Development of a Wafer Positioning System for the Sandia Extreme Ultraviolet Lithography Tool

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Abstract

A wafer positioning system was recently developed by Sandia National Laboratories for an Extreme Ultraviolet Lithography (EUVL) tool[1]. The system, which utilizes a magnetically levitated fine stage to provide ultra-precise positioning in all six degrees of freedom, incorporates technological improvements resulting from four years of prototype development.[2] This paper describes the design, implementation, and functional capability of the system. Specifics regarding control system electronics, including software and control algorithm structure, as well as performance design goals and test results are presented. Potential system enhancements, some of which are in process, are also discussed.

Introduction

Magnetic levitation (maglev) is emerging as an important technology for wafer positioning systems in advanced lithography applications. The advantages of maglev stem from the absence of physical contact. The resulting lack of friction enables accurate, fast positioning. Maglev systems are mechanically simple, accomplishing full six degree-of-freedom suspension and control with a minimum of moving parts. Power-efficient designs, which reduce the possibility of thermal distortion of the platen, are achievable.

History of Maglev Positioning at Sandia

In the late 1980s, a concept for a magnetically levitated fine positioning technique was developed at MIT by Dr. David Trumper. The technique appeared to offer numerous advantages over conventional approaches. The maglev technique is frictionless, generates no wear particles, and requires no lubrication. A maglev system requires relatively simple fabrication techniques, offering cost advantages. Designs with extremely high power efficiency are readily achievable to minimize the possibility of thermal distortion of the platen. GCA Corp. viewed this new technology as very promising for lithography applications. They began implementing a plan to incorporate maglev positioning technology into GCA steppers. However, barriers to this plan included several difficulties in the application of the technology, such as the nonlinear aspects of the actuators, and implementing the multi-input, multi-output control strategy which is required. These difficulties prompted GCA and SEMATECH, through the Sandia/SEMATECH Cooperative Research and Development Agreement (CRADA), to seek assistance from Sandia in the development of a maglev fine stage control system. The first part of our effort, during CY '92, was the development of a control system for a prototype maglev fine stage. By the time of GCA's demise in mid-1993, proof-of-concept testing of the stage system had been successfully accomplished at Sandia. Peak-to-peak positioning noise of less than 20 nm was demonstrated. The ARPA Advanced Lithography Program funded a study that specified control system improvements needed for commercial application. Knowledge gained during these efforts has been applied to the development of the wafer stage system for the EUVL program.

The EUVL Project

The demand for smaller critical dimensions in integrated circuits has driven projection lithography to shorter wavelengths. Deep ultraviolet systems, operating at 248 nm, are commercially available and 193 nm lithography is under development. Research and development to extend this trend to extreme ultraviolet (EUV) wavelengths, in the range of 11 nm to 14 nm, is underway at Sandia National Laboratories in Livermore, California. The EUVL project is supported by the Department of Energy through a CRADA between Sandia National Laboratories and AT&T Bell Laboratories and by the ARPA Advanced Lithography Program. An EUVL laboratory tool using a 10x reduction Schwarzschild camera and magnetically levitated wafer stage driven by a digital feedback controller facilitate this research. Figure 1 shows a drawing of the tool[1]. This system represents the first attempt at integrating all major subsystems into an EUVL laboratory tool, suitable for device fabrication experiments. Further development

