micromanipulator studied in this research is a 3-degree-of-freedom (DOF) parallel manipulator with RRR serial linkages. It uses a monolithic, flexure hinge, compliant mechanism, actuated by 3 PZT stack actuators, see Figure 1. Flexure hinges are thin sections of material that deform under load to provide rotational motion. These hinges act as joints, which are joined by thicker sections of material, which do not deform and act as rigid links. The end-effector platform is bolted to the ends of the 3 linkages, as indicated by the triangle in Fig. 1. The end-effector has degrees of freedom in the x and y-axis and rotation about the z-axis. This compliant mechanism was developed by a collaborating research group [9-11].

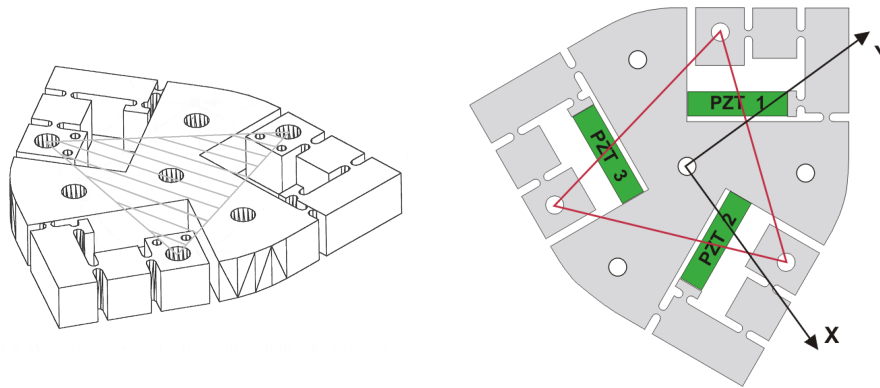


Figure 1 - Schematics of the compliant mechanism – 3D view (left) and top view of mechanism and PZT (right). The triangle represents the end-effector

This type of parallel compliant mechanism amplifies the motion of the PZT actuators and provides all planar degrees of freedom using a mechanism manufactured from a single piece of material. This makes manufacturing simple and cost effective and does not require the assembly of multiple stages possessing only one or two DOF. This makes the 3 DOF stage compact and minimizes stage mass. In addition the symmetry of the design make the mechanism unsusceptible to kinematic changes due to thermal expansion. For these reasons this particular topology of mechanism, which will be referred to herein as the *planar 3RRR* compliant mechanism, is of great interest and has been investigated by a number of researchers [3,5,9,13,14].

A common disadvantage of parallel mechanisms is that they demonstrate significant coupling between degrees-of-freedom and their dynamics are often highly non-linear and complex to model. This makes controller design of the manipulator difficult. In such coupled-parallel manipulators model-based control (MBC) and other non-linear control techniques have been applied to de-couple the actuators and improve control [1,15]. The difficulty in applying MBC lies in deriving a dynamic model that is accurate, yet computationally efficient enough, to be useful for real-time control. In the case of micromanipulators, where the natural frequency and the potential operating frequency are far higher than macro-manipulators, there is an additional need for a computationally efficient controller. If a manipulator is designed to possess uncoupled dynamics then the problem of control is simplified.

A dynamic model was developed for this particular compliant mechanism by a previous researcher [11]. This model suggested that the mechanism was a coupled system. Simulation indicated that PD control was ineffective which suggested the need for non-linear control such as MBC. However, the experimental observations discussed in this paper suggest that the system is actually uncoupled for motion within the operating bandwidth. The objective of this paper is to develop an understanding of the uncoupling property in this compliant mechanism because such a property will improve control efficiency and effectiveness enormously.

2. RELATED WORK

The original work conducted at the Advanced Engineering Design Laboratory (AEDL) of the University of Saskatchewan involved the modeling of the compliant mechanism. Kinematic and dynamic models of compliant mechanisms are commonly derived using a pseudo-rigid-body-model (PRBM). This assumes that the flexure hinges act as revolute joints with torsional springs attached, while the thick sections act as rigid links. A PRBM was developed for this particular manipulator. Using the PRBM a kinematic model was derived using a Constant-Jacobian method [12] and a dynamic model was derived using the Lagrangian method [11].

