

A Fuzzy Logic Based Adaptive Feedforward PI Controller for Nanometer Positioning

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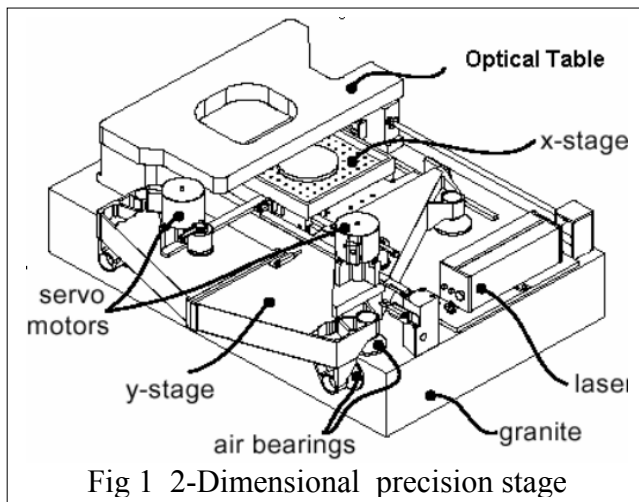
Abstract

A technology driver in high precision manufacturing is a position measurement and control system which allows manufacturers to control the movement of their equipment at extremely high levels of precision. Performances of controllers play important roles in nanometer level positioning. A robust, disturbance resistant controller is necessary for nanometer positioning. However, the time varying and nonlinear properties of plants frequently result in the performance degradation of widely used PID controllers.

The performance of feedback system can be improved considerably by combining PI feedback control with feedforward control together. Feedback controllers are very capable of compensating disturbances because feedback controllers are basically error driven. However, they often suffer from a trade-off between high performance and robust stability. With good dynamic property knowledge available, a feedforward controller may be able to prevent control errors, because feedforward controller output is based on the reference, instead of the error signal. Feedforward controllers improve the control performance by including a feedforward term to the PI output so that the controller can react to the command more quickly in order to bring the plant to the desired setpoint. A fuzzy logic controller will adjust the feedforward and PI feedback gains (K_{ffv} , K_{ffa} , K_{ffd} , K_P and K_I) to adapt the change of dynamic behavior caused by the time varying and nonlinear properties inherent in the positioning systems.

The developed control algorithm is simulated in MATLAB, and is implemented with a TMS320M67 DSP in an experimental nanolithography stage. A X-Y grating based metrology is used to measure the position of stage, which is more robust to environmental change and more suitable with high performance servomechanisms. Experiments show that stage will follow 10 nm step input with nm level steady state error, which is mainly caused by floor and acoustic vibrations.

1. Introduction



A robust and disturbance resistant controller is necessary for nanometer positioning. However, the time varying and nonlinear properties inherent in the system dynamics frequently result in degradation of PID controller performance. For example, air-bearing supported capstan drives are one of several systems used in precision positioning stages (such as the one presented here). They exhibit very low friction and no backlash. However, capstan friction results in non linearity. Open loop testing indicates that the