of EUV technology is aimed at the goal of building a practical lithography tool capable of producing microelectronics devices having critical dimensions of less than 0.13 μm.
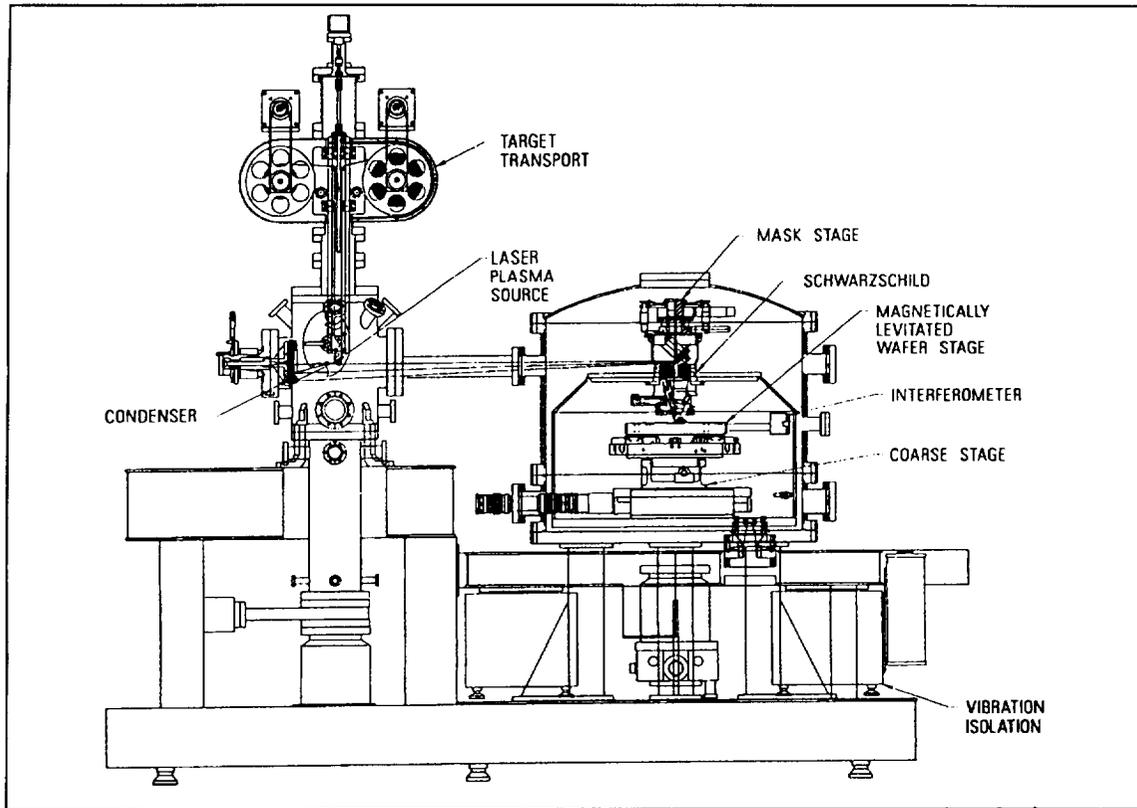

Figure 1. Drawing of EUV Lithography tool

The EUVL Wafer Positioning System

Operational Requirements

The wafer positioning system for the EUVL system represents the first use of maglev technology for fabrication of integrated circuits. The system must provide a highly stable and accurate platform for the successful imaging of 0.1 micron features. The following attributes are necessary for achieving this goal.

Overall positioning range: The EUVL system requires a limited positioning range. It will be used for creation of small footprint devices and does not need to cover the full range indicated by the size of silicon wafers. The coarse stage travel is limited to ± 37 mm in the Y axis and ± 50 mm in the X axis, X and Y being horizontal axes, in the plane of the wafer. The coarse stage is controlled to position the center of the fine stage to within 2 μm of the final position.

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Fine stage range: The fine stage, as designed, is accurate over a ±150 μm range in both X and Y axes.

Stability: The positioning system must be capable of holding a target wafer sufficiently still to allow creation of a 100nm feature with no appreciable smearing. For this implementation, X/Y positioning noise of up to 10nm p-p (at a high probability) of X/Y image motion was deemed acceptable.

Absolute position: Errors of less than 10nm @ 3 sigma for 1 cm travel.

Interface: The stage control system must be able to communicate with the EUVL executive computer system. It also must provide the interface to the grazing incidence focus system and indirect alignment system.

Operating environment: The stage assembly and position measuring laser interferometers must reside in a vacuum chamