Sensors & Transducers, Vol. 178, Issue 9, September 2014, pp. 83-87

Sensors & Transducers

Synchronization Control Scheme for Hybrid Linear Actuator Based on One Common Position Sensor with Long Travel Range and Nanometer Resolution

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Received: 4 May 2014 /Accepted: 29 August 2014 /Published: 30 September 2014

Abstract: To overcome the limitations of the independent stacked hybrid actuator with multiple sensors, a new hybrid linear actuator combines the advantages of both technologies: piezo actuator for extremely high accuracy and motorized stage for long travel ranges. A hybrid linear actuator prototype is developed for testing in our satellite tracking antenna pointing control system. For the maximum absolute positioning accuracy, host positioning controller depends only on one common position sensor for both the coarse and fine positioning at the same time. Synchronization control scheme shows promising results for extremely small steps, high repeatability and good linearity over long travel ranges. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Piezo, Motor, Hybrid, Actuator, Control, Sensor.

1. Introduction

Actuator is a device that can produce force or motion (displacement). Electromagnetic actuators can be used for long travel range of motion but are limited in positioning accuracy due to their own noise level and stiffness, therefore, this technology is far below the nanotechnology requirements. Piezo actuators convert electrical energy directly to mechanical energy, and have no stiction friction, backlash because of no rotating or sliding parts, and excellent dynamic characteristics because of deriving their motions from solid-state crystalline effects. Thus, the motion in nanometer to sub-nanometer incremental motions within the travel range of micron up to millimeter becomes possible. Furthermore, there are no moving parts in contact with each other to limit resolution. Good nano-positioning systems can track the target of several nanometers within a few milliseconds. However, nanotechnology currently meets two predominantly mechanical requirements: accurate positioning with nanometer or sub-nanometer resolution, at the same time, long travel range up to one inch or more [1]. The above-mentioned improvements can be achieved by the novel mechatronic design principal: an integration of piezo technology into classic motorized system.

This paper introduces a new hybrid linear actuator (also known as translator) design has extreme high resolution, high dynamics and high load capacity especially for antenna pointing control system. This design overcomes the limitations of conventional precision positioning equipment by combining the well-known advantages of piezo drives (extremely high resolution and very fast response) with a servo-motor and lead screw (long travel ranges and high holding forces) arrangement.

2. Hybrid Actuator

2.1. Piezo Walk Actuator

The two traditional principles for high linear accuracy and long travel range had been utilized.

Fig. 1 shows that the first approach is based on walking drive mechanism, which features high stiffness, compactness but low speed. This non-resonant piezo motors can offer higher resolutions and forces than ultrasonic piezo motors. This actuator combines the d33 piezo deformation for longitudinal effect with d15 piezo deformation for the shear effect, and may be preloaded from both upper and lower sides onto a moving runner (the figure shows only one side). They usually consist of several individual piezo actuator units and generate motion through a succession of coordinated clamp/unclamp and expand/contract cycles. Each extension cycle provides only a few microns of motion, but running at hundreds to thousands of Hertz, and thus achieves continuous motion within the range of millimeter per second. As a result, this structure needs a number of high resolution sensors and a synchronous controller for step and analog control of its hybrid piezo stacks [2].

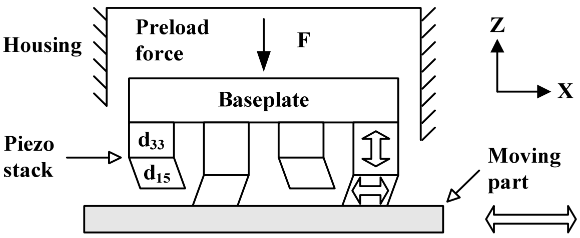

Fig. 1. Basic Principle of a Piezo Walk Actuator.

2.2. Traditional Hybrid Linear Actuator

Fig. 2 shows that the second approach is the combination of piezo ultrasonic stage with piezo flexure actuated stage, and the former is for high speed coarse positioning and the latter is for fine positioning. A flexure is a frictionless, stictionless hinge-like device that relies upon the elastic deformation (flexing) of a solid material to permit motion.

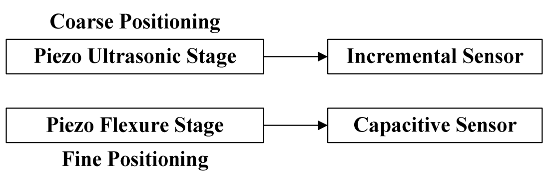

Fig. 2. Serial Stacked Hybrid Actuator with Separated Sensors.

