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Large dynamic range tracking of an XY compliant nanomanipulator with cross-axis coupling reduction

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ABSTRACT

This paper presents a novel design on a large range compliant XY nanomanipulator with spatial constraints to reduce parasitic motions. Aiming at periodic trajectory tracking of the proposed XY parallel compliant nanomanipulating system, a disturbance observer based (DOB) repetitive control structure is developed such that the cross-axis coupling effects and the stiffness nonlinearity can be treated as disturbances with harmonic and non-harmonic components for rejection purposes. The mechanical design prototype is fabricated and the proposed control algorithm is experimentally validated, where enhanced tracking performance with cross-axis coupling reduction is demonstrated by achieving tracking errors less than 80 nm and a motion stroke over 1 mm.

1. Introduction

Recently there is an increasing need of nanomanipulation including positioning, griping, and injecting in nanoscale. To provide those operations with nanometric motion quality, compliant nanomanipulators are preferred thanks to no friction of compliant mechanism during the operation. And some typical applications of nanomanipulation include scanning probe microscope, nanoassembly and semiconductor inspection. More recently to meet more sophisticated manipulating tasks with larger motion strokes, nanomanipulating systems of millimeter-stroke and nanometric (<100 nm) motion quality have been widely investigated with many important applications [1,2]. In particular, the mechanical design and control of multi-axis compliant nanomanipulators have attracted considerable research efforts, see [3–6] and references therein.

Although some important results, such as [7], reported the design and control of XY nanomanipulators with potentials to achieve both millimeters stroke and nanometric motion accuracy, effective ways on dynamic range tracking are relatively limited comparing to positioning results [7]. As an important motion errors source, the cross-axis coupling effect adversely affects the tracking accuracy and precision of compliant manipulators (usually are parallel mechanisms by design), and its adverse effect becomes more significant with the increase of the stroke.

To improve the tracking accuracy of an XY compliant mechanism, the effect of cross-axis couplings of XY compliant manipulators needs to be attenuated. On one hand, compliant mechanism design and optimization can be utilized to restrict cross-axis coupling, for example [8]. Very recently some researchers were aware of the importance of spatial constraints due

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to its effectiveness to further reduce cross-axis couplings, for example [9,10]. On the other hand, control techniques have been utilized to reduce cross-axis couplings of compliant mechanisms, such as robust control design, H_∞ control design, and inversion-based feedforward controller combined with PID control, for example, [11–13].

To further improve the dynamical performance of large range compliant mechanisms supporting various tracking/scanning applications, we propose a novel large range XY compliant nanomanipulator with spatial constraints to suppress cross-axis couplings. And the cross-axis coupling terms in the stiffness model of the nanomanipulator are explicitly given and approximated as equivalent disturbances in the input channel. We further establish an input/output control model for the planar motion system by treating the nonlinear stiffness as disturbances containing odd harmonics of the input in each axis, where a disturbance observer (DOB) based control structure (see [14,15] and references therein) is combined with repetitive control [16] to effectively track periodic trajectories while attenuating the harmonic and non-harmonic equivalent disturbances induced by cross-axis couplings and stiffness nonlinearities. Stability analysis is also briefly conducted to check if the closed-loop system satisfies the robust stability criteria. The design prototype is fabricated and the control algorithm is experimentally validated, achieving better tracking performance than existing results in various trajectory scenarios.

The rest of the paper is organized as follows: in Section 2 a self-developed XY nanomanipulator is briefly introduced and its stiffness model is provided. In Section 3, the cross-axis coupling of the XY nanomanipulator is analyzed, and the effect of nonlinear stiffness is treated as an equivalent disturbance by a Hammerstein model. Then a disturbance observer-based repetitive controller is designed to control the XY nanomanipulator with reduced cross-axis coupling in Section 4. Finally numerous simulations and experiments are conducted to show the effectiveness of the proposed analysis and control strategy for large range tracking of an XY compliant nanomanipulating system in Section 5 followed by conclusions in Section 6.

2. A large range compliant XY nanomanipulator with spatial constraints

In this paper, we develop a novel large range compliant XY nanomanipulator with spatial constraints to reduce parasitic motions. The schematic is shown in Fig. 1, and the mechanism design is briefly introduced as follows. First of all, the trapezoid guidance module is realized by two pairs of flexure beams, which are placed in a spacial layout to achieve a compact size. Also these beams with different lengths are connected by a T-shaped bar. Second, the kinematic decoupling module is realized by the double parallelogram flexure connecting the motion stage and the T-shaped bar. The overall arrangement of the manipulator is symmetric, and the detailed mechanical design is referred to [10].

To see the force and motion relationship of the proposed compliant XY nanomanipulator, we will analyze its stiffness model, which can be derived as shown in Fig. 2. Note that the first subscript of stiffness symbol K refers the type of the flexure, meaning that "p" and "g" denote the decoupling and guidance modules respectively; the second subscript of stiffness symbol K refers the direction of stiffness, meaning that "a" and "t" denote the axial and transverse direction respectively; the third subscript of stiffness symbol K refers the axial direction, meaning that "X" and "Y" denote the X and Y axes respectively. As a result, the notations in Fig. 2 can be easily understood, for example, K_{gtX} denotes the transverse stiffness of the guidance module in X axis.

In what follows, the static analysis will be based on X axis, where the result of Y axis can be obtained similarly and hence omitted due to the space limit, thanks to the symmetric design. Note that the motion error between the T-shaped bar and the motion stage is less than 0.4%. Hence the motion error is neglected in the following analysis. With some algebraic manipulations and force analysis, the equivalent stiffness of the XY nanomanipulator in X axis can be obtained as

$$K_{\mathrm{X}} = 2K_{\mathrm{gtX}} + 2K_{\mathrm{ptY}} + \frac{2K_{\mathrm{ptY}}K_{\mathrm{gtX}}}{K_{\mathrm{paX}}}, \tag{1}$$

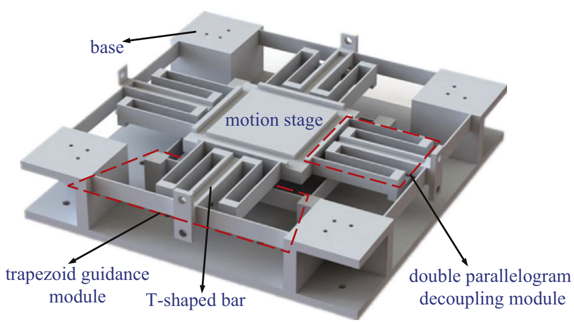

Fig. 1. A self-developed compliant XY nanomanipulator with spatial constraints.