The dynamic model of a compliant mechanism differs from a standard joint mechanism as its joints have stiffness equivalent to the stiffness of the flexure hinge. The modeling of parallel manipulators is generally quite complex as the actuators are mechanically coupled and inertial variations are directly felt at each actuator. In the case of the parallel-compliant manipulator the stiffness is also coupled adding extra complexity. The dynamic model developed in [11] represents the stiffness, inertia and damping by complex non-linear 3x3 matrix. It has been shown in [11] that there are strong couplings among the three actuators in the mechanism that makes the conventional proportional and derivative control law fail.

A number of researchers have established dynamic models and developed controllers for coupled-parallel micromanipulators. Fite and Golfarb developed a spatial 3 DOF compliant manipulator for which they derived a dynamic model using the Lagrangian method [1,16]. They reported that the parallel compliant manipulator they had developed possessed highly coupled inertia and stiffness, which were represented by full 3x3 matrix. In order to control this manipulator they applied feedforward stiffness cancellation to decouple the dominant dynamics and then applied independent feedback to each actuator. However, modeling error suggested the additional use of a sliding mode controller to provide effective control. Tsai and Yen investigated servo system design of a planar 3 DOF fine motion stage using a multivariable system identification process[17]. They noted that there was coupling between degrees-of-freedom in the system dynamics. Rather than determining the coupled dynamic model and applying a MIMO controller they took a simple approach and applied a diagonal controller on the MIMO system. This proved a valid approach as they noted that the non-diagonal coupling terms were relatively small compared to the main diagonal entries. The manipulators mentioned above all used topologies considerably different to that considered in this paper.

To improve dynamic behavior a decoupling design method has been proposed [6]. Tomita et al considered a 6-dof ultraprecision stage using a parallel linkage mechanism and proposed a synthesis method to approximately decouple each degree of freedom. They derived a dynamic model that was used to determine geometric parameters that would render the stiffness coupling terms close to zero. They successfully designed and built a manipulator with approximately decoupled dynamics at the desired frequency of 50Hz. The mechanism they considered had a different topology to the planar 3RRR mechanism and its actuators were arranged orthogonal or parallel to each other.

Several researchers have investigated the use of the planar 3RRR manipulator topology discussed in this paper. Ma and Angeles studied the direct kinematics and dynamics of a non-compliant manipulator and suggested an efficient method to derive these models [13]. Their work was purely theoretical and the coupling between degrees-of- freedom, and control considerations were not discussed. Gosselin and Angeles also considered the kinematics of this same non-compliant manipulator and applied four design criteria to obtain an optimized design [14]. The planar 3RRR mechanism has also been used in a number of compliant manipulators. Gao and Swei designed a 6-DOF manipulator that used the planar 3RRR mechanism with flexure hinges as a base stage [5]. They considered a kinematic analysis of the manipulator but did not consider the dynamic behavior. Hesselbach, Plitea, and Thoben designed a planar 3RRR compliant manipulator and built a non-compliant prototype. They discussed kinematic analysis and optimization of such a manipulator [2]. Ryu et al. designed and built an optimized planar 3RRR micromanipulator using flexure hinges [3]. Their method aimed to maximize the end-effector rotation. A dynamic model of the mechanism was derived and used to calculate the natural frequency. Natural frequency, maximum material stress and out-of-plane stiffness were then used as optimization constraints. They did not discuss control of the manipulator or coupling.

Kim et al. considered the planar 3RRR mechanism, with base joint compliance, as a RCC device [18]. They investigated the kinematics and compliance of the mechanism in order to determine the RCC characteristics of the mechanism. They established that this mechanism possesses a RCC point, at which the compliance matrix is decoupled

in the object space. This occurs when the mechanism is in a symmetrical configuration and all joint compliances are symmetrical.

It is interesting to note that there has been lack of study in the current literature on compliant mechanisms in terms of integrated design and control of such systems with particular attention to decoupling of active joint motions or actuations. Some studies on this direction in the case of conventional multi-DOF mechanisms have been performed [19].

