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PRE-6397; No. of Pages 11
ARTICLE IN PRESS
Precision Engineering xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Precision Engineering
journal homepage: www.elsevier.com/locate/precision

A planar 3-DOF nanopositioning platform with large magnification

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 15 March 2016
Accepted 30 April 2016
Available online xxx

Keywords:
Nanopositioning
Large magnification
Displacement loss
Preload
Micro/nano manipulation

ABSTRACT

Piezo-actuated flexure-based precision positioning platforms have been widely used in micro/nano manipulation. A conventional major challenge is the trade-off between high rigidity, large magnification, high-precision tracking, and high-accuracy positioning. A compact planar three-degrees-of-freedom (3-DOF) nanopositioning platform is described in which three two-level lever amplifiers are arranged symmetrically to achieve large magnification. The parallel-kinematic configuration with optimised sizes increases the rigidity. Displacement loss models (DLM) are proposed for the external preload port of the actuator, the input port of the platform and the flexible lever mechanism. The kinematic and dynamic modelling accuracies are improved by the compensation afforded by the three DLMs. Experimental results validate the proposed design and modelling methods. The proposed platform possesses high rigidity, large magnification, high-precision circle tracking and high-accuracy positioning.

1. Introduction

Planar nanopositioning platforms play a crucial role in precise and accurate nanoscale positioning. The applications involve precision mechanical scanning in scanning probe microscopy (SPM) [1–5], nanoimprint lithography [6,7], micro-/nano manipulation [8–10], and micro-/nano surface metrology measurement [11]. Compared to a two-degrees-of-freedom (2-DOF, x & y) positioning platform [1,4,5], the planar 3-DOF platform increases the DOF and is capable of correcting possible undesired coupling between major axes. The serial-kinematic planar 3-DOF platform has a large workspace, good dexterity, decoupling, linear kinematic, and simple forward kinematic [2,12–14]. The parallel-kinematic configuration has high structural stiffness, high precision, low inertia, and wide bandwidth. The parallel structure combined with equilateral symmetry and planar geometry limits the thermal drift in position and orientation. For micro-/nano manipulation, a conventional major challenge is the trade-off between high rigidity, large magnification, high-precision tracking, and high-accuracy positioning. The parallel configuration has much more potential [6,9–11,15–19]. Planar parallel 3-DOF nanopositioning platforms have been widely used in wafer positioning [6,7], optical alignment [20], and micro/nano manipulation [9].

The traditional configuration of precision positioning platforms consists of one or more revolute, prismatic or sliding joints. Such joints always bring about backlash, friction, stick-slip, noise, or slow response. To achieve a high positioning accuracy, flexure hinges are used to replace traditional kinematic pairs [21,22]. Compliant mechanisms can be modelled using the pseudo-rigid-body model (PRBM) approach. This method assumes that the flexure hinges behave as revolute joints with torsional springs, and that the thicker sections of the mechanism act as rigid links. This enables the traditional optimal design method for planar 3-DOF parallel platforms to be applied, in which the global conditioning index, stiffness index, payload index and velocity index are used [23,24].

The piezoelectric ceramic actuator (PCA) gives sub-nanometer resolution, high generated force, wide dynamic response range and rapid motion, without mechanical play or wear. A widely-used type of PCA is the packaged PCA (PPCA) fabricated as multiple-layer piezoelectric stacks protected by a case. The internal preload makes the stacks ideal for dynamic applications, as well for tensile loads. The strain gauge sensor (SGS) embedded in the PPCA is used to measure the nominal displacement of all the stacks. A controller using data from the SGS has been developed to overcome hysteresis, creep and nonlinearity of the piezoelectric actuator [25]. The controller is a semi-closed-loop controller for the whole platform; however, actual input displacement of the platform differs from the nominal displacement of the PPCA, due to the external preload stiffness of the PPCA and the input stiffness of the platform. The displacement loss model (DLM) for the external preload port of the PPCA and the input port of the platform were important factors that needed to be considered. In particular, for

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http://dx.doi.org/10.1016/j.precisioneng.2016.04.016
0141-6359/© 2016 Published by Elsevier Inc.

Nomenclature

$\boldsymbol{F}$	system force matrix
$\boldsymbol{K}$	system stiffness matrix
$\boldsymbol{x}$	system displacement vector
J	forward-kinematic Jacobian matrix
ϕ	center of the hinge, $\phi \in$ {k, a, b, c, A, B, C}
$\phi_i\varphi_i$	link between ϕ_i and φ_i, $\varphi \in$ {k, a, b, c, A, B, C}.
ψ	link or moving plate, $\psi \in \{a_ib_i, b_ic_i, A_iB_i, B_iC_i, p\}$
θ	rotational angle along z axis
x, y, z	reference axes, deflections
δ_{ϕ_i}	equivalent translational displacement of ϕ_i
δ_{PPCA}	nominal displacement of the PPCA
δ_{pr}	variation of the preload displacement due to the displacement of actuator
$[\sigma]$	allowable stress
$\sigma_{\max}$	maximum stress
θ_{ϕ_i}	rotational angle of ϕ_i
I_ψ	moment of inertia of ψ
$k_{\theta\phi}$	equivalent rotational stiffness of ϕ
k_k	equivalent input stiffness of the platform
k_{PPCA}	equivalent stiffness of the PPCA
k_{pr}	equivalent stiffness of the external preload mechanism
L_k	length of the link A_iB_i, B_iC_i, C_ip, A_ip, a_ib_i, b_ic_i, A_ic_i, C_iC_j and A_iA_j, k = 1, 2, 3, 4, 5, 6, 7, 8, 9, i, j = 1, 2, 3, $j \neq i$
l_k	dimensionless parameter of the length L_k, k = 1, 2, 3, 4
m_ψ	mass of ψ
Q_i	generalized non-conservative forces
q_i	linearly independent generalized coordinates
r_l	displacement loss factor of a lever amplifier
r_{l_b}	bending displacement loss factor of a lever amplifier
r_{l_d}	drift displacement loss factor of a lever amplifier
V_ψ	velocity of ψ
3RRR	3-revolute-revolute-revolute
disp.	displacement
DLM	displacement-loss model
DOF	degree of freedom
E	Young's modulus
F	force
I	flexure cross-sectional moment of inertia
M	bending moment
max	maximum
o	center of the fixed plate, origin of the coordinate system
p	center of the moving plate
PPCA	packaged piezoelectric ceramic actuator
PRBM	pseudo-rigid-body model
SGS	strain gauge sensor

a highly rigid platform with large magnification, two DLMs are essential in both the kinematic and dynamic models.

Because of the limited stroke provided by the PPCA, a displacement-magnifying mechanism is required to enlarge the workspace of the platform. In comparison with bridge-type amplifying mechanisms [14] and the Scott Russell mechanism [2,19,26], the commonly used lever amplifier is simple and efficient [10,27–32]. Scire and Teague [27] used a two-stage lever to obtain an output motion of about 68 μm. Piezoelectric actuators with a stroke of 2.25 μm produce an output of only around 38 μm. This motion loss is due to epoxy bonding and its coupling to the lever system, and to stretching of the flexure-hinge. Furukawa and Mizuno [28] utilised a planar eight-bar linkage to magnify the motion. The deflection of the input bars and the stretching of each flexure hinge were modelled in the design equations. Jouaneh and Yang [29] proposed a general approach for the design of flexure-hinge-type lever mechanisms. Min et al. [30] described an analytic lever model and its experimental verification. The PRBM approach was the basis of the analysis, kinematic and dynamic modelling, and experiments on compliant mechanisms. For levers with large magnification, the modelling error of the PRBM increases significantly. In the present study, a third DLM of the flexible lever mechanism is therefore proposed to compensate for losses in the PRBM.

2. Platform design

2.1. Design of a new external preload mechanism

The PPCA has a sub-millisecond response and generates a high-frequency motion. A high-frequency or large-amplitude nanoscale driving displacement is necessary for some micro/nano applications. The PPCA needs to maintain a constant connection status with the platform during the whole positioning procedure. Since extraneous lateral forces or moments may damage the PPCA, an appropriate external preload mechanism is essential for the desired PPCA movement in the axial direction. Shear stresses or large tensile stresses must not be directly applied to the PPCA.

Originally, traditional external PPCA preload mechanisms typically utilised two wedges to generate a thrust force [17], as shown in Fig. 1(a). Since the equivalent thrust force between two wedges is not in the axial direction, a lateral force or moment cannot be avoided and the initial preload displacement cannot be controlled directly. Although some special mechanisms may be used to adjust the downward displacement of one of the wedges with fine resolution, the forward displacement of the other wedge cannot be measured or controlled. The second typical preload mechanism uses a screw and a block [1,3,5,6,9,10,14,15,19,32], as shown in Fig. 1(b). Also in this case, the preload displacement cannot be measured, and a lateral force or moment is produced during the adjustment of the screw.

The preload displacement may vary greatly, especially during a long-term or high-frequency positioning procedure. A new external preload mechanism has been designed, as shown in Fig. 2. A steel ball is seated in a hemispherical cavity in the preload block. The interaction of the steel ball and the preload block precludes the generation of lateral force or moment. The ball eliminates torque during adjustment using the fine-tooth screw. A laser interferometer uses a reflector to measure any minute variation of the preload displacement that may occur.

2.2. Design of a two-level lever amplifier

The platform uses three two-level lever amplifiers to expand the workspace of the moving plate, as shown in Fig. 3.

The flexible lever with a high amplification ratio experiences bending deformation and pivot drifting. The traditional PRBM method would calculate a higher amplification ratio than the simulation or experiment. The analysis of the displacement loss is conducted in Section 3.

2.3. Optimization of the main design parameters

The 3-revolute-revolute-revolute (3RRR) parallel mechanism obtains high accuracy and precision, high rigidity and outstanding dynamic characteristics. This simple and convenient configuration has been widely applied in planar 3-DOF nanopositioning [7,9,12,13,16–20].