CONTROL OF A 2 DOF LONG-RANGE AND 6 DOF SHORT-RANGE STAGES FOR NANOMETER POSITIONING

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OVERVIEW[*]

This abstract presents the work towards development of an 8 axis controller that simultaneously controls a 2 degree-of-freedom (DOF) long-range (50 mm) and a 6 DOF short range stage (4 μm, 160 μRad) [1]. The long-range stage is used for traverse in *X*- and *Y*- axis while the short-range stage corrects for any error motions generated by the long-range stage for nanometer positioning capabilities. The system can be separated into 2 controllers, long-range stage and short-range stage, cascaded together. The short-range stage operates to keep the position errors at nanometer levels with feedback from a laser interferometer (Zygo DMI 4004). The long-range stage can be controlled for position from rotary encoders while it attempts to maintain the short-range stage in its mid range.

A dSPACE real time hardware interface is used to perform all controls with a sample rate of 10 kHz while monitoring the laser interferometers, encoder and controlling in all 8 axes. Programming and system simulation is performed in Matlab™ Simulink software.

To date the short-range controller has been tested utilizing, for now, a nest of 6 capacitance gages to determine controller performance under closed loop. While actuating the z axis linearly, under closed-loop control, with a 100 nm sinusoidal amplitude a cross coupling of the X and Y axis was measured to be approximately 3 nm RMS, which is approaching the measurement resolution of this test set-up.

To further test controller strategies a single-axis system was also constructed and tested. This stage had a range of 50 mm and was also able to maintain nanometer level position errors over a 25 mm sinusoidal traverse.

Further results of controller performance and transformation matrices will be presented at the conference. Construction of the stage and integration of laser interferometer feedback is also expected to be completed. Details of construction, interfacing and performance testing will be presented. Furthermore, due to limited amount of space for this abstract the reader is encouraged to view the references for further information.

SINGLE DOF LONG-RANGE STAGE

This section provides a brief overview of an experimental program to develop and optimize control of the single axis long-range stage, see Figure 1. A more comprehensive report of this study will be prepared for publication in the near future.

To perform controller analysis a single DOF long-range stage was built utilizing ultra-high molecular weight polyethylene (UHMWPE) bearings [2] that slide against optically polished Zerodur® flats. Translations are generated with the use of an Aerotech BA10 servo amplifier and an Aerotech BMS60 brushless DC motor with an internal integral 1000 count per revolution rotary encoder with an 100 times multiplier in conjunction with an 3.1 threads per mm feedscrew and a UHMWPE nut [3]. Translations of the stage are measured with a Zygo DMI 4004 interferometer system. Located on top of the single DOF long-range stage is a single DOF piezo short-range stage with an attached planar mirror for positioning feedback. The amplifier, motor encoder, and interferometer are connected to a dSPACE 1103 PPC controller board for real time data acquisition.

Initial tests of the long-range stage were undertaken to determine the transfer functions of the stage using a simple open loop controller in conjunction with a dynamic signal analyzer for the long-range stage only.

Once the transfer function is known a closed loop controller was developed, see Figure 2.

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The closed loop controller encompassed a backlash compensation and a variable gain to maximize performance of the long-range stage. The backlash compensation is comprised of a memory block (stores previous commanded position), sign block (determines the new direction), a gain, and a rate limiter (this is set to keep corrections within the bandwidth of the controller). The variable gain controller was advantageous since it allows the controller to be operated under different gain settings as the velocity of the stage is changed. The variable gain controller is comprised of a derivative block (this measures the speed of the stage), absolute block (abs, to assure the signal remains positive), and a saturation block (limits the gain). Lead compensation is also used to stabilize the motor drive. Figure 3 shows the closed loop response of the single DOF long-range stage under closed loop control. During short traverses (approximately 0.01 Nm torque at an input amplitude of 0.5 V is applied by the motor) the first resonant frequency occurs at approximately 150 Hz and 25 Hz for longer traverses (approximately 0.1 Nm of torque at an input amplitude of 5 V is applied by the motor). For short traverses the implied torque demand on the motor results in small rotations so that the bearings inside the motor do not rotate. Therefore, the motor during short traverses can be modeled as a stiff spring resulting in the higher resonant frequency. Figure 4 shows the single DOF long-range stage performance with the amplifier operating as a current source generating a torque at the motor of 0.1 Nm. The stage was able minimize positioning rms controller error to 0.1 μm over a traverse of 5 mm in 1000 s.

This system resulted in control of the long-range stage to within the range of the short-range mirror stage. With combined long- and short-range control it was possible to demonstrate controller errors having an rms value of 0.7 nm over a traverse of 500 μm [1]

6 DOF SHORT-RANGE STAGE

A third generation, 6 DOF, short-range stage was also tested under a simple PID closed loop controller. The short-range stage utilizes 6 single crystal PZT tubes oriented in a 2-2-2 configuration capable of traversing 4 μm and rotations of 160 μRad, for further information on the first generation see Seugling *et al.* [4]. Amplifiers from InsituTec HV150031 are used to drive the PZT's up to approximately 1000 V. The short-range stage lowest resonant frequency was determined to be approximately 210 Hz in the x-axis, while the z-axis had the highest at approximately 510 Hz. Further tests showed a cross coupling under closed loop control of the actuators to be less than 3 nm rms when the z-axis is actuated with a 100 nm sinusoidal amplitude, while monitoring the x- and y-axis, see Buice *et al.* [5] for further information.

COMPLETE CONTROLLER DESIGN

For final system implementation it is desirable to implement the above mentioned stages into one instrument giving nanometer positioning capabilities over traverses of 50 mm in 2 axis. The 6 DOF short-range stage is utilized in conjunction with the stacked long-range stage (giving 2 axis of motion) to drive the errors generated by the long-range stage into the nanometer positioning error regime. However, to further complicate the controller strategy it is desired to maintain the short-range stage in its mid traverse ranges by using the long-range stages to compensate any linear motion generated by the short-range stage in the x- and y-axis. Figure 5 shows a block diagram indicating major features of the closed loop controller that is under development. This controller includes user interface, probe (AFM, STM, *etc.*), imagining software, long- and short-range controller strategies (mentioned in previous sections), 6 DOF interferometric measurement system, and independent measurement of the short-range stage. Furthermore, the controller is a modular design to enable additional operations without requiring substantial recording of software. For instance it is desirable in the future to implement a long-range z-axis and addition of probes to allow for multiple measurements to be performed simultaneously during one operation.

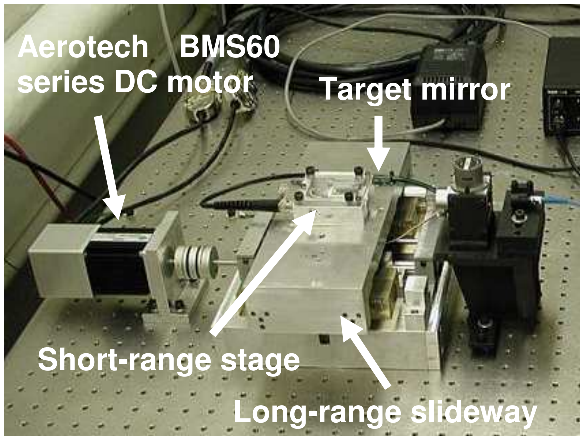

FIGURE 1. Test set-up of single DOF long- and short-range stage for controller implementation.

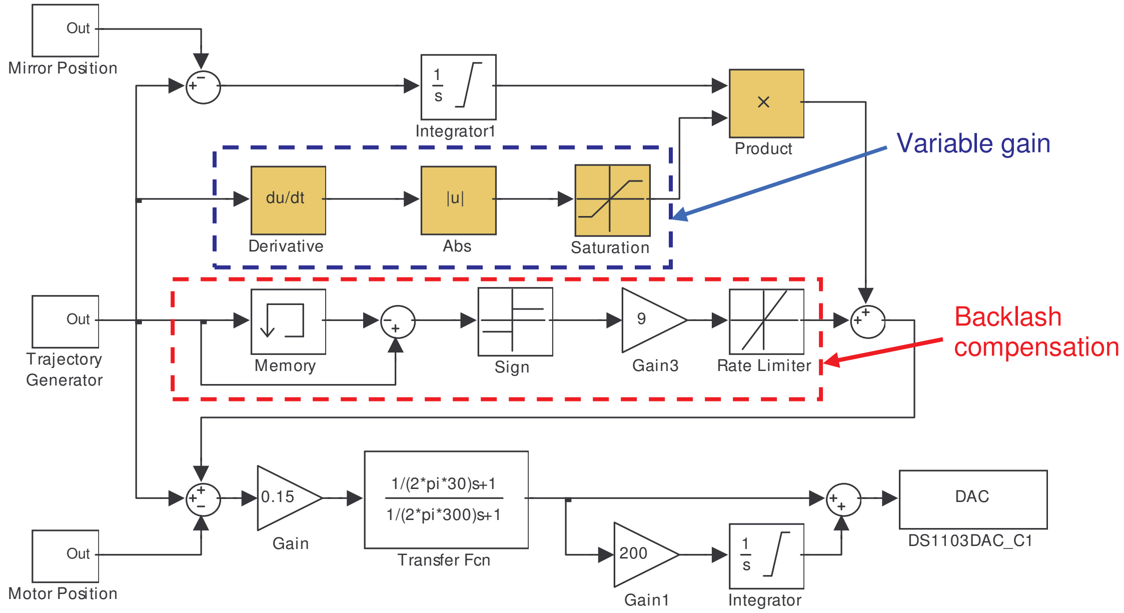

FIGURE 2. Closed loop controller for single DOF long-range stage with backlash compensation and variable gain.

