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A novel compliant micropositioning stage with dual ranges and resolutions

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A B S T R A C T

Dual-range stages are demanded in precision positioning applications that call for fine resolution in a smaller motion range and coarse resolution in a larger range. Traditional dual-range stages are realized using two actuators, which complicates the mechanism and control design procedures. This paper presents the design and testing of a novel dual-range, dual-resolution precision positioning stage driven by a single linear actuator. The stage structure is devised with leaf flexures to achieve a large stroke. Strain sensors are employed to provide different resolutions in the two motion ranges. To quantify the design of the motion ranges and fine/coarse resolution ratio, analytical models are established and verified through finite element analysis simulations. A proof-of-concept prototype is fabricated for experimental investigations and the experimental results validate the effectiveness of the proposed design. The reported ideas can also be extended to the design of multi-axis micropositioning stages.

1. Introduction

Micro-/nanopositioning systems are widely applied in the domain of precision manipulation and assembly. Resolution and range are the two fundamental performances in a precision positioning stage. Due to the sensing limitations, a high positioning resolution is usually obtained in a small motion range while a large range is achieved with a low resolution. In practice, many applications demand a micropositioning stage with both a large range and a high resolution to execute diverse tasks. For instance, in scanning probe microscopy, a positioning stage with a large range and high resolution is needed to scan a large specimen surface with a fine imaging resolution [1]. A dual-range positioning stage offers a promising solution by delivering both large range and high resolution using the combined coarse and fine stages.

To generate a micropositioning stage with dual ranges and resolutions, the dual-actuation approach is commonly employed to construct a dual-servo stage. This type of dual-stage is generally composed of a coarse stage and a fine stage that are connected in serial. The former provides a large motion range with coarse positioning resolution and the latter delivers a smaller range with fine positioning resolution. For example, dual-servo stages based on different actuation principles have been developed in the literature [2–8]. In the aforementioned works, various types of actuators have been adopted to drive the positioning stages. To achieve a precise positioning, piezoelectric actuators have been popularly employed. Nevertheless, the drawback of a piezoelectric actuator is its short stroke (typically, tens of micrometers) and piezoelectric nonlinearity (e.g., hysteresis and creep) [9,10]. The voice coil motor (VCM), another linear actuator based on electromagnetic principle, is capable of delivering a longer stroke without nonlinear effect. Hence, a VCM is more suitable to drive a micropositioning stage with large motion range [11]. In addition, sliding guideways are typically used to guide the output motion of the stage [3,5]. In contrast, flexure bearings are more preferred for precision engineering applications due to their merits in terms of no backlash, no friction, vacuum compatibility, and easy manufacturing [12]. Thus, flexures have been widely employed in the recent development of micropositioning systems [13–16].

The major issue of a dual-servo stage arises from the interference caused by the interaction between the coarse and fine stages. It has been shown that the interaction behavior of a dual-servo stage can lead to an unstable open-loop control system [17]. To mitigate this adverse interference effect, control and mechanical design approaches have been developed. For instance, the interference behavior can be reduced by designing a multiple-input-multiple-output (MIMO) control system [18,19]. Additionally, the interaction effect can also be alleviated by resorting a careful mechanical design [7]. Even so, employing two types of actuators complicates the control and mechanism design processes.

Here, we devise a novel single-drive micropositioning stage with dual ranges and dual resolutions. In particular, we propose a conceptual design for a dual-range and dual-resolution compliant stage based on an unequal-stiffness compliant mechanism. In

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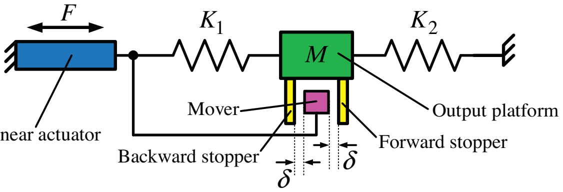

Fig. 1. Schematic of a micropositioning stage with dual ranges.

the small and large ranges, the mechanism is designed to exhibit different stiffness values, which are contributed by leaf flexures suffering from different bending deformations. The large and small deformations are monitored using two strain sensors to offer fine and coarse resolutions for the two ranges, respectively. Rather than dual-servo stages, the presented technique enables the achievement of a dual-range motion by adopting a single actuator. This reduces hardware costs and control design effort. Moreover, the single-drive design eliminates the conventional interference effect. We use both simulation and experimental investigations to verify the proof-of-concept design.

The remainder of this paper is organized as follows. Section 2 presents the conceptual design of the dual-range, dual-resolution stage. Then, the mechanical design of a flexure-based compliant stage is outlined in Section 3, where the motion range, resolution ratio design, and sensing and actuation issues are addressed in detail. Section 4 reports on a case study and provides a performance evaluation of a compliant stage through both analytical modeling and finite element analysis (FEA) approaches. A fabricated prototype stage is described in Section 5, where a collection of experimental studies are performed to verify the conceptual design. Section 6 concludes this paper.

2. Conceptual design

The conceptual design of a micropositioning stage with dual ranges and dual resolutions is detailed in this section.

2.1. Design of a compliant stage with dual ranges

The schematic for a one-axis, dual-range micropositioning stage is depicted in Fig. 1. The output platform M is actuated by a linear actuator through a compliant guiding bearing #1, which has an effective stiffness K_1. In addition, the platform M is connected to a fixed base via a compliant guiding bearing #2, which exhibits a stiffness K_2. To yield two motion ranges for M, a mechanical mover is linked to the driving end of the actuator. The bidirectional translation of the mover is constrained by two mechanical stoppers, which are fixed on the output platform M. It is notable that the two stoppers move along with the output platform M. Without loss of generality, it is assumed that the clearances (δ) between the mover and the two stoppers are identical.

Referring to Fig. 1, once the actuator drives the output platform to move forward (to the right), both bearings #1 and #2 are compressed. The overall equivalent stiffness can be expressed as

$$K_{\text{range1}} = \frac{1}{(1/K_1)+(1/K_2)}. \quad (1)$$

Assume that the relationship of $K_1 < K_2$ holds. After a particular driving displacement of D_1, the mover translates over a distance of δ (i.e., the clearance between the mover and forward stopper) with respect to M. Then, it contacts the stopper. The corresponding displacement R_1 of the output platform can be calculated in view of the relationship:

$$K_1(D_1 - R_1) = K_2 R_1, \quad (2)$$

which describes the driving force of the actuator. It allows the following generation:

$$R_1 = \frac{K_1}{K_1 + K_2} D_1. \quad (3)$$

Afterwards, if the driving continues in the forward direction, only the bearing K_2 will be deformed in that the deformation of bearing K_1 is stopped by the forward stopper. Under this situation, the overall stiffness of the mechanism becomes:

$$K_{\text{range2}} = K_2. \quad (4)$$

After the moment when the mover contacts the forward stopper, if a maximal driving displacement D_2 is produced by the actuator, then D_2 will be transmitted as the displacement of the output platform M. Hence, the overall output displacement of M can be derived as follows:

$$R_{\text{all}} = R_1 + R_2 = \frac{K_1}{K_1 + K_2} D_1 + D_2. \quad (5)$$

Thus, the forward motion range of M is divided into two intervals of $[0, R_1]$ and $[R_1, R_1 + R_2]$, which are assumed to be the smaller and larger ranges, respectively.

Similarly, the output platform can also be driven to move in the backward direction. Its backward motion range is divided into two intervals of $[-R_1, 0]$ and $[-R_1 - R_2, -R_1]$ by the backward stopper.

Unlike the conventional variable stiffness mechanism, which usually exhibits a specified stiffness profile [20,21], the proposed design possesses two discrete stiffness values in the overall motion range. In the small and larger ranges, the equivalent stiffness of the system is unequal, although the stiffness remains constant in each range. In the next section, a dual-resolution stage is devised based on the aforementioned dual-range design.

2.2. Design of a compliant stage with dual resolutions

Given the foregoing analysis, it is observed that in the smaller motion range of $[-R_1, R_1]$, the deformation is experienced by both bearings, whereas in the larger motion ranges of $[-R_1 - R_2, -R_1]$ and $[R_1, R_1 + R_2]$, the deformation of the mechanism is attributed to bearing #2 alone. In the smaller range, the deformations Δ_1 and Δ_2 of the bearings #1 and #2 are related by:

$$K_1 \Delta_1 = K_2 \Delta_2, \quad (6)$$

which describes the driving force of the actuator.

Assume that $K_1 < K_2$, then it can be deduced from (6) that $\Delta_1 > \Delta_2$, i.e., the deformation of bearing #1 is greater than that of bearing #2. It is known that strain type sensors can be employed to measure the displacement of compliant mechanisms indirectly by detecting the varying strain of deformed material [22]. If the same kind of strain sensor is adopted to measure the two different deformations, the larger the deformation is, the larger the output signal amplitude will be. That is, a larger deformation results in a higher signal-to-noise ratio, i.e., higher measurement resolution.

Therefore, the deformation of bearing #1 can be monitored using a strain sensor to obtain a higher position resolution in the smaller range of $[-R_1, R_1]$. However, the deformation of bearing #2 can be measured with a lower resolution in the larger ranges of $[-R_1 - R_2, -R_1]$ and $[R_1, R_1 + R_2]$ by the same type of sensor. In this way, a micropositioning stage with dual ranges and dual resolutions is devised. Specifically, the higher and lower resolutions are generated in the smaller and larger motion ranges, respectively.

3. Mechanism design

An embodiment of the proposed compliant stage is designed as shown in Fig. 2. The leaf flexures are adopted to enable a large