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Low-stiffness dual stage actuator for long rage positioning with nanometer resolution

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ABSTRACT

This paper presents a dual stage actuator (DSA) capable of long-stroke positioning with nanometer resolution without an additional vibration isolation. The DSA system is composed of a linear motor and a compact Lorentz actuator used as the coarse and fine actuators, respectively. Since the fine actuator is constructed for a low-stiffness, the disturbances from the base are mechanically reduced and rejected by means of a feedback control. In addition, this system only requires one sensor measuring the fine actuator position, because the coarse actuator velocity and position can be estimated from the transmissibility of the fine actuator. Experimental results demonstrate that the DSA moves 100 mm and reaches the ±30 nm error band (peak-to-peak) in 0.41 s. At static positioning, the DSA achieves a precision of ±2.5 nm (peak-to-peak).

1. Introduction

In applications where high-precision positioning over a long range is required, a single actuator may not be able to achieve the desired performance. To satisfy the requirements, a long-stroke coarse actuator can be combined with a short-stroke fine actuator as a dual stage actuator (DSA). In nano-positioning DSA systems, only the fine actuator requires nanometer precision. Based on the choice of this fine actuator and the corresponding system design, DSAs can be broadly categorized by the spring constant of the fine actuator into high-stiffness, low-stiffness, and zero-stiffness systems.

High-stiffness systems can be realized by using piezoelectric materials as the fine actuator, which have a high intrinsic stiffness. Piezos have the advantages of easy miniaturization, high precision, high actuation force and fast response. They can be combined with a variety of coarse actuators in DSAs. For example, piezos are mounted onto Lorentz actuators (voice coil motor) and applied to hard disk drives (HDDs) [1] or magnetic tape recording systems [2]. Piezos' relatively high force and high stiffness are also used with linear motors in a feed drive system for machining [3]. However, due to the high stiffness of piezoelectric actuators, it is difficult to reject disturbances transmitting from their base, such as floor vibrations and coarse actuator oscillation [4]. While remedies have been taken, for example by adding passive damping for shock resistance [5], zero stiffness systems are best used to mechanically decouple the fine and coarse actuation.

A zero-stiffness DSA can be constructed by installing Lorentz [4] or reluctance actuators [6] as the fine actuator, because its base and moving part can be mechanically decoupled by design. Particularly Lorentz actuators are commonly used due to their high linearity [7]. They are often combined with commutated motors [8–10] and applied to wafer scanners for lithography [11], as well as to robot arms for automatic assembly [12]. In these systems, the movable parts are suspended typically pneumatically or magnetically to ensure zero stiffness. Therefore, these setups tend to be heavy and bulky with air feet for pneumatic suspension or require several sensors and actuators for magnetic levitation [13]. In addition, the heavy moving parts cause a compromise between the achievable acceleration and the sensitivity to disturbances, limiting either the operational speed or the positioning accuracy, commonly referred to as the “mass dilemma” [4].

Low-stiffness actuators can be found in optical disk drives (ODDs) such as CD/DVD players, where the Lorentz actuators' moving part is loosely suspended by wires, thus mechanically coupling their moving part and the base with lowered stiffness [14]. These actuators have been mounted on a motor-worm-gear for the coarse actuation [15]. For the operation of the ODDs, the DSAs do not obtain the absolute position of the fine actuator, but the position error signal [16,15]. Furthermore, there is no sensor for the coarse actuation. Instead, the coarse actuator is controlled based on the control input to the fine actuator [17].

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In comparison with high-stiffness and zero-stiffness DSAs, low-stiffness systems have the advantages of avoiding complicated design to float the moving part, while the low spring constant of the fine actuator reduces the transmission of disturbances from the coarse actuator. However, the challenge remains in control design for the rejection of the residual disturbances to achieve high-precision positioning.

For control of DSA systems, multi-input multi-output (MIMO) control design [18–21] may be applied, since they are regarded as a system with multiple inputs. Another strategy to control DSAs is to design single-input single-output (SISO) controllers for the fine and coarse actuators in a certain configuration, such as the decoupling or the master–slave [22,23]. By using the SISO control design, the order of controllers can be lower than that of MIMO [24], while the SISO design allows the freedom of selecting the control design techniques individually for the fine actuator and the coarse actuator. In fact, discrete SMC was successfully applied to the fine actuator, while proximate time-optimal control was used for the coarse actuator [25].

In general, the fine actuator and the coarse actuator of a DSA have different objectives to complement each other. While the fine actuator realizes the precision motion, the coarse actuator carries the fine actuator for the long range motion. To fulfill their own roles, the actuators have different types of control challenges. For the precision motion, the fine actuator typically requires a high control bandwidth and high disturbance rejection. In contrast, the coarse actuator needs to move fast enough to track the motion trajectory over a long range. To overcome the challenges, this paper proposes a SISO control design that utilizes the freedom to select control design techniques to individually solve the distinct control problems.

