



Design and dynamics of a 3-DOF flexure-based parallel mechanism for micro/nano manipulation

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ABSTRACT

This paper presents the mechanical design and dynamics of a 3-DOF (degree of freedom) flexure-based parallel mechanism. Flexure hinges are used as the revolute joints to provide smooth and high accurate motion with nanometer level resolution. Three piezoelectric actuators are utilized to drive active links of the flexure-based mechanism. The inverse dynamics of the proposed mechanism is established by simplifying flexure hinges into ideal revolute joints with constant torsional stiffnesses. Finite element analysis is used to validate the performance of the proposed 3-DOF flexure-based parallel mechanism. The interaction between the actuators and the flexure-based mechanism is extensively investigated based on the established model. Experiments are carried out to verify the dynamic performance of the 3-DOF flexure-based mechanism.

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1. Introduction

Micro/nano positioning technique is considered as one of the key enabling methodologies in science and engineering applications. It plays a crucial role in modern technologies including scanning tunnel microscopy, atom force microscopy, X-ray lithography, nanoimprint lithography, bio-medicine, micro/nano surgery, and micro/nano surface metrology and characterisation [1–5]. In these engineering and scientific fields, the requirements for motion resolution and positioning accuracy are generally within the range of several to a few hundreds of nanometers. In addition, high dynamic performance is another potential requirement for some applications to achieve wide working range. There are a number of factors affecting the characteristics of positioning systems, including micro/nano manipulation mechanisms. The main factors include their topology and mechanical structures, actuators and transducers, sensing and measurement techniques, and control methodologies [6–9].

The typical configuration of a conventional positioning mechanism consists of one or more revolute joints, and/or one or more prismatic/sliding joints in which a ball-screw is commonly utilized to convert rotational motion to linear motion [10,11]. To improve dynamic characteristics of a precision positioning mechanisms, linear servomotor or voice coil motor (VCM) may also be utilized

[12,13]. However, these mechanical kinematic pairs have a number of shortcomings such as backlash, stick-slip, noise, and slow response. These make it difficult for conventional mechanisms to meet with the requirements of modern nanotechnology. Therefore, different configurations must be developed to overcome these problems encountered in conventional mechanisms.

Recent research efforts have been directed towards mechanical design of micro/nano manipulation mechanisms and systems. One of the best approaches is to utilize flexure-based mechanisms, where conventional kinematic pairs are replaced by flexure hinges. These types of joints have a number of advantages including no backlash, zero friction, and negligible hysteresis [14,15]. In addition, such flexure-based mechanisms can be monolithically manufactured using wire electro discharge machining (WEDM) technique, and thus reducing assembly errors and guaranteeing the machining accuracy [16,17]. Further, with the aid of fixturing systems including modular and reconfigurable fixturing methodologies and using 3-2-1 locating and constraining technique [18–20], the flexure-based mechanisms can be combined with the conventional macro-positioning stages to form dual positioning systems. Thus, a larger range of precision positioning mechanism can be achieved [21–24].

Based on applied voltage, a piezoelectric actuator can generate continuous expansion and retraction motions with infinite resolution, zero backlash, and wide dynamic response range. Therefore, combining a flexure-based mechanism with piezoelectric actuators as the driving actuators, a piezo-driven flexure-based mechanism becomes one of the best choices for micro/nano manipulation

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[25,26]. It must be emphasized that there exist nonlinearities such as hysteresis and creep when a piezoelectric actuator is controlled by voltage command signal. It is necessary to develop closed-loop control methodologies to improve the positioning accuracy of the piezo-driven mechanisms [27,28]. A number of control methodologies including robust control, adaptive control, and neural network control are developed to overcome the nonlinearity of the piezoelectric actuator, and to improve the dynamic performance of the piezo-driven mechanisms [29–32]. The development of these techniques for flexure hinges, novel micro-actuators, and strategies for precision positioning will enable establishment of the micro/nano manipulation systems with high dynamic performance and resolution [33–40].

Planar positioning mechanisms are expected to be widely used in the micro/nano manipulation systems. Recent studies have been focused on the flexure-based mechanisms capable of translations in x and y directions. Using piezoelectric actuators, these types of mechanisms can generate decoupled motions in the orthogonal directions. However, the xy micro/nano manipulation systems cannot compensate the orientation errors induced by the misalignment and assembly. In order to overcome this problem, a 3-DOF planar flexure-based mechanism is proposed to implement translations in x and y directions and rotation about z axis [41,42]. Both serial kinematic mechanism and parallel kinematic mechanism are developed to fulfill the requirements in micro/nano manipulation. Due to the advantages including high stiffness, low inertia, and balanced mechanical structure, it is becoming evident that the closed-loop piezo-driven parallel mechanisms made up of flexure hinges have a considerable potential for the applications in micro/nano manipulation tasks [43,44].

