A Robust Control Scheme of Nanopositioning Driven by Ultrasonic Motor

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ABSTRACT

An innovative nanopositioning control system is proposed in this paper. A commercial ultrasonic motor (Nanomotion Co. model HR4) is employed to generate 3-mode motions of different scales. A multi-scale positioning control scheme can thus been developed by integrating the 3 driving modes. A new displacement sensor LDGI (Linear Diffraction Grating Interferometer) is developed and served as the displacement feedback. The uncertainty of LDGI system has been proved less than 10nm in 15mm. By phase subdivision technique the resolution of LDGI can be interpolated to 0.25nm. With this hardware system a software-based controller is developed. A self-tuning module, called Back Propagation Neural Network (BPNN), is added to a PID control loop. This self-tuning PID controller shows more robust than conventional ones, especially when some unpredictable disturbance occurs. Experiments show that this system is able to reach the steady state in 2 seconds without notable overshoot or vibration and hold the position for a long time with the positioning error less than 3nm. When some disturbances occur the system can build a new steady state in 2 seconds.

Keywords: Nanopositioning, multi-scale system, BPNN, robust control

1. INTRODUCTION

In commercial applications like semiconductor manufacturing, high position resolution as well as throughput is important. Sometimes large travel range and high positioning accuracy are both required. The term “multi-scale control” is thus introduced to describe a control system with acceptable performance in both nanoscale and macroscale operations [1]. A commercial ultrasonic motor HR4 [2], with different driving modes, can actuate a large stroke length over several millimeters and fine steps in nano scale. At present, linear encoders are most commonly used in machine tool as the position feedback sensor, but they intrinsically have constraint on the resolution of the system because of their large grating pitch [3-4]. Laser interferometer can also been used for positioning control, but it needs a comprehensive system for vibration isolation and temperature control [5]. A new sensor LDGI (Linear Diffraction Grating Interferometer) can meet the requirement of both long stroke and high resolution [6-7]. For such a positioning system, with the scale ratio (range/accuracy) larger than 10^6, conventional PID controller cannot build the steady state quickly or keep it for long. A self-tuning module called Back Propagated Neural Network can adjust the gains of Kp, Ki and KD on line. A BPNN-based PID controller [8-9] for nanopositioning shows more robust than conventional ones [10], but how to hold the position for long time remains another problem.

2. CONFIGURATION OF THE NANOPositionING SYSTEM

Configuration of this nanopositioning system is shown in Fig.1. The central table is moved by an active linear guide in push-pull mode, which is actuated by the HR4 ultrasonic motor through a friction force on the ceramic plate. On the other side of the table, a holographic grating is mounted on the passive linear guide whose displacement is synchronized to the table and is detected by a Linear Diffraction Grating Interferometer (LDGI). Since the displacement sensor is in line with the moving axis, it observes the law of Abbé Principle [11-12]. The displacement sensor LDGI outputs sine and cosine waves when the table is moved, like the conventional linear optical encoder. LDGI signals are amplified by a chf19@163.com; phone 0551-2903823; fax 2903823
process circuit and sampled by an NI-DAQ card PCI-6259. After the software process the current displacement and speed can be calculated and then the optimized driving voltage can be determined by a software-based controller and sent to the motor HR4 through PCI-6259 and AB2 driver.

2.1 Integration of 3 driving modes of HR4

The ultrasonic motor HR4 is employed to generate 3-mode motions of different scales. A multi-scale positioning control scheme can thus been developed by integrating the three following driving modes: In AC mode, HR4 generates a successive motion with 4 piezoelectric elements in the stroke length from 0.1mm-20mm; then in GATE mode HR4 drives the table in short steps of 20-50nm and the total stroke length is within several microns; at last in DC mode, HR4 works like a conventional PZT actuator to adjust the position in several nanometers and to hold the position for a long time.

In AC mode the system needs a low and stable speed. Inconstant speed with notable acceleration will cause instability of the mechanic system. In this mode the speed is calculated at every millisecond. Unlike the conventional stepping motor, which has strict relationship between the voltage frequency and the speed, the ultrasonic motor needs a close-loop control scheme. Although the positioning error of AC mode can be measured and compensated in GATE and DC mode, to improve the control efficiency, it’s necessary to reduce the positioning error in AC mode because the movement in GATE mode is very slow. Experiments show that 1mm/s is acceptable to maintain the stability of this system and if the speed is less than 1mm/s it doesn’t show notable improvement. After AC-mode driving the table is close to the target point with the positioning error within 5µm, which can be measured by LDGI signals.

In GATE mode, HR4 makes the table move in short steps with random increments of 20-30nm. With the displacement feedback, HR4 moves the table in GATE mode until the position to the target is within 30nm.

DC-mode control is the key technology to this study. Theoretically, the maximum travel length in DC mode is 300nm, but because of the influence of the friction and deformation of the mechanic elements, the practical travel length is 150nm. For a conventional PZT actuator, a characteristic curve is often used to describe the relationship between displacement and driving voltage. It’s based on one hypothesis that the friction is constant at every position, which is not
possible due to uneven surface finish conditions. A close-loop control scheme is thus necessary in DC mode. It is to compensate the positioning error after the GATE mode [10]. The position of the table, however, cannot be held by static force because the piezoelectric elements of HR4 and other mechanic elements will release the stress. Besides, some unpredictable disturbance may affect the position.