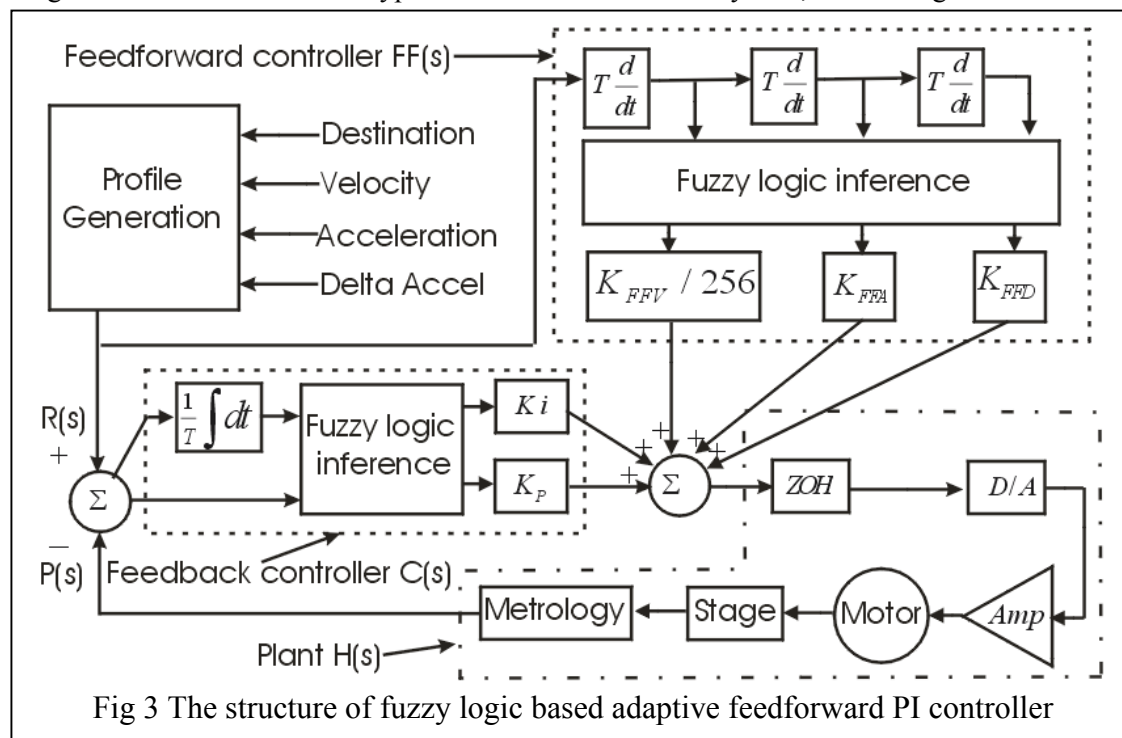
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frequency responses of in macro (1 μm maximum amplitude) and micro (50 nm) range motion are different.

Fixed gain PID controllers are not robust enough and further improvement is needed. Rao and Ro stated that state feedback controllers had better robustness and disturbance rejection capability than PID controllers do. Ro and Hubbel adopted Model reference adaptive control (MRAC) theory in controlling a stage. As a result, separate mathematical models and MRACs had to be developed for micro and macro modes according to the scale of the movement. Although this dual-model MRAC did improve the consistency between micro and macro modes as opposed to a single model MRAC , the problem of deciding the proper threshold for switch from micro to macro mode would make a dual model MRAC controller unsuitable for, say, a 500 nm movement.

2 Design of Fuzzy Logic Based Adaptive Feedforward PI Controller

A block diagram of an analog PI controller with fuzzy logic based adaptive feedforward loop is shown in Fig 2. The PI feedback controller is designed for robustness and accuracy. The integrator increases the type number of the system, allowing it to track



with no (or limited) error. In other words, the integrator will eliminate steady state error to guarantee nm level control accuracy. However, implementing an I-controller by itself will cause instability, and it must be combined with a proportional action to stabilize the system. On the other hand, the PI controller does not help to speed up the system response. Feedforward controllers improve the control performance by including a feedforward term to the PI output so that the controller can react to the command more quickly, in order to bring the plant to the desired setpoint. Note that this function is outside the feedback control loop, and thus does not affect the system's stability. Feedforward helps to minimize following error during motion, by generating most of the DAC output signal from the motion profile rather than the position error.