It is noted that the flexure-based parallel mechanisms demonstrate a number of different characteristics compared with conventional parallel kinematic mechanisms. The established methodologies for conventional parallel kinematic mechanisms will suffer from shortcomings such as revolute center offset and additional rotational stiffness of flexure hinges. Such a system will demonstrate the unique characteristics in the working range of micro/nano level. Further, studies of the interaction between the flexure-based mechanism and piezoelectric actuators are also a crucial factor to guarantee the dynamic performance of such systems. Therefore, it is necessary to develop the design and dynamics evaluation methodologies for piezo-driven flexure-based parallel mechanisms.

This paper presents the mechanical design methodology of a 3-DOF flexure-based mechanism. A monolithic flexure-based 3-revolute–revolute–revolute (3-RRR) parallel mechanism is utilized to implement planar motions. Three piezoelectric actuators are used to drive the active links of the flexure-based mechanism. The displacement of each piezoelectric actuator is amplified by the levers of the flexure-based mechanism. By simplifying flexure hinges into revolute joints with constant torsional stiffnesses, the dynamics of the proposed mechanism is established. Finite element analysis is used to validate the performance of the proposed 3-DOF flexure-based parallel mechanism. The interaction between the actuators and the flexure-based mechanism is extensively investigated based on the established finite element model. Experiments are also carried out to verify the dynamic performance of the 3-DOF flexure-based mechanism.

2. Mechanical design

The photos of the 3-DOF flexure-based parallel mechanism are shown in Fig. 1. This micro/nano manipulation mechanism has three flexure-based kinematic chains connecting the moving platform and the stationary frame. It belongs to 3-RRR parallel kinematic

mechanism. Three piezoelectric actuators are respectively mounted on three modular fixtures axially configured and symmetrically located at the circumference of a circle and in contact with the active links of each kinematic chain. Three high precision capacitive sensors are used to measure the actual displacement of the moving platform for closed-loop displacement feedback control of the flexure-based mechanism. The capacitive sensors are held on the adjustable brackets between the moving platform and the stationary frame. The initial clearance between the plates of the capacitive sensor can be set through the adjustable brackets. The moving platform can provide planar motions driven by three flexure-based kinematic chains, which also preload three piezoelectric actuators. A three channel amplifier controlled by a digital computer is used to supply control voltages for the expansion and retraction of the piezoelectric actuators. In order to eliminate nonlinearity of piezoelectric actuator, closed-loop control should be utilized to eliminate the hysteresis and creep, as well as the motion errors in flexure-based mechanism. Based on the established displacement mapping and control models, it is feasible for real-time calculation from the sensor signals of the position and orientation errors and compensation control voltages to be supplied to the three piezoelectric actuators to adjust the position and orientation of the moving platform. Thus, the motion and positioning accuracy can be improved.

Three flexure-based kinematic chains are used to support the moving platform. Compared with other types of flexure hinges, circular flexure hinge with rectangular cross-section has higher motion precision for rotational accuracy and is the optimal choice as the revolute joint for precision mechanism design and construction. These flexure-based kinematic chains provide both a vertical stiff guidance mechanism for moving platform and a spring preload for piezoelectric actuators. The magnitude of preload can be set by adjusting the fixture blocks along the radial directions. Three ball tips are added between the piezoelectric actuators and the driving points on the active links to avoid bending and torsional moments acting at the actuators, since the piezoelectric ceramic can withstand large compressive force but generally weak against shear and stretching stresses. Thus, the contact condition between the piezoelectric actuator and the driving point may be assumed to be Hertzian contact. In order to maintain the contact condition during the motion of such mechanism, a suitable preload is necessary for the piezoelectric actuators.

The selected piezoelectric actuator can generate a displacement up to 60 μm , has an axial stiffness of 15 N/ μm and can deliver a maximum driving force of 800 N. A digital computer is used to implement numerical control, user interface and supervisory control operations. The capacitive sensors have nominal resolution of 0.1 nm over a measuring range of 100 μm with a bandwidth of 0–10 kHz. The control voltage is supplied to the piezoelectric actuator through a 16 bits D/A converter and amplifier module PI E-505.00. The piezoelectric amplifier module has a nominal amplification factor of 10 ± 0.1 , and can output and sink a peak current of 2000 mA and an average current of 300 mA. The strain gauge embedded inside the piezoelectric actuator is utilized to measure the actual displacement, and to establish a closed-loop control through a servo-module PI E-509.X3.

The dimensions of the flexure hinges and their positions on the links significantly influence the characteristics of the micro/nano manipulation mechanism, especially its working range and the effectiveness of the preload. Considering the stiffness of the flexure mechanism along driving directions of piezoelectric actuators, the maximum steady-state output displacement of each piezoelectric actuator can be written

$$s = \frac{k_{pzt}k_c}{k_{pzt}k_c + k_{pzt}k_s + k_c k_s} s_0 \quad (1)$$

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