The above control process is described in Fig.2. The details of different-mode controls will be described in following sections.

![Flow chart of this control scheme. The details of different modes will be illustrated in following sections.](image)

2.2 LDGI signal process

In the LDGI system, the grating pitch serves as the unit of displacement measurement. The holographic grating used is 1200 lines per millimeter. The LDGI generates one period of signal when the table moves 416nm. Some distortions on the ideal signals, such as DC drift, amplitude variation and phase error, are corrected by a software module. With a programmable zero crossing comparator and a counter, long-stroke displacement can be measured. For the two signals with a phase shift of 90°, pulse counting only calculates the displacement to the integral numbers of the quarter pitch. The resolution is still limited to 104nm. For less than quarter pitch motion it has to be done by the phase subdivision method [10, 13-14]. With this method the resolution is determined by the precision of AD converter of PCI-6259 (16-bit).

The input limits of PCI-6259 are ±10V. So the input range is r=20V. The average amplitude of the signal is: a=4V. The resolution of PCI-6259 is 216. So the average resolution of displacement measurement $\Delta S_{\text{min}}$ can be evaluated by:

$$\Delta S_{\text{min}} = \frac{208}{2^{16} \cdot 2a / r} \approx 0.004nm \quad (1)$$

This theoretical resolution, however, makes no sense when the minimal effective digit is considered. In this study, despite of the noise and some low-frequency disturbance, 10mV change of LDGI signal can be detected effectively. So the practical resolution should be:

$$\Delta S_{\text{min}} = \frac{208 \times 10 \times 10^{-3}}{2a} \approx 0.25nm \quad (2)$$

3. DESIGN OF BPNN-BASED PID CONTROLLER

In conventional PID control scheme, constant gains $K_P$, $K_I$ and $K_D$ should be tested by simulation and experiments. When the system condition changes these parameters should be tested again. In this study, the friction of the linear guides may change unpredictably. Experiments show that no constant set of $K_P$, $K_I$ and $K_D$ can work.

A self-tuning module, called Back Propagated Neural Network is thus introduced in this controller to determine the optimized set of $K_P$, $K_I$ and $K_D$ in real time.
The structure of the control loop (take AC-mode speed control for example) is shown in Fig.3.

\[
J(k) = \frac{1}{2} \sum_{r=1}^{N} [r(k+1) - y(k+1)]^2
\]  

(3)

Fig. 3. The structure of the BPNN-based PID control loop

Suppose \( r(k) \) is the desired output and \( y(k) \) is the actual output. The performance figure function has to be inducted as:

Steepest descent of this performance figures function is the rule to adjust \( K_p, K_i \) and \( K_d \) [9, 15].

This BPNN-base PID control scheme is used in AC mode and DC mode. In AC mode the controlled parameter is the speed of the table and in DC mode the displacement is controlled.

A feedforward compensation on driving voltage is employed because there is an unpredictable friction change at the instant when the table starts moving. The controller will force the driving voltage to reduce when it finds the table starts moving. This operation is prior to any adjustment by the BPNN-base PID arithmetic.

This BPNN-based PID controller shows more convenient and robust than conventional ones. This software-based controller has worked well on the author’s another system but detailed tests were not sufficient [10].

4. POSITIONING EXPERIMENTS

The speed can be controlled around 1mm/s in AC mode, as shown in Fig.4. The speed curve seems not smooth enough because in every “while loop” during the movement, the signal section to calculate current speed is very short and the relative error of displacement measurement is notable. It doesn’t mean sudden change in every millisecond.

Fig.5 shows the last step in GATE mode and the early performance in DC mode. The control system is able to converge in less than 2 seconds. Fig.6 shows the system is able to hold the position for long time with the positioning error less than 3nm. Fig.7. shows the controller can rebuild the steady state in 2 seconds when a disturbance takes place.
Fig. 5. This controller is able to converge in 2 seconds in DC mode.

Fig. 6. This controller can hold the position for long time with the positioning error less than 3nm.

Fig. 7. This controller can rebuild the steady state in 2 seconds when some disturbance takes place.

5. CONCLUSION

This paper presents a positioning control strategy by integrating three driving modes in different scales. In millimeter scale AC mode is used to move the table successively. In micrometer scale GATE mode is used to compensate the
positioning error after AC mode. In nanometer scale DC mode is to adjust and hold the position for long time. In order to obtain fine stability and fast software computation, some special features are as follows:

1. Multi sampling rates are used in different modes respectively. In AC mode for instance, sampling rate of 50kHz is set when the desired speed is 1mm/s, which means about 18 points are processed in one waveform cycle. In GATE mode and AC mode the sampling rates are lower.

2. Signal process is carried out after AC mode and the result is used to correct the signals in GATE and DC mode.

3. In GATE and DC mode, only the displacement is recorded. In order to reduce the memory space in time, the buffer of signal data is cleared when displacement is calculated in every “while loop”.

4. The upper limit and the lower limit are set on the variation of the voltage, in case of unreasonable output of the neural network.

5. A self-diagnosing module will be activated when there’s some trouble. For example, when a notable vibration of controller output is detected the controller will force the table to stop.

ACKNOWLEDGEMENT

The work reported forms part of a research program funded by the Natural Science Foundation of China (50420120134).

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