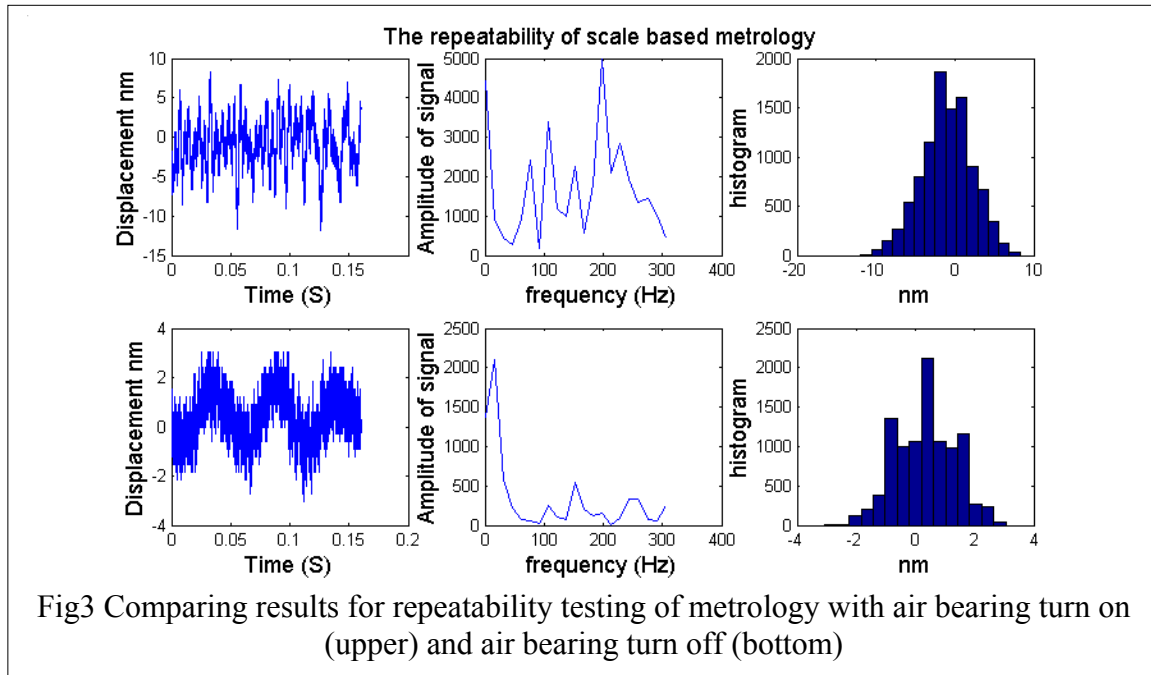
The performance of feedforward and feedback controller depends on the dynamic behavior of plant. Also, feedforward controllers may require large control signals which are beyond the permissible maximum output of the drive. A fuzzy logic controller will adjust the

feedforward and feedback gain (deciding the proper threshold for switching from micro to macro mode) according to the reference gain to deal with those issues.

3 Simulation and Experiment Setup

The proposed control algorithm is simulated in MATLAB. Simulation results show that the fuzzy logic adaptive controller will adapt to change of dynamic behavior caused by the time varying and nonlinear properties inherent in the positioning system dynamics. The testbed for optical Nanolithography which is used to investigate the result of adaptive feedforward controller (shown in Figure 1) is an interferometric lithography stepper, featuring an air-bearing stage, with capstan drive, with HP laser interferometers for feedback. This stage is configured as a stacked-slide X-Y stage. The moving stage is supported by air bearings on the granite surface table.

An XY grid-based planar encoder system is used to measure 2-dimensional ultra-precise

