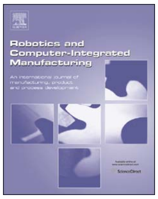
Robotics and Computer-Integrated Manufacturing 44 (2017) 77–96

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

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



Design and control of a 6-degree-of-freedom precision positioning system

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ARTICLE INFO

Article history:
Received 24 October 2015
Received in revised form
27 June 2016
Accepted 1 August 2016

Keywords:
6-DOF positioning system
Piezoelectric actuators (PEAs)
Kinematic model
Tracking control

ABSTRACT

This paper presents the design and test of a 6-degree-of-freedom(DOF) precision positioning system, which is assembled by two different 3-DOF precision positioning stages each driven by three piezoelectric actuators (PEAs). Based on the precision PEAs and flexure hinge mechanisms, high precision motion is obtained. The design methodology and kinematic characteristics of the 6-DOF positioning system are investigated. According to an effective kinematic model, the transformation matrices are obtained, which is used to predict the relationship between the output displacement from the system arrangement and the amount of PEAs expansion. In addition, the static and dynamic characteristics of the 6-DOF system have been evaluated by finite element method (FEM) simulation and experiments. The design structure provides a high dynamic bandwidth with the first natural frequency of 586.3 Hz. Decoupling control is proposed to solve the existing coupling motion of the 6-DOF system. Meanwhile, in order to compensate for the hysteresis of PEAs, the inverse Bouc-Wen model was applied as a feedforward hysteresis compensator in the feedforward/feedback hybrid control method. Finally, extensive experiments were performed to verify the tracking performance of the developed mechanism.

1. Introduction

Over the past several decades, as one of the best solutions for the micro/nano operating problems in industry, such as nanoimprint, cell operation, scanning probe microscopes, high density data recording, optical instruments, measurement systems and micro/nano manipulations [1–7], a precision positioning system usually possesses a number of advantages such as high positioning accuracy, fast response speed, appropriate workspace, satisfactory stability and dynamic characteristics [8,9]. It is mainly composed of three parts, namely, the actuation unit, guide mechanism and end-effector. The piezoelectric actuator (PEA) is the main type of actuator which is often used to drive a positioning mechanism because it offers the extremely fine resolution, quick response, large force generation, high electrical-mechanical power conversion efficiency and small volume. Moreover, in order to guarantee positioning accuracy, one of the best choices is to utilize flexure based mechanism for the motion guidance because the flexure based mechanism is capable of improving the motion accuracy due to the advantages of flexure hinges including no backlash, free of wear, no lubrication, and low friction. Thus, it is important to determine the static and dynamic performance of the positioning system.

Recent research efforts have been directed towards the design and control methodologies of multi-DOFs precision positioning systems. The micro/nano operating industry fields are distinguished with respect to systems for planar positioning, systems for out-of-plane positioning and combinations of both. A flexure-based mechanism for ultra-precision operation with 1-DOF, and a 3-DOF planar micro/nano manipulation were presented by Tian et al. [10,11]. Qin et al. focused on design two different type 2-DOF decoupling positioning stages [12,13]. Li et al. proposed a parallel-kinematic high-bandwidth XY nanopositioning stage [14]. Cai et al. [15]. focused on design a planar 3-DOF stage with T-shape flexible hinge mechanism. In addition, there have also been some out-of-plane positioning systems. A 3-DOF micro-positioning table was investigated in Ref. [16]. Another nanoprecision 3-DOF vertical positioning system was presented in [17], which can be used in various optical alignment systems. Lee et al. [18] proposed a three-axis out-of-plane nanopositioning stage with a new flexure structure, which had the aperture to measure the bio-specimen.

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http://dx.doi.org/10.1016/j.rcim.2016.08.005
0736-5845/

Nomenclature

a, b, c	parameters of Bouc-Wen model
h	hysteresis variable
d_{33}	piezoelectric constant
V	applied voltage
d	displacement output of the free PEA
k_{pzt}	stiffness of PEA
k_c	equivalent stiffness of Hertzian contact
k_{fh}	equivalent stiffness in vertical direction of elliptical flexure hinge
X, Y, Z, O	cartesian coordinates of a point
r, R	radius of the moving platform and the moving circular ring, respectively
x, y, z	displacements in the X-, Y-, Z-axes
θ_x, θ_y, α	angle rotation about the X, Y-axes and Z-axes
$\boldsymbol{T}_{in,}^{-1}$ $\boldsymbol{T}_{out}^{-1}$	transformation matrix of the in-plane and out-of-plane 3-DOF stage, respectively.
$\boldsymbol{T}^{-1}$	transformation matrix of the 6-DOF stage
$\boldsymbol{I}$	input displacements matrix
$\boldsymbol{O}$	output displacements matrix $\boldsymbol{O}$
δ_1, δ_2, δ_3	elongation of the PEAs in the in-plane 3-DOF stage
δ_4, δ_5, δ_6	elongation of the PEAs in the out-of-plane 3-DOF stage
P_z	moving coordinate O_d–$X_dY_dZ_d$ relative to the reference coordinate O–XYZ translated along the Z-axis
P_x, P_x and T_z	moving coordinate O_s–$X_sY_sZ_s$ relative to the coordinate O_d–$X_dY_dZ_d$ translated along the X-, Y- and Z-axis, respectively
$\boldsymbol{T}_d$	transformation matrix of the moving coordinate O_d–$X_dY_dZ_d$ relative to the reference coordinate O–XYZ
$\boldsymbol{T}_s$	transformation matrix of the moving coordinate O_s–$X_sY_sZ_s$ relative to the reference coordinate O–XYZ
$\boldsymbol{T}_{sd}$	transformation matrix of the moving coordinate O_s–$X_sY_sZ_s$ relative to the coordinate O_d–$X_dY_dZ_d$