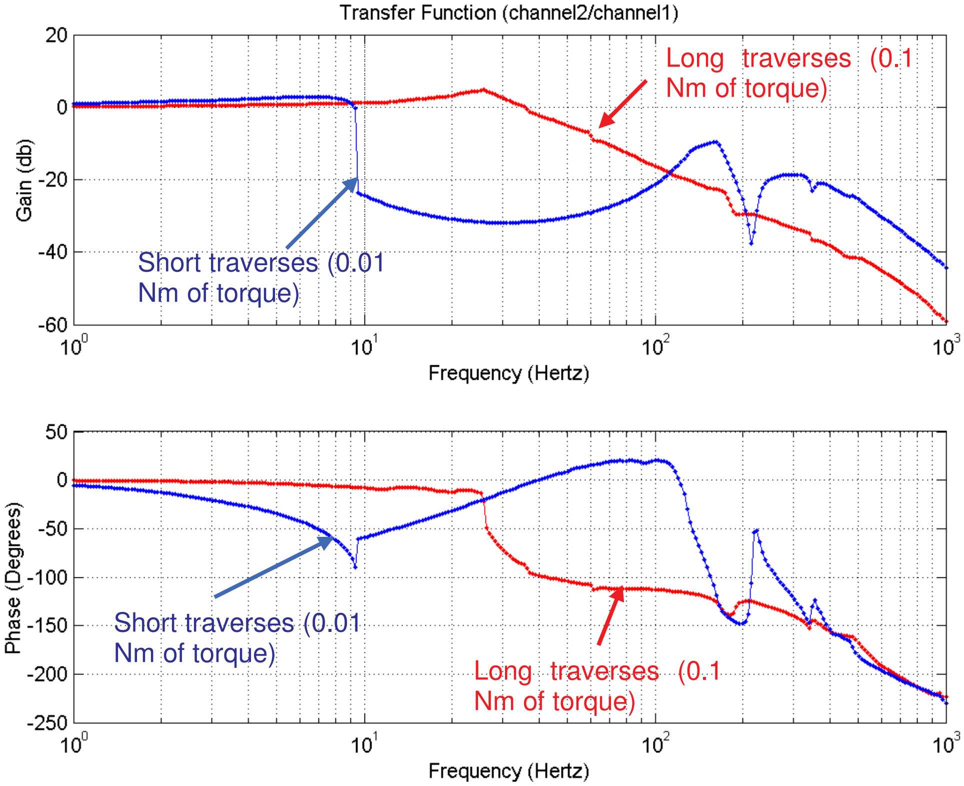

FIGURE 3. Closed loop response of motor control used in variable gain controller

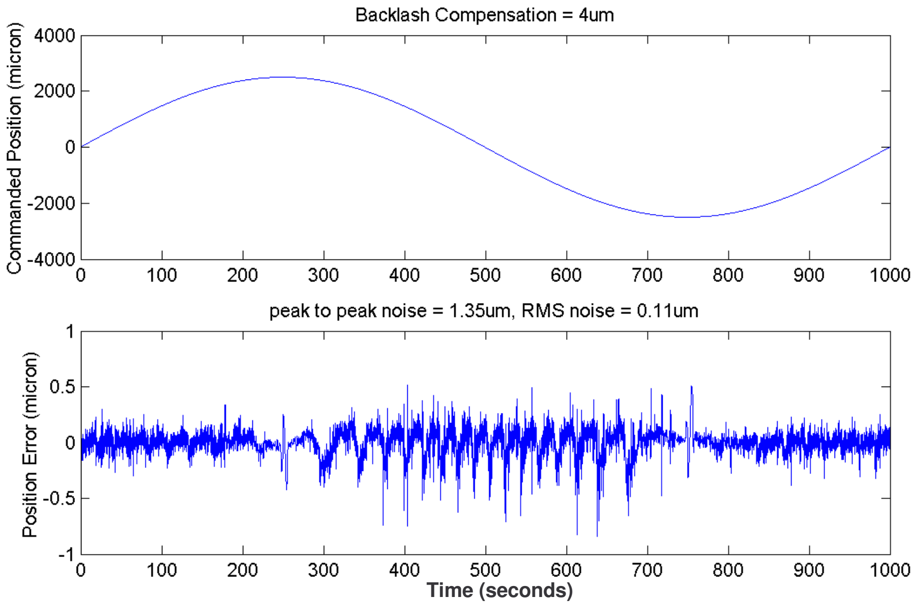

FIGURE 4. Performance of single DOF long-range stage under closed loop with backlash compensation and variable gain controller. Peak-to-peak noise is 1.35 μm with an rms noise of 0.11 μm.

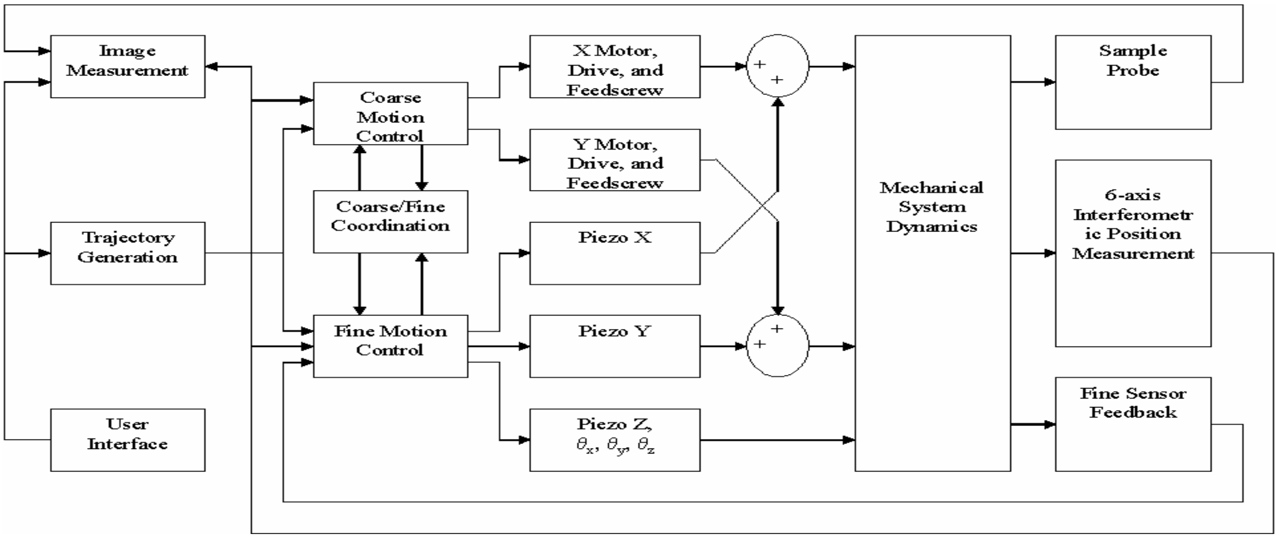

FIGURE 5. Complete simplified controller schematic for 2 DOF long-range and 6 DOF short-range stages.

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