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Research paper

Optimal design of a planar parallel 3-DOF nanopositioner with multi-objective

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ABSTRACT

Planar parallel three-degrees-of-freedom (3-DOF) nanopositioners have been used for sample scanner in scanning probe microscopy (SPM), wafer positioner in nanoimprint lithography, micro/nano manipulation, and precision machining. The performance evaluation indexes involve workspace, natural frequency, input coupling ratio, precision/accuracy, speed, payload capability, and output compliance. The tradeoff of multiple indexes is an important factor needing to be considered in the process of designing a nanopositioner. Stress, input stiffness, fatigue reliability, and force transmission are also the main constraints. This paper describes an optimal approach of selecting 16 key parameters of a planar parallel 3-DOF nanopositioner. Seven performance indexes and four constraints are involved in modelling the nanopositioner. A general analysis, optimization, and decision-making method is presented. All the modified-Pareto-optimality solutions are obtained using a multi-objective particle swarm optimization (MOPSO) algorithm. Different applications select preferred Pareto solutions from the same Pareto front. Several optimization cases are given to show the high efficiency of the proposed modelling and optimization method. Two design examples are given based on the corresponding demand of two typical application cases, respectively. The simulation and experimental results validate the proposed modelling and optimization method. The research results of this paper are helpful to design a planar parallel 3-DOF nanopositioner for different applications.

1. Introduction

Planar nanopositioners have been widely employed in precise and accurate nanoscale positioning. The application cases involve nanoimprint lithography [1,2], precision mechanical scanning in scanning probe microscopy (SPM) [3–7], micro-/nano manipulation [8–13], precision machining [14] and micro-/nano surface metrology measurement [15]. Above application cases have different prior demand on the performance of nanopositioners. Speed, precision, and accuracy are the prior factors for wafer positioning in nanoimprint lithography [1,2]. Speed, bandwidth, precision, and accuracy have more priority for the scanner in SPM [3–7]. For micro-/nano manipulation, a conventional major challenge is the trade-off between high rigidity, large magnification, high-precision tracking, and high-accuracy positioning [8,9,11,12]. More potential applications

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of planar nanopositioners involve x-ray/optical lithography, semiconductor inspection systems, mask alignment, surface profilometers, micro/nano-surgery, biological cell manipulation, micro/nano-assembly, micro-photonics packaging and testing, optical disks such as high density DVDs (HD-DVDs) [16,17].

To achieve a high positioning accuracy, flexure hinges are used to replace traditional kinematic pairs [18,19]. 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 parallel 3-DOF platforms to be applied. Another popular modeling approach is the screw theory [20], especially in stiffness modeling [21]. The Jacobian matrix can be regarded as the local performance index for evaluating the velocity, accuracy and rigidity mapping characteristics between the driving variables and the moving plate [22,23]. Computational analysis, such as finite element analysis, is typically adopted as an evaluation method prior to the fabrication [7,24]. The computational consuming time and modeling accuracy always conflict with each other, especially for the multi-objective optimization with sufficient design variables and constraints. The prototype test is also essential to validate the calculation and simulation results.

Abundant configurations have been proposed to develop a compliant parallel nanopositioner. Ortho-planar mechanisms are "mechanisms with links that can be simultaneously located in a plane with motion out of that plane" [25]. Ortho-planar springs are very compact and easy to manufacture because they can be made from a single piece of material. The primary disadvantage is that they are change-point mechanisms and has the potential of going into an alternative configuration. Lamina emergent mechanisms (LEMs) are mechanical devices fabricated from planar materials (lamina) with motion that emerges out of the fabrication plane [26]. LEMs offer the potential for high-performance, compact devices that can be fabricated at low manufacturing cost, but with the tradeoff of challenging design issues. Many application cases were provided in [27]. Double-layer planar springs are also competitive choices [28].

Parameter optimization plays a crucial role in seeking a competitive balance of multiple performance indexes. A lot of prior work on the optimization of micro/nano positioners has been done by other researchers. Scire et al. [29] optimized a micropositioning stage to achieve maximum mechanical displacement gain and rigidity. Ryu et al. [1] optimized a micromotion stage to maximize the yaw motion of the output body. Chang et al. [30] optimized a micropositioner to achieve maximum displacement gain and the minimum angular deviation. Elmustafa et al. [14] optimized a nanopositioner for a high stiffness and large load carrying ability. Wang et al. [24] optimized a micropositioner to minimize the input coupling ratio to a negligible level. Kim et al. [31] optimized a nanopositioner to maximize the system bandwidth (first resonance frequency). Tang et al. [6] optimized a nanopositioner to maximize the natural frequency. Wadikhaye et al. [32] optimized a nanopositioner to achieve a high natural frequency along with an acceptable travel range. Qin et al. [7] optimized a micropositioner to maximize workspace. Huang et al. [33] optimized a flexure-based mechanism to achieve a large displacement and a high first natural frequency. As mentioned above, the performance evaluation indexes of a nanopositioner involve workspace, natural frequency, input coupling ratio, precision, accuracy, speed, payload capability, fatigue, and stiffness. The tradeoff of multiple indexes is an important factor needing to be considered in the process of designing a nanopositioner. One or two indexes are the popular optimization objectives in the previous research. The whole performance indexes with sufficient design variables have been challenging tasks due to the complexity and difficulties in modeling and optimization approach.

The main contribution of the current research is the modelling and optimal design method of a planar parallel 3-DOF nanopositioner. The proposed method can obtain the Pareto front using multi-objective particle swarm optimization (MOPSO). Different application can select a preferred Pareto solution from the same Pareto front using the corresponding decision-making method. The remainder of the paper is organised as follows. The optimization model of a planar parallel 3-DOF nanopositioner is established in Section 2. Seven performance evaluation indexes and four constraints are introduced in Section 3 and Section 4, respectively. The modified Pareto optimality via MOPSO is given in Section 5. Several optimization cases are shown in Section 6. Then the experimental validation of two typical application cases are conducted in Section 7, followed by a brief conclusion in Section 8.

2. Optimization model

2.1. Basic structure

Compared to a two-degrees-of-freedom (2-DOF, x & y) nanopositioner [3,6,7], the planar 3-DOF platform increases the DOF and is capable of correcting possible undesired coupling between major axes. The planar 3-DOF platform has a serial or parallel configuration. The serial-kinematic platform has a large workspace, good dexterity, decoupling, linear kinematic, and simple forward kinematic [4,13,15,31,34,35]. The parallel-kinematic configuration has high structural/mechanical 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. All the actuators can be located at the base to reduce the active mobile mass and lead to high loading capacity. The 3-revolute-revolute-revolute (3RRR) parallel mechanism possesses high accuracy and precision, high rigidity and outstanding dynamic characteristics. This simple and convenient configuration has been widely applied in planar parallel 3-DOF nanopositioners [2,3,9,11,12,24,34–36]. Then the 3-RRR configuration was selected as the basic structure of the nanopositioner in this paper.