This paper proposes a low-stiffness DSA system capable of high-precision positioning over a long range. The disturbances reduced by the low stiffness are further rejected by feedback control. Due to the compact design, the moving part of the fine actuator is light and rigid enough to achieve a sufficient control bandwidth to reject the disturbances and to overcome the mass dilemma, retaining both operational speed and position accuracy. Furthermore, the DSA does not require any displacement sensors for the coarse actuation, because the necessary information can be estimated from the low-stiffness design and the residual transmissibility of the fine actuator. For control of the DSA, the control design techniques are individually selected for the fine and coarse actuators, based on the system analysis.

This paper is organized as follows. Section 2 introduces the low-stiffness DSA system. In Section 3 the system is modeled, and disturbances are analyzed. In Section 4 controllers and motion trajectories are designed with an observer. Section 5 presents experimental results, and Section 6 concludes the paper.

2. System description

Fig. 1 shows a DSA setup that is built on a pick-and-place machine (CAT(2a), Philips, Amsterdam, Netherlands), which is directly placed on the fifth floor of a building without external vibration isolation, such as an optical table [26]. This machine has six linear motors, and one of them is used as the long-stroke coarse actuator of the DSA. The linear motor is guided by roller bearings and operated by a servo driver in force control mode. For safety reasons, the actuation force is limited to about ±250 N by software. As the fine actuator, a Lorentz actuator of a laser pickup (SF-HD65, Sanyo, Osaka, Japan) is used. The resistance and inductance of the coil are 4.8 Ω and 71 μH, respectively, and the voltage over the coil is proportional to the current up to approximately 11 kHz. Because this is sufficiently higher than a target control bandwidth of 1 kHz in control design, a voltage amplifier is utilized to drive the actuator although the Lorentz force is proportional to the current. The actuation range of the fine actuator is limited to approximately ±1 mm. To optically measure the fine actuator position, the objective lens is replaced by a cube-corner retroreflector (43–305, Edmund optics, Barrington, USA), which has a diameter of about 7 mm with a weight of about 0.35 g, and a single-path heterodyne Michelson interferometer (10899A, Agilent Technologies, San Francisco, USA) is mounted with a polarizing beam splitter on the platform for the real time control of the DSA. The interferometer has a resolution of 1.25 nm and detects movement up to 0.40 m/s. An additional retroreflector is mounted on the coarse actuator to measure its position with a second interferometric detector and a polarizing beam splitter; however, this second sensor serves only for evaluation and not for control of the DSA.

The servo driver, the voltage amplifier and the interferometers are all connected to a rapid prototyping control system, where controllers are implemented at a sampling frequency of f_s = 20 kHz by using the CPU (DS1005, dSpace GmbH, Paderborn, Germany). While the FPGA of the prototyping control system (DS5203, dSpace GmbH, Paderborn, Germany) is used to communicate with

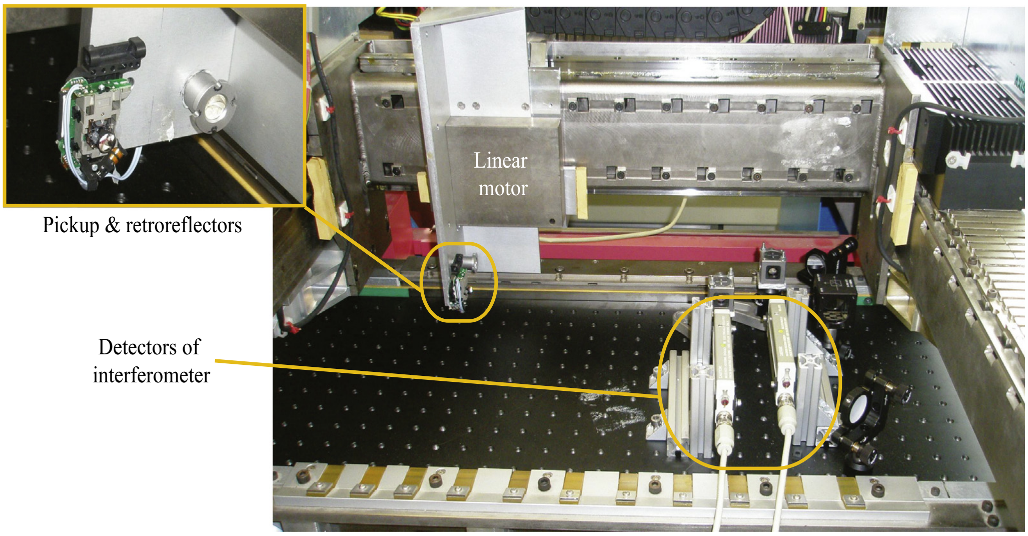

Fig. 1. Photograph of the low-stiffness DSA.