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High-speed vertical positioning stage with integrated dual-sensor arrangement

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ABSTRACT

This article presents a novel vertical positioning stage with a dual-sensor arrangement suitable for scanning probe microscopy. The stage has a travel range of 8.4 μm and a first resonance frequency of 24 kHz in the direction of travel. The sensor arrangement consists of an integrated piezoelectric force sensor and laminated piezoresistive strain sensor. The piezoelectric force sensor exhibits extremely low noise and introduces a zero into the dynamics which allows the use of integral force feedback. This control method provides excellent damping performance and guaranteed stability. The piezoresistive sensor is used for tracking control with an analog PI controller which is shown to be an approximate inverse of the damped system. The resulting closed-loop system has a bandwidth is 11.4 kHz and 6σ-resolution of 3.6 nm, which is ideal for nanopositioning and atomic force microscopy (AFM) applications. The proposed vertical stage is used to replace the vertical axis of a commercial AFM. Scans are performed in constant-force contact mode with a tip velocity of 0.2 mm/s, 1 mm/s and 2 mm/s. The recorded images contain negligible artefacts due to insufficient vertical bandwidth.

1. Introduction

Compact, high-bandwidth nanopositioning systems have been employed in a wide range of applications, including precision alignment of fiber optics [1], scanning probe microscopy [2–5], beam steering systems [6] and cavity ring-down spectroscopy in optical applications [7,8]. Piezoelectric stack actuators are used in these precision systems due to the high force and stiffness. However, piezoelectric stack actuators exhibit hysteresis over a large range and creep at low frequencies. These nonlinearities can cause tracking errors greater than 20%.

Many forms of feedback and feedforward control have been applied to eliminate vibration, hysteresis and creep [9–11]. Inversion-based feedforward techniques [11–13] can be used to suppress the sharp resonance behavior and improve the tracking performance of nanopositioning systems without the need of a sensor. However, the main disadvantage of feedforward control is the need for an accurate model and a stable resonance frequency. A nonlinear model, which may be computationally demanding to invert, is also required for hysteresis and creep compensation.

Sensor-based feedback control is one of the most commonly used techniques for controlling piezoelectric systems [11,13–16]. This approach is simple, insensitive to modeling error, and effectively reduces nonlinearity. Damping controllers, such as integral resonant control [17–19], positive position feedback [20–23], resonant control [24] and polynomial-based controller [25] have been used to suppress resonances and reduce the bandwidth limitations imposed by mechanical resonances. However, when a damped system is included in an integral tracking loop, the closed-loop system is still limited by a low gain margin [26]. Moreover, the wide bandwidth of a damping controller can introduce sensor-induced positioning noise to the system.

Capacitive sensors are among the most popular sensors used in nanopositioning systems owing to their low noise, high resolution and relatively low cost [27]. They can be easily installed in the lateral axis of nanopositioning systems as shown in Fig. 1(a). However, for the vertical axis of a compact nanopositioner, the installation of the sensor becomes challenging. As shown in Fig. 1(b), additional mass on the moving platform may be needed to serve as a target for the sensor, which increases the physical size and reduces the resonance frequency.

In this work, a dual-sensor system is proposed for controlling vibration and nonlinearity in a piezoelectric driven, high-speed vertical stage. The technique utilizes a piezoelectric force sensor and a piezoresistive strain sensor to estimate displacement. The two sensors are bonded to the piezoelectric stack actuator directly which

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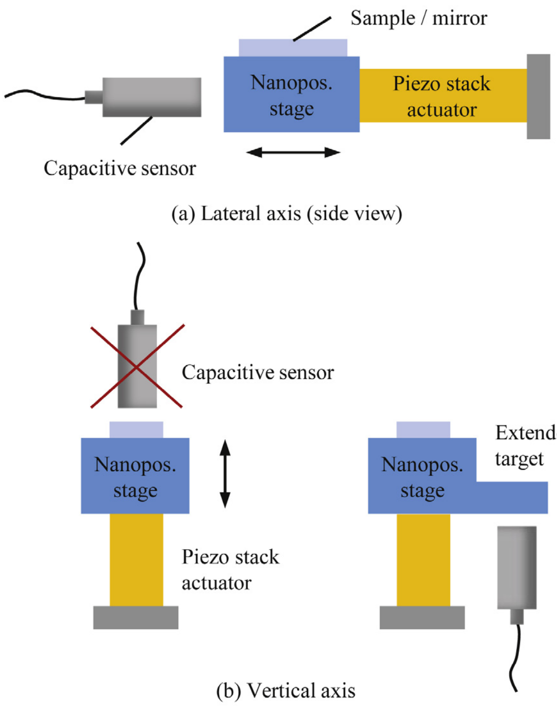


(a) Lateral axis (side view)

(b) Vertical axis

Fig. 1. Installation of a capacitive sensor on the lateral and vertical axes of a nanopositioner.

allows for an extremely compact design. The piezoelectric force sensor provides a wide bandwidth with low noise at high frequencies [28,29]. Although piezoelectric force sensors have excellent AC properties, the sensitivity is temperature dependent and they are not suitable for low-frequency measurements due to the capacitive source impedance which imposes a first-order high-pass response. To overcome these limitations, a piezoresistive strain sensor is used for tracking control and to augment the force sensor at frequencies below 10 Hz. Piezoresisitive strain sensors can be directly bonded to a stack actuator without affecting the dynamic performance. The sensitivity of piezoresistive sensors is typically two orders of magnitude greater than metal foil strain sensors so sub-nanometer resolution can be achieved at kHz bandwidths [27].

