Robotics and Computer Integrated Manufacturing 56 (2019) 95–105

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

# Development and control methodologies for 2-DOF micro/nano positioning stage with high out-of-plane payload capacity

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ARTICLE INFO

*Keywords:*
XY stage
Flexure mechanisms
Payload capability
Tracking control

ABSTRACT

Two of the key issues to meet the requirements of micro/nano manipulation in some complex cases are the adequate workspace and payload capacity of the moving platform. This paper presents the development and control methodologies for a 2 degrees of freedom (DOF) flexure-based micro/nano positioning stage with the capabilities of decoupling motion and out-of-plane payload. The moving platform is horizontally supported by two orthogonal double parallel four-bar linkages, which are connected to the base through another four double parallel four-bar linkages. In order to improve the out-of-plane stiffness, four flexure links are utilized to vertical support the moving platform. Two voice coil motors are used for the actuation of the moving platform to obtain large working range. To investigate the static and dynamic characteristics, finite element analysis is preformed, the dynamic model of the positioning system is established, and the system identification is conducted using Adaptive Real-coded Genetic Algorithm (ARGA). In order to further improve the performance, the sliding model control with a PID type sliding surface technique is developed. A number of experimental testing has been conducted to validate the established models and the performance of the micro/nano positioning stage. It is noted that the developed stage has the capability of translational motion stroke of 2.13 mm and 2.02 mm in the $X$ and $Y$ axes, and the resolution is less than 250 nm. Further, it has excellent trajectory tracking and payload capabilities.

## 1. Introduction

The micro/nano positioning stages are widely used in variety fields, such as biomedical science [1], micro-manufacturing [2], lithography [3] and scanning electron microscopy [4]. A large number of piezo-driven positioning stages have been designed due to high resolution, wide bandwidth, high stiffness and compact size of piezoelectric actuators [5–8]. However, the fatal shortcoming of piezo-driven stage is small stroke. Thus, the piezo-driven stage cannot completely satisfy a number of requirements for large workspace. In order to achieve a large motion range, many researchers selected the voice coil motor (VCM) instead of the piezoelectric actuator. There are several VCM driven stages reported in [9,10]. Compared with piezo-driven stages, these kinds of stages can obtain a working range more than 1 mm with a high resolution. In order to guarantee positioning accuracy, one of the best choices is to utilize flexure based mechanism as guide mechanism due to the advantages of flexure hinges including no backlash, free of wear, no lubrication, and low friction.

In the past few decades, the flexure based mechanisms are generally developed by replacing the conventional joints of the parallel mechanism with flexure hinges. Typically, Stewart and Delta mechanisms [11,12]are widely utilized on account to provide adequate motions in spatial or planar applications in micromanipulation system. The flexure based parallel mechanisms have been confirmed to be applicable for the micro/nano positioning stages due to it has the advantages including low inertia, high accuracy, and identical behavior in each axis [14,15]. In many developed flexure hinge mechanisms, the notch-type hinge and leaf-spring hinge are the most popular and widely utilized. Especially, the leaf-spring hinges are capable of achieving large working range.

However, cross-axis couplings generally exist in many flexure-based mechanisms, which may cause modeling and controlling complexity and positioning accuracy reduction [13]. Thus, it is necessary to develop the decoupled parallel mechanisms to eliminate such short comings. In addition, the payload capability of the flexure-based

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https://doi.org/10.1016/j.rcim.2018.08.007
Received 30 March 2017; Received in revised form 24 January 2018; Accepted 28 August 2018
0736-5845/ 

mechanisms is also an important design criterion. The structural integrity should be guaranteed even a micro-positioning stage under a large payload. In other words, to ensure the motion stability of a large-range stage under a large load or out-of-plane interference, one needs to increase the thickness of flexure hinges to enhance the out-of-plane stiffness or use magnetic-levitation [16]. However, the above approaches will increase the cost and complexity. A suitable design is to use spatial compliant mechanisms to improve the out-of-plane stiffness without increasing the thickness flexure hinges. Such as, in Ref. [17], spatial compliant mechanism was utilized to improve the out-of-plane stiffness and can guarantee the decoupling translational motion. Unfortunately, the effectiveness of the structure has not been confirmed by experiments.

Therefore, the motivation of this research is to design a new flexure XY micro/nano positioning stage with a workspace range of $2 \times 2$ mm$^2$. The new concept of spatial support compliant mechanism is proposed to achieve an excellent out-of-plane stiffness. Based on the idea of parallel mechanisms and spatial support compliant mechanisms, the XY stage is designed and fabricated with wire electrical discharge the machining (WEDM) technique. Large-range, decoupled motion and high payload capability are all validated by experiments.

The hysteresis effects generally exist in such kind of VCM driven positioning system [18–20]. The problem of hysteresis nonlinearities mainly arises from the nonlinearity of the employed VCM, which works based on the electromagnetic principle [19]. The relationship between the applied voltage and output displacement is nonlinear and this can lead to a large positioning error. Thus, the hysteresis should be reduced/eliminated to improve positioning accuracy. To solve the nonlinearity problem, it is necessary to establish a hysteresis model of the positioning system and thus compensate the output displacement using feedforward control. In the past decades, many researchers have presented a number of methods to model the hysteresis, such as Bouc-Wen model [21,22], Maxwell model, Preisach model [23,24] and Prandtl-Ishlinskii model [25,26], etc. The feedforward control based on an inverse hysteresis model is typically employed to compensate the hysteresis. In fact, feedforward control combined with a feedback control is formed to eliminate or reduce the external disturbance and further improve the positioning accuracy of the micro/nano positioning system. Many studies have adopted traditional PID (proportional-integral-derivative) as a feedback controller. Compared with PID, sliding mode control (SMC), a nonlinear approach, has been utilized in the precision positioning system as a more effective and simple way to manage uncertain nonlinear systems [27]. Particularly, SMC with PID sliding surface (SMC-PID) and saturation function has been employed to obtain a faster transient response with less steady-state error and eliminate undesirable oscillations. Therefore, SMC-PID combined with a feedback compensate control is a more effective control method to improve the tracking accuracy.

In this paper, a XY stage is designed and experimentally tested. The remainder of this paper is organized as follows: Section 2 introduces the mechanical the design of the 2-DOF (Degree of Freedom) stage with spatial support compliant mechanism. In Section 3, finite element analysis (FEA) has been performed to validate the static and dynamic characteristics of the XY stage. A dynamic model of the system is established and system identification is then implemented in Section 4. In Section 5, the control scheme for the system is presented. The experimental tests are conducted in Section 6, and Section 7 concludes this paper.

## 2. Mechanical design

A XY micro/nano positioning stage with large working range and payload capability is proposed. As shown in Fig. 1, the designed XY stage mainly consists of an upper stage, four vertical support links, a base and two VCMs.

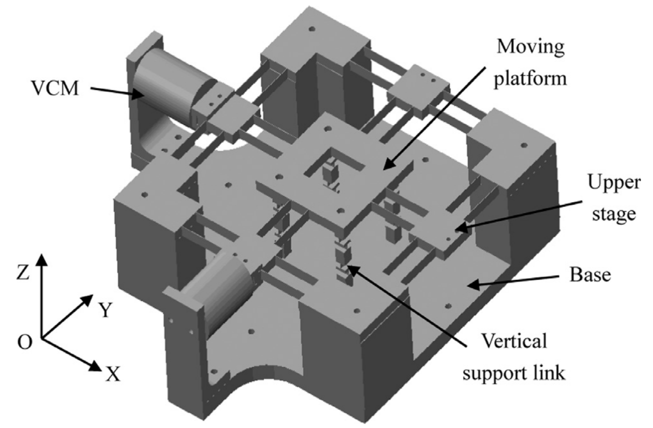


**Fig. 1.** 3D solid model of the XY stage.

### 2.1. Upper stage

The upper stageis evolved from the 4PP-E (P stands for prismatic joint and E denotes planar joint) decoupled parallel mechanism. The double parallel four-bar linkages are used as the P joints, and symmetrically arranged. The central platform is connected to four linkages through two orthogonal double parallel four-bar linkages, and then to the fixed frame through another sixteen leaf springs. The leaf parallelogram orthogonal to the X-axis is highlighted shown in Fig. 2. Compared with the other types of flexures, the leaf flexures are employed to generate a large elastic deformation and the stress concentration is not severe. In addition, the longitudinal stiffness of the leaf spring is high, while its transverse stiffness is low. As a result, when the VCM in the X-axis is activated, the leaf parallelogram parallel to the X-axis transmits the motion to the central moving platform due to its high rigidity; while the leaf parallelogram and leaf springs orthogonal to the X-axis function as a prismatic joint due to their low transverse stiffness. As a result, the VCM #1 does not suffer from transverse displacement if the stage is driven by VCM #2. Similarly, VCM #2 does not move in transverse direction once the stage is actuated by VCM #1. Therefore, an input decoupling is accomplished by the XY stage. It means that the proposed upper XY stage owns an attractive totally decoupling property.

### 2.2. Spatial structure (vertical supports)

A spatial structure is applied to increase the load-carrying capacity of the stage, as shown in Fig. 3.The Hook's compliant series mechanism (HCSM) used as vertical support links is designed to guarantee excellent out-of-plane stiffness for heavy payload, which has been developed in the previous work [18]. The basic unit of HCSM is Hook's joint shown in Fig. 3(a). Each Hook's joint is composed of two circular hinges and the axes of these circular hinges are located in one plane for a compact physical dimension. Therefore, in this case, the out-of-plane motions, including rotation about the X- and Y-axis or translation in the Z-axis, are suppressed.

However, circular flexures provide high out-of-plane stiffness but small in-plane deflection (bending). They are suitable for applications which require accurate positioning over a relatively small range. It means that the HCSM are not suitable for long range. In additions, severe stress concentration of the HCSM was found, which is not conducive to the proposed mechanism with longer fatigue life. Considering the reasons above, the HCSM was abandoned in this paper. In comparison, leaf-spring flexures have relatively low bending stiffness, making them attractive for high displacement-orientated applications. For the same deflection, leaf-spring flexures have lower maximum stress than circular flexures. They are superior in achieving better flexibility with longer fatigue life. Based on the above considerations, four Hook's compliant series mechanisms are replaced by four right