Table 1 compares the features of the classic direct-drive piezo stage and piezo ultrasonic stage. Direct-drive piezo stages offer a resolution of less than one nanometer and are available as add-ons to motorized drive stages. Piezo stages can achieve extremely high accelerations up to 10,000 g and respond to input in less than 0.1 ms, and are frictionless and backlash-free.

Table 1. Comparison of Piezo Flexure Stage and Piezo Ultrasonic Stage.

Name	Piezo Flexure Stage	Piezo Ultrasonic Stage
Resolution	0.00001 [μm]	0.1 [μm]
Range	10 to 500 [μm]	5 to 1000 $\times 10^3$ [μm]
Sensor (typ.)	Capacitive sensor	Incremental optical sensor
Power Dissipation	About zero for static position Passive sensor probe & target	Small Motor power Sensors power

Piezo ultrasonic stages consist of a stator, a piezo ceramic oscillator and a slider (friction bar) which is attached to the moving part of the stage. Piezo ultrasonic stages are direct-drive systems which not use lead screws or gear heads and are backlash-free, In addition, they neither cause nor are influenced by magnetic fields. Piezo ultrasonic stages can achieve high dynamic performance and very smooth motion. Additionally, when they are switched off, the self-locking effect is very favorable for long-term stability [2].

This stacked (independent) hybrid motion system can provide sub-nanometer resolution, but the absolute accuracy at the platform is limited to the accuracy of the coarse (fast) piezo ultrasonic stage. The positioning errors of the single stages accumulate for the overall system that leads to large errors. Furthermore, the system requires two sensors: capacitive sensor for piezo flexure stage and incremental optical sensor for piezo ultrasonic stage, and two independent controllers [2].

2.3. Promising Hybrid Linear Actuator

Promising hybrid linear actuator approach is the integration of one common extreme high resolution incremental sensor into a flexure stage which is driven by both piezo and motor (or piezo-ultrasonic) actuator at the same time. This structure combines the advantages of both technologies: piezo actuator for extremely high accuracy and motorized stage for long travel ranges. Since the both of coarse and fine positioning are only depended by one common sensor, thus a single control system are formed to obtain the maximum absolute positioning accuracy, but needs a sophisticated synchronization control scheme.

Fig. 3 shows that a hybrid linear actuator consists of a DC motor plus led screw in series with a piezo stack. A motor-driven lead screw with a nut is coupled to the sled of the stage. The nut can be preloaded to reduce backlash. Compared to ball screws, lead screw has self-locking effect but exhibits higher friction than recirculating ball screw. In addition, the predictable effects of low velocity and shorter lifetime lead to require more motor power and maintain.

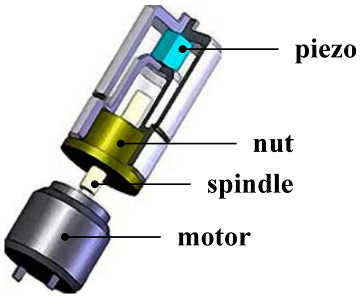

Fig. 3. Piezo Actuator for Fine Adjustment and Motor Stage for Long Travel Range.

3. Antenna Pointing Control System

The above new hybrid linear actuator had been tested in our satellite tracking antenna pointing control system for a specific vehicle. Large amplitude motion with time constants measured in a few seconds is required to move between satellites, whereas fine control is required to track a given non-geostationary satellite. The combination of DC motor and lead screw supports large displacements, such as tens of millimeters, but is dynamically slow when tracking the reference demand. Conversely the typical piezo stack only supports a maximum displacement of ±0.1 mm, but has a very fast dynamic response. The mechatronic combination of the two actuator technologies may achieve a long travel range and high resolution results.

As shown in Fig. 4, the position signal is fed to the host positioning controller by using one common laser position sensor. The host controller outputs piezo stack and DC motor control signal, respectively. The control structure consists of two paths: One to control the motor using its own speed sensor; the other to control the piezo stack and positioning signal feedback to the host controller by one common position sensor. Normalizing some level limits are necessary to stabilize the control function and prevent overflow errors in the D/A or D/PWM parts.

Indirect motion metrology is cheap, but does not qualify for state-of-the-art nanopositioning. Likewise, any sensor based on friction does not qualify either. Examples of indirect metrology are motor-mounted rotary encoders and piezo-resistive strain sensors mounted on actuators or flexures (measuring the strain of the flexures-thereby inducing friction and errors-instead of the motion). High-performance nanopositioning systems employ non-contact direct metrology, placed to measure motion where it matters most to the application. Examples of direct metrology are capacitive sensors, laser interferometers and non-contact optical, incremental encoders [3].

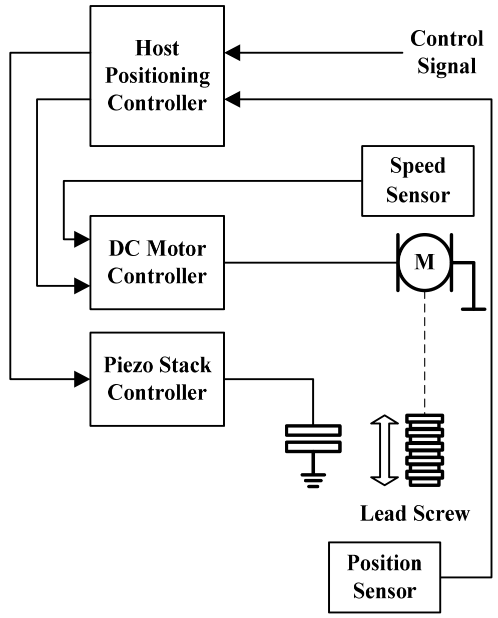

Fig. 4. Antenna Pointing Control System Structure.

As shown in Fig. 5, the high-pass filter passes demands to the piezo stack over short time periods, and thereafter washes the demand out. Then, the combination of DC motor and lead screw picks up the demand to maintain the correct steady state. Since the piezo actuator is driven at a higher bandwidth than the motorized actuator, the host positioning controller is necessary to divide the frequency response between the piezo actuator and the motorized stage; otherwise both actuators would try to compensate for their respective motion. All output signals are normalized to the range of ± 5 V.

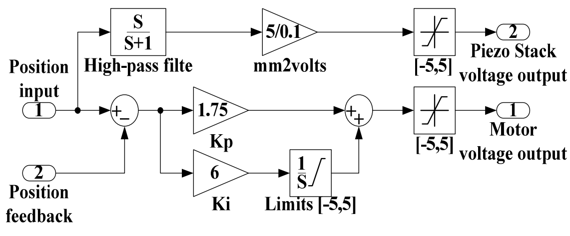

Fig. 5. Host Positioning Controller.

As shown in Fig. 6, the 12 V DC motor works in the current feedback control servo loop. A few advantages of DC motor are no vibration, smooth operation, wide speed range and good low-speed torque. For best performance, PWM and H-bridge driver combine to serve as the motor power. The current controller uses the PID algorithm, and the cutoff frequency of 20 Hz low pass filter processes the current feedback signal.

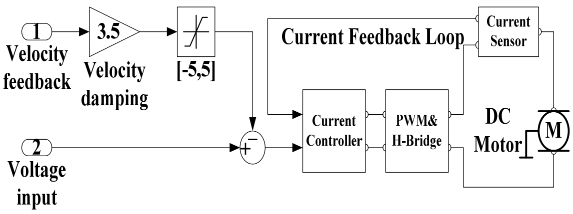

Fig. 6. DC Motor Controller.

As shown in Fig. 7, since the basic transfer function of piezo actuator is substantially simpler than that of a servo DC motor, so that the piezo stack controller is quite easy to design. 300 volts is applied to piezo stack that results in a 0.1 mm maximum displacement. Moreover, the series resistance is used to add electrical damping to improve the convergence of simulation, and thus avoid an index 2 topology result: a voltage source is connected directly in parallel with a capacitor.

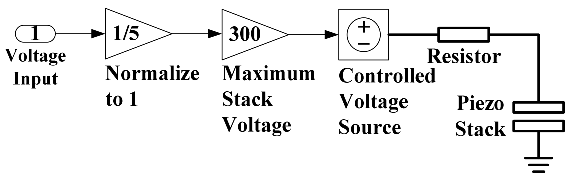

Fig. 7. Piezo Stack Controller.

4. Test and Analysis

According to the above control scheme, a hybrid linear actuator prototype was developed for testing. As shown in Fig. 8, the load mass is set to 10 kg, and a 0.05 mm step positioning at 0.2 seconds is used for testing. If piezo stack actuator is disabled, the output displacement overshoot is about 25 µm. When the piezo stack is enabled, the overshoot is a few microns. This fully shows the piezo material has a very fast dynamic response.

As shown in Fig. 9, a 100 mm step positioning at one second is used for testing. When the piezo input / control voltage drops to 0, the positioning task has been basically completed. In this actuator, although the maximum displacement of the piezo stack is supported by only ±0.1 mm, the large stroke displacement of 100 mm can be achieved as a result of the DC motor and the lead screw drive mechanism. After about 15 seconds, a piezo input voltage and DC motor speed both drop to 0 attributed to the self-locking effect of the lead screw. Thereby the active sensor and the controllers consume only a small amount of energy, and the rest has been reduced to zero.

As shown in Fig. 10, a 20 mm incremental motion per 15 seconds at 10 periods is used for testing. The maximum deviation from the trajectory is measured less than ±10 mm.

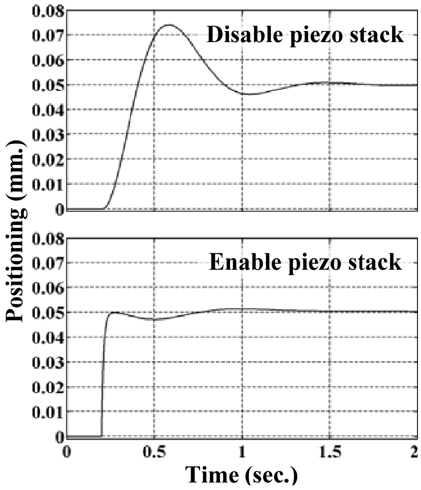

Fig. 8. Step Response of 0.05 mm Linear Positioning.

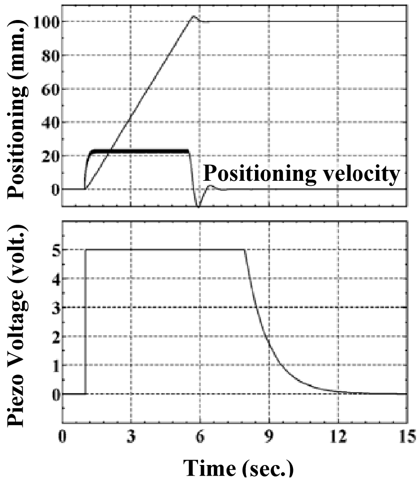

Fig. 9. Step Response of 100 mm linear positioning and the corresponding piezo voltage.

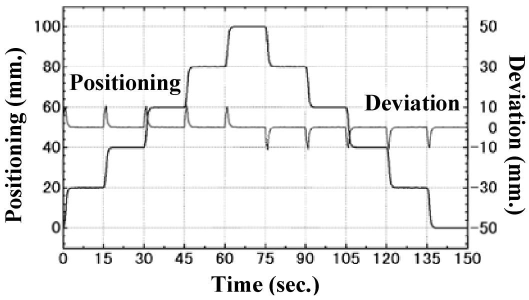

Fig. 10. 20 mm incremental motion and the corresponding deviation measured by external laser interferometer.

The small range step response is dominated by the piezo actuator in this system. In dynamic motion operation, the piezo actuator can compensate rapidly the friction caused by the surface roughness. The stage has a very small hysteresis attributed to the flexure design. The synchronization control and a two path control algorithm shows promising results for extremely small steps, high repeatability and good linearity over long travel ranges. Some influence from the resonant frequency should be cancelled in future design. Since the test results are basically consistent with the design requirements, this hybrid linear actuator verifies the feasibility as one of multi-axis antenna pointing control system.

5. Conclusions

This Hybrid linear actuator design includes not only selecting high resolution sensor within long travel range, processing the resulting high-frequency signal, and designing the respective controller, but also considering the interaction of electric or mechanical factors on the resolution and accuracy. Moreover, the motor driven part and the piezo actuators both have resonant properties. Considering more rapid dynamic response, these resonant terms from the two actuators should be cancelled by some suitable notch filters.

This hybrid linear actuator synchronously performs the motion function of the two positioning controller by one common high-resolution sensor, thus forms a fully integrated motion system, so that the motor and the piezo actuator can act on together at any time. The result is far better than a coarse-adjust & fine-adjust system, and some effects like startup stick, slip and backlash can be completely compensated and a motion profile with high stability of velocity can be followed. Attributed to the high stiffness of the piezo material, achieving a few nanometers positioning only takes up a few milliseconds, which is significantly faster than a conventional, higher-inertia, linear-motor driven stages. Furthermore, minimal increments can be reliably executed within the range of the sensor resolution. Thus from startup to settling, every action reflects the inherent advantages of both the motor stage and the piezo actuator.

Acknowledgements

This work is supported by Natural Science Foundation of Shaanxi Province, China (Grant No. 2010JM7020), Key Science and Technology Program of Shaanxi Province, China (Grant No. 2011K09-06).

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