The performance of the proposed vertical system is demonstrated on a commercial AFM where the vertical axis of the AFM is replaced by the high-speed vertical stage. Many common modes of scanning probe microscopy (SPM), such as constant-force AFM and constant-current scanning tunneling microscopy, require a vertical feedback system to regulate the interaction force between tip and sample. A major speed limitation in these modes is the vertical feedback bandwidth [2,3,30–32]. During a high-speed scan, an AFM system with a low vertical feedback bandwidth is unable to track sharp features in a sample topography. This leads to the "smudging" feature edges in the image [13,30]. The most commonly used vertical feedback controller in an AFM is an integral controller. The vertical bandwidth can therefore be estimated as ω_n/P, where ω_n is the resonance frequency and P is the peak magnitude [33]. By increasing the resonance frequency of the vertical stage, and actively damping the resonance using force-feedback, the maximum vertical feedback bandwidth can be improved significantly.

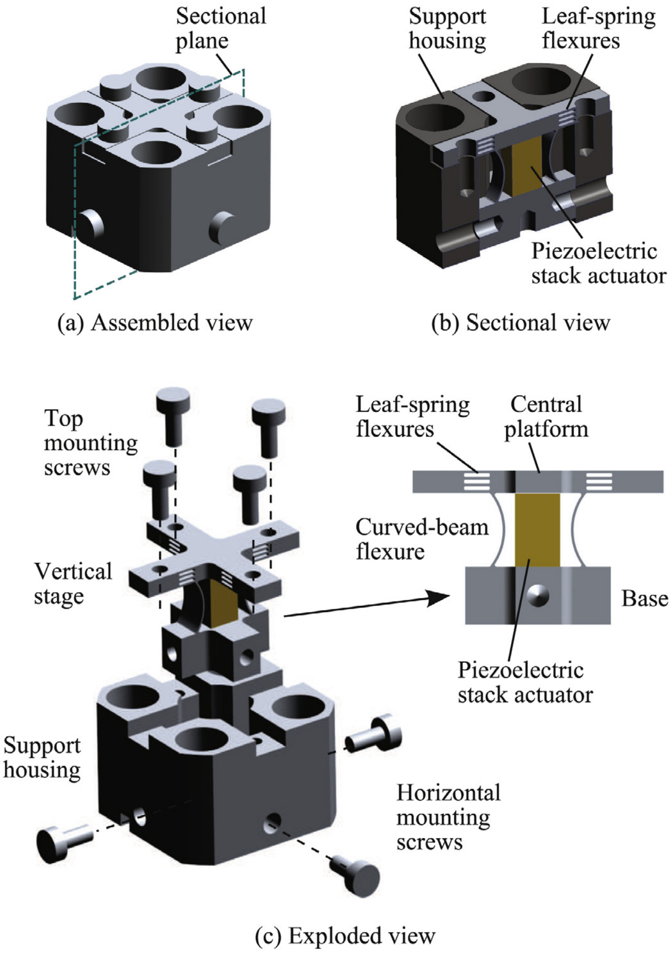
The remainder of the paper proceeds as follows. Section 2 presents the design of the vertical stage and the preload mechanism. This section also discusses the design of the actuator and sensor arrangement. Feedback control strategies using the dual-sensor arrangement are presented in Section 3. Experimental results can be found in Section 4. Section 5 reports the position noise of the sensors and closed-loop system. The vertical system is then used for Atomic Force Microscopy (AFM) in Section 6. The article is concluded in Section 7.

2. High-speed vertical stage design

Fig. 2 illustrates the proposed high-speed vertical stage which consists of four sets of leaf-spring flexures arranged orthogonally. These flexures allow the central platform to move vertically while simultaneously restraining the lateral motion. A 7 mm × 7 mm × 11.5 mm piezoelectric stack actuator is used to deform the flexures elastically and to drive the central platform.

2.1. Actuator and sensors

The piezoelectric stack actuator is constructed from four 2-mm plate stacks (NOLIAC NAC2021) bonded in series to a 2-mm NAC2021 force sensor as shown in Fig. 3. A 0.5-mm ceramic plate is used to separate the sensor and actuator in order to minimize Poisson coupling from the actuator to sensor. Two more ceramic plates are glued to each end of the actuator respectively to electrically isolate the actuator from the nanopositioner. The piezoresistive strain sensor is a Micron Instruments SSGH-060-033-1000PB half-bridge which is glued to the side of the actuator for displacement measurement.



(a) Assembled view

(b) Sectional view

(c) Exploded view

Fig. 2. High-speed vertical stage. (a) Assembly view showing the vertical stage being mounted to its support housing. (b) Sectional view showing the vertical stage, support housing and piezoelectric stack actuator. (c) Exploded view of the vertical stage.