3. EXPERIMENTAL STUDY

3.1 COUPLING INVESTIGATION

An investigation was conducted to experimentally determine the magnitude of coupling between actuators for the operating bandwidth of the system. The final manipulation system will use visual end-effector feedback, which currently has an operating frequency of approximately 10Hz. With improved computing hardware it is likely that this operating frequency will increase in the near future. This investigation considered coupling at a frequency of up to 80Hz (500rad/s). The coupling in a range of poses throughout the joint-space was considered to observe how position of the mechanism effected the degree of coupling.

3.2 EXPERIMENTAL SET-UP

The micromanipulation stage developed at the AEDL consists of 3 Tokin AE0505D16 PZT stack actuators assembled into a flexure hinge, compliant mechanism, as shown in Figure 1. This mechanism provides the end-effector with 3 DOF in a plane. Each unloaded actuator has a maximum displacement of approximately 18 μ m. These PZTs are each powered by a Piezosystem Jena ENT 400/20 power supply coupled to an ENV 400 amplifier module. Each power unit provides a 60W bi-polar output with voltage range of -10 to 150V. Strain gauges are mounted to the PZTs to determine their displacement. The PZT are each wired to a Measurements Group 2120B strain gauge conditioner, which are coupled to a 2110B power supply. The amplifiers and strain gauge conditioning circuitry are connected to a dSPACE DS1102 DSP controller board via inbuilt DAC's and ADC's. A schematic of the experimental set-up is shown in Figure 2.

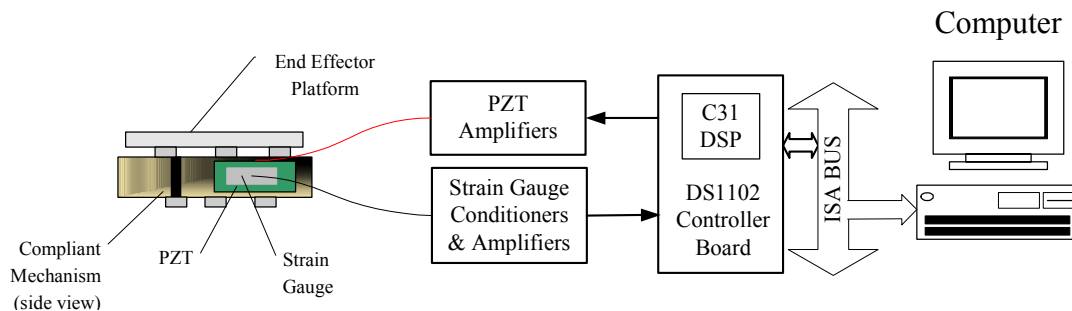


Figure 2 - Schematic of the experimental set-up

3.3 METHOD

A sinusoidal voltage was applied to PZT 3 while a constant voltage was applied to PZT 1 and 2. This caused a sinusoidal displacement of PZT 3 and caused forces to be transmitted through the mechanism to PZT 1 and 2. As the voltage to PZT 1 and 2 is constant, any displacement observed in these PZTs is due to external forces acting on them. These forces were those transmitted via coupling of the compliant mechanism from PZT 3. In effect PZT 1 and 2 acted as force sensors. This is demonstrated schematically in Figure 3.

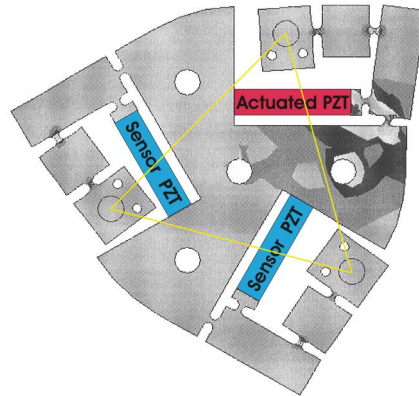


Figure 3 - Schematic demonstrating transmission of coupling forces from actuated PZT to sensor PZT

By varying the frequency of the sinusoidal input the velocity and acceleration of the mechanism was varied. This allowed observation of the static behavior at very low frequencies and dynamic behavior at higher frequencies. The frequency was varied through a range from 0.08Hz – 80Hz (0.5 – 500 rad/sec). The amplitude and offset of the sine wave remained constant. For each different frequency a time segment was recorded that captured 3 periods of the sine wave. Figure 4 shows the data recorded for a quasi-static case when the input frequency was 0.08Hz. This data was then input to a data processing program that used an averaging technique to remove the signal noise and then determine the maximum, minimum and amplitude of each PZT displacement sinusoid.

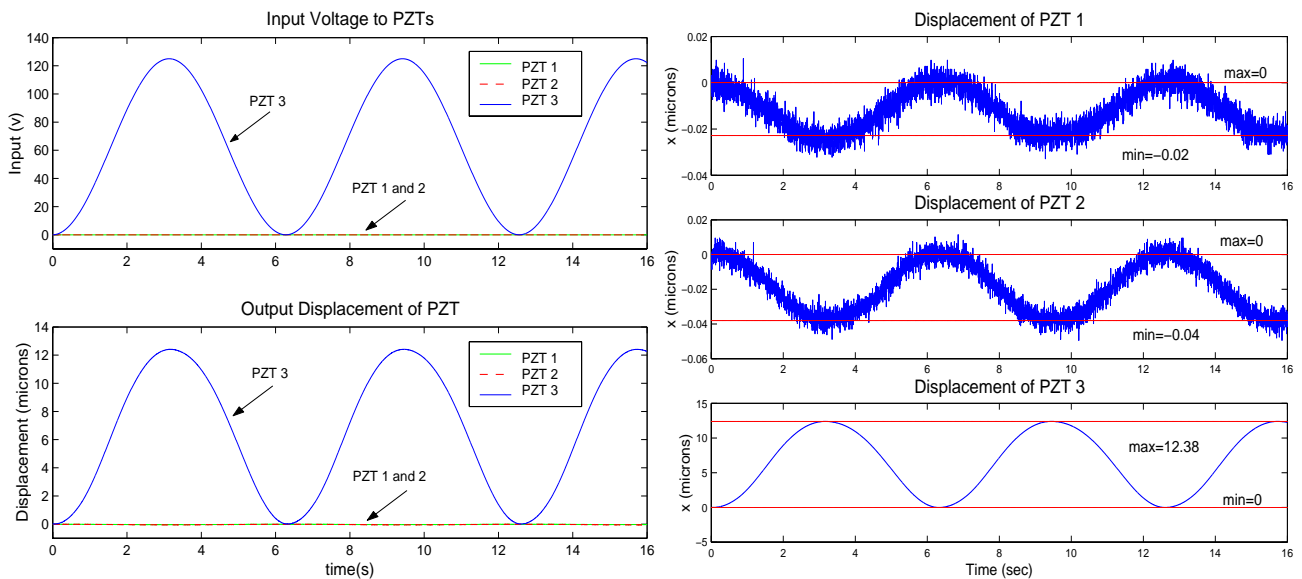


Figure 4 - Data recorded for an input frequency of 0.08 Hz. The left plot shows the output displacements on the same axis. The right plots show each PZT displacement on an individual axes and show values for the max and min displacement.

This procedure was repeated several times with different constant voltages applied to PZT 1 and 2. Thus PZT 1 and 2 were displaced to different points and the pose of the compliant mechanism changed. This ensured that differences in coupling due to mechanism pose were observed. The displacement amplitude of the actuated PZT and the sensor PZTs could then be compared to determine the magnitude of coupling. The author introduced a factor called the *coupling-ratio* that indicates the magnitude of coupling.

$$CR = \frac{x_amp(sensor)}{x_amp(actuator)} * 100\%$$

Where

CR = Coupling-Ratio

$x_amp(sensor)$ = the displacement amplitude of PZT 1 or PZT 2

$x_amp(actuator)$ = the displacement amplitude of PZT 3

By taking various averages of the coupling-ratio data for each PZT, it was possible to observe different trends. To give an indication of how coupling varies with frequency all CRs recorded for particular frequency were averaged. To indicate how coupling varies with pose all CRs recorded for a particular pose were averaged.

3.4 RESULTS

Numerous sets of displacement data were recorded. The frequencies and input voltages at which the data was recorded are shown in Table 1 below. The different input voltages applied to PZT 1 and 2 caused the position of the mechanism to vary to a range of poses throughout the joint-space. This range of inputs ensured that the results demonstrate the coupling for a general range of operating conditions. For each different pose data was recorded at every frequency.

Table 1- PZT input voltages and PZT 3 sin wave input frequencies of recorded data

PZT 1 Input -Volts	PZT 2 Input -Volts	PZT 3 Input - Volts
0	0	Sin Wave – O.S.=57.6, Amp=57.6
57.6	0	Sin Wave – O.S.=57.6, Amp=57.6
57.6	57.6	Sin Wave – O.S.=57.6, Amp=57.6
115.2	0	Sin Wave – O.S.=57.6, Amp=57.6
115.2	57.6	Sin Wave – O.S.=57.6, Amp=57.6
115.2	115.2	Sin Wave – O.S.=57.6, Amp=57.6
Sin Wave Frequencies (rad/sec) -		
0.5,1,2,5,10,20,40,60,80,100,150,200,250,300,350,400,450,500		

EFFECT OF FREQUENCY

The average coupling-ratio of all different poses is plotted vs. frequency in Figure 5.

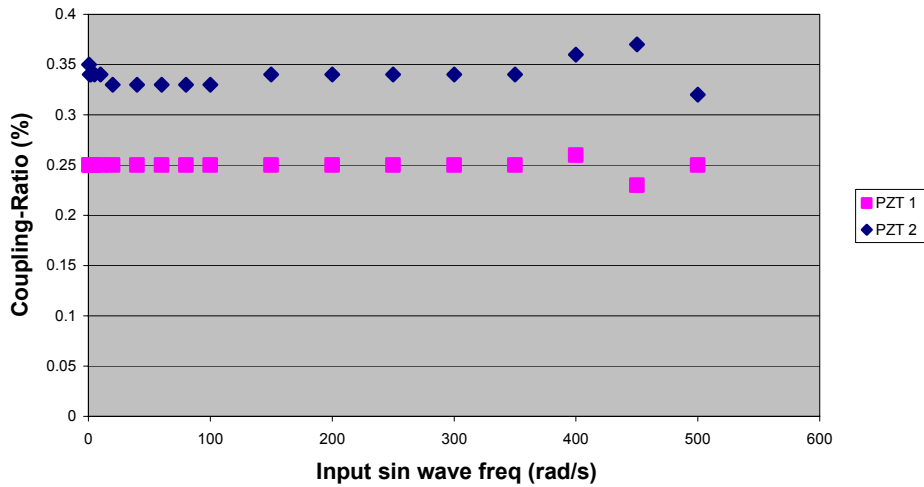


Figure 5 - Plot of the average coupling-ratio for each frequency

It can be observed that for both PZT 1 and PZT 2 there is some variation in coupling-ratio at different frequencies. At low frequencies the static coupling can be observed. This is fairly insignificant. The variation of CR for PZT 2 at low frequencies is unexpected and unexplained. At frequencies above 55Hz (350rad/sec) it can be observed that there is variation in coupling for both PZT 1 and 2. This indicates that dynamic coupling due to inertia and damping of the mechanism begins to have some effect at these frequencies. However for this frequency range dynamic coupling is less than 0.4%, which is considered insignificant.

It is noted that PZT 2 experiences a greater magnitude of coupling than PZT 1. This is thought to be due to the different orientation of these PZTs relative to PZT 3.

EFFECT OF POSE

By applying the different constant voltages to PZT 1 and 2, as given in Table 1, the joint positions of the mechanism could be varied. In Table 2 below the different poses of the mechanism are specified in joint-space by PZT displacements. The displacements given for PZT 1 and 2 correspond to zero displacement of PZT 3. When the displacement of PZT 3 changes the displacement of PZT 1 and 2 will decrease slightly, as indicated by the coupling-ratio. Table 2 gives the average minimum and maximum of the sinusoid displacement of PZT 3. The minimum and maximum displacement varies with frequency by about $\pm 0.5\mu\text{m}$. This is due to drift of the PZT. For each pose the coupling-ratios of every different frequency input were averaged. These are also given in Table 2.

Table 2 - Averaged coupling-ratios for different poses.

Displacement PZT 1 (μm)	Displacement PZT 2 (μm)	Displacement PZT 3 (μm)	Average C-R PZT 1 (%)	Average C-R PZT 2 (%)
0	0	0-12 (± 0.5)	0.19	0.31
8.3	0	0-12 (± 0.5)	0.23	0.31
8.3	8	0-12 (± 0.5)	0.24	0.38
15.5	0	0-12 (± 0.5)	0.28	0.31
15.5	8	0-12 (± 0.5)	0.27	0.38
15.5	15	0-12 (± 0.5)	0.28	0.42

From the data in Table 2 it can be observed that the pose of the mechanism has an effect on the magnitude of the coupling. This effect is more significant than the effect of frequency on the coupling, yet even the maximum magnitude of coupling is less than 0.5%, which is considered insignificant.

4. DISCUSSION

It was observed that the magnitude of coupling between actuators was relatively small for all poses and frequencies tested. As the observed range of poses and frequencies was distributed across the joint-space and operating bandwidth these results prompt the general conclusion that the dynamics coupling of this manipulator are insignificant for the given operating conditions. This is in conflict with simulation results and suggests that the dynamic model derived for this mechanism in [11] may need to be reexamined. Furthermore this suggests that modeling and control of this compliant mechanism may in fact be very simple. Independent feedback or open-loop control that has been developed for a single actuator may be applied to each PZT with the compliant mechanism considered as a simple load on each actuator. It is thus not necessary to use MBC or other decoupling control methods. Simple PI control has been applied to the micromanipulator with encouraging results. Initial investigation indicated that the performance of PI control was as effective when controlling the micromanipulator as when controlling a single PZT. Thorough investigation needs to be conducted to satisfactorily demonstrate the performance of PI control.

Two considerations are mentioned to suggest why the uncoupled property of this topology of compliant micromanipulator is observed. Firstly considering the stiffness coupling. The work by Kim et al. [18] indicates that there is a point of stiffness decoupling in the object space when the mechanism is in a symmetrical configuration and the base joint compliances are equal. The center of the manipulator workspace coincides with this point of decoupling. It appears that the workspace is small enough that the mechanism does not deviate far from this decoupling point and coupling does not become significant. In addition the stiffness of the three actuators are similar enough to ensure decoupling. Secondly considering the inertia and coriolis/centripetal forces. As the scale of the manipulator decreases the magnitude of inertial forces decreases in proportion with the volume, so inertia forces become relatively less significant compared to the stiffness forces. Goldfarb and Speich noted this effect and in the control design of their manipulator suggested that inertial terms might be neglected while stiffness terms were included in feedforward control [1]. So too in the case discussed here it is apparent that for the operating bandwidth inertia coupling has negligible effect.

5. CONCLUSIONS AND FUTURE WORK

This paper discusses the results of an experimental investigation into the dynamics coupling of a planar 3-DOF compliant mechanism. These results highlight the observation that the compliant mechanism dynamics coupling is insignificant, for the operating bandwidth of the manipulator. The advantage of such an uncoupled mechanism is that its modeling and control is greatly simplified, this may save considerable effort in controller design. Future study will demonstrate the effectiveness of independent joint feedback control for this manipulator. Future work will also be conducted to determine what other configurations of parallel compliant mechanisms result in un-coupled dynamics. It is intended that a design methodology should be developed that can be used to design parallel compliant mechanisms that possess simple un-coupled dynamics. Thereby controller design can be simplified and control performance improved through structural design.