Shao et al. [19] presented a novel precision tilt positioning mechanism for inter-satellite optical communication. Furthermore, combinations of in-plane and out-of-plane system have been explored and utilized. A flexure hinge-based XYZ atomic force microscopy scanner was presented by Kim et al. [20]. In Ref. [21] a three translational DOF complaint perpendicular parallel micromanipulator with monolithic structure was proposed. Eichmann et al. [22] designed a high-precision xyz-measuring table for the determination of the 3D dose rate distributions of brachytherapy sources.

From the above literature review, it can be seen that most of the existing precision positioning systems are featured by one to three-DOF motions [10–22], which cannot meet the needs of manipulations in some cases. For example, an atomic force microscope designed for nanometrology in Ref. [23], which used a 6-DOF nanopositioning stage to carry the sample carrier. Thus, it is necessary to develop novel positioning stages with 6-DOF motions in some special systems, which could extend workspace and improve flexibility of the operation ends.

This paper focuses on the design of a 6-DOF precision positioning system which can be utilized for micro/nano operating of the high precision system. Recently, many kinds of 6-DOF precision positioning systems have been reported. A piezoelectric actuator-based micromanipulator with six degrees of freedom was proposed in [24]. Richard et al. [25] presented a 6-DOF piezoelectrically actuated fine motion stage that could be used for three-dimensional error compensation with a long-range translation mechanism. Liang et al. [26] presented a 6-DOF parallel mechanism based on three inextensible limbs, which were connected to three planar 2-DOF movements in the base plane. A novel 6-DOF precision positioning table was presented in [27], which was assembled by two different 3-DOF precision positioning tables. A novel flexure based 6-DOF parallel positioning system for aligning the precision optical elements was presented by Kang et al. [28]. A low stiffness 6-DOF compliant precision stage was proposed in Ref. [29]. From the literature review, it is noted that the 6-DOF precision positioning systems can be considered as a system for combinations of in-plane and out-of-plane stages. However, based on the current manufacturing process technology of precision positioning in micro/nano operating industry fields, the 6-DOF positioning system does not monolithically manufactured like as one-three-DOF positioning stages by wire electrical discharge machining technique. It means that manual assembly is needed. Therefore, in this paper, the proposed 6-DOF precision positioning system is assembled by two different 3-DOF precision positioning stages (as shown in Fig. 1). It has a simple structure and can easy be assembled, which significantly reduce the assembly errors and improve the system positioning accuracy. Such design strategy will improve the system stability and ensure that the system has good dynamic characteristics, rapid response and higher robustness against external disturbances.

In the past decade, different phenomeno-logical hysteresis models have been established. Such as Preisach models [30,31], Maxwell model [32], Duhem models [33], Bouc-Wen models [34–36], and Prandtl-Ishlinskii models [37] were developed to describe the hysteresis effect, which are then used to construct the inverse models for hysteresis compensation. It has already been verified that the Bouc-Wen model is suitable to describe the hysteresis loop of PEA [38]. In reference [39] the hysteresis nonlinearity was described by a dynamic backlash-like model. In order to improve the positioning accuracy, many control methods have been proposed for tracking control of a piezoelectric-actuated nanopositioning stage. Feedforward controllers and feedback controllers were used for the hysteresis and vibration compensation [40], respectively. Meanwhile, hybrid control is popular applied for high-precision control of piezo-actuated positioning stages, which combines the advantages of the feedforward and feedback control. With such a control method, many works [41–44], have been recently reported and confirmed the feasibility of the control method for high-precision control of piezo-actuated positioning stages. However, there are some other control methods have been reported, such as proxy-based sliding-mode control [45].

This paper is organized as follows: Section 2 starts with the mechanical design of the 6-DOF positioning system. Section 3 provides the kinematic analysis of the system. In Section 4, FEA has been performed to investigate the static and dynamic characteristics of the 6-DOF system. Experimental setup and results have been provided in Section 5. Finally, conclusions are presented in Section 6.

2. Mechanical design

Fig. 1 shows the 3D solid model of a 6-DOF precision positioning system. It includes two main components, i.e. an in-plane 3-DOF positioning stage and an out-of-plane 3-DOF positioning stage.