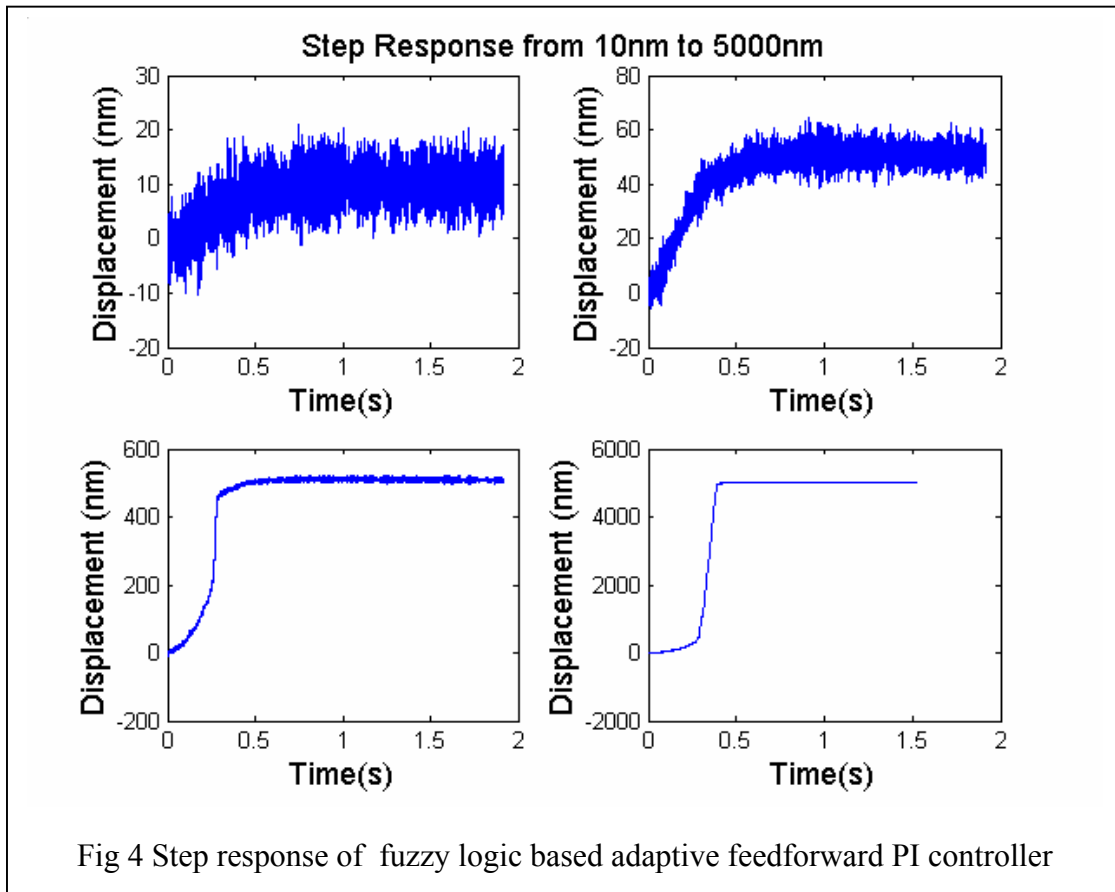


planar displacements of stage, which avoids the turbulence effects which are commonly encountered with laser interferometers or the Abbe errors associated with separate linear scales. The 2-D grid measurement resolution is 0.3nm. The update rate for this metrology is 375 kHz, which is suitable for high performance servo-mechanisms.

The control algorithm is implemented digitally with TMS320C67 digital signal processor which is mounted on an Innovative Integration M67 card. This is a 32-bit standard full-size PCI card. The digital position outputs of the X-Y grating based metrology are accessed through the DSP card parallel digital I/O connector, which is faster than through the PC's bus. The sampling period is 10 μ s. The 16 bit D/A output of the DSP is amplified and then drives the DC motor.

4 Results And Future Work

The measurement noise is shown in Fig 3. When the stage is not floated (resting on granite plate), the amplitude of measurement noise is about 2.5 nm. Comparatively, the amplitude of measurement noise is about 8.5 nm when stage is floated. This may be because the air-bearing is more sensitive to the vibration disturbance from floor or the air pressure in the air bearing changes with time. The controller is tested with different size of step input. The stage will follow 10 ,20 ,50 ,500 and 5000 nm step input with the steady state error around nano-meter level after filtering out the vibration disturbance (Shown in Fig 4).



The PI feedback controller ensures the control accuracy of stage motion. Adaptive feedforward controller improve the transient control performance considerably when there are the changes of dynamic behavior caused by the time varying and nonlinear properties inherent in the positioning systems.

In our current approach, the gain of feedforward controller is determined by trial and error based on experiments. One possible approach in the future is *learning* feed-forward (LFF) controllers. LFF may be able to prevent control errors, because its output is based on the reference, instead of the error signal. They are not necessarily based on a physical process model and are potentially able to learn and reproduce an 'arbitrary' continuous function to any desired degree of accuracy, even if it concerns non-linear and/or time-variant functions.

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