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REFERENCES

1. J. Speich and M. Goldfarb, "A compliant-mechanism-based three degree-of-freedom manipulator for small-scale manipulation," *Robotica*, **18**, pp. 95-104, 2000
2. J. Hesselbach, N. Plitea, R. Thoben, "Advanced technologies for micro assembly," Proceedings of the International Society for Optical Engineering, **3202**, pp.178-190, 1998.
3. J. Ryu, D. Gweon, K. Moon, "Optimal Design of a Flexure Hinge Based XY θ Wafer Stage," *Precision Engineering*, **21**, pp. 18-28, 1997.
4. P. Kallio, Q. Zhou, M. Lind, and H. Koivo, "Position Control of a 3 DOF Piezohydraulic Parallel Micromanipulator," Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.770-775, 1998.
5. P. Gao and S. Sweï, "A six-degree-of-freedom micro-manipulator based on piezoelectric translators," *Nanotechnology*, **10**, pp. 447-452, 1999 .
6. Y. Tomita, F. Sato, K. Ito, and Y. Koyanagawa, "Decoupling Method of Ultraprecision Stage using Parallel Linkage Mechanism," *International Journal Japan society of Precision Engineering*, **26**(1), pp. 47-53,1992.
7. Y. Ohya, T. Arai, Y. Mae, K. Inoue, and T. Tanikawa, "Development of 3-DOF Finger Module for Micro Manipulation," Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 894-899, 1999.
8. T. Arai, R. Larssonneur, Y. Jaya, "Calibration and Basic Motion of a Micro Hand Module," Proceedings of the International Conference on Industrial Electronics, Control, and Instrumentation, **3**, pp. 1660-1665, 1993.
9. G. Zong, W. Zhang, W. Xu, and S. Bi, "A Hybrid Serial Parallel Mechanism for Micro-Manipulation," The 5th Applied Mechanisms and Robotics Conference, 1997.
10. W. Zhao, S. Bi, and G. Zong, "Experimental Study of a Series-Parallel Micro Manipulator," *Journal of Beijing University of Aeronautics & Astronautics*, 2000.
11. J. Zou, "Kinematics, Dynamics and Control of a Particular Micro-Motion System", Masters Thesis, printed by the Advanced Engineering Design Laboratory, University of Saskatchewan, 2000.
12. W. Zhang, J. Zou, G. Watson, W. Zhao, G. Zong, and S. Bi, "Constant-Jacobian Method for Kinematics of a 3-DOF Planar Micro-Motion Stage," *Journal of Robotic Systems*, **19**(2), pp. 63-79, 2002.
13. O. Ma and J. Angeles, "Direct Kinematics and Dynamics of a Planar 3-DOF Parallel Manipulator," ASME, Mechanical Systems Analysis, Design and Simulation, Advances in Design Automation, pp. 313-320, 1989.
14. C. Gosselin and J. Angeles, "The optimum kinematic design of a planar three-degree-of-freedom parallel manipulator," *Journal of Mechanisms, Transmissions and Automation in Design*, **110**, pp. 35-41, 1988.
15. A. Codourey, "Dynamic Modeling of Parallel Robots for Computed-Torque Control Implementation," *The International Journal of Robotics Research*, **17**, No.12, pp. 1325-1336, 1998.
16. K. Fite and M. Goldfarb, "Position Control of a Compliant Mechanism Based Micromanipulator," Proceedings of the 1999 IEEE International Conference on Robotics and Automation, May, pp. 2122-2127, 1999.
17. K. Tsai and J. Yen, "Servo system design of a high-resolution piezo-driven fine stage for step-and-repeat microlithography systems," Proceedings 25th Annual Conference of the IEEE Industrial Electronics Society, **1**, pp.11-16,1999.
18. W. Kim, B. Yi, and W. Cho, "RCC characteristics of planar/spherical three degree-of-freedom parallel mechanisms with joint compliances," *Journal of Mechanical Design, Transactions of the ASME*, **122**(1), pp.10-16, 2000.
19. F. Wu, W. Zhang, Q. Li, and P.R. Ouyang, "Integrated Design and PD Control of High Speed Closed-loop Mechanisms," *ASME Journal of Dynamics, Measurement and Control* (accepted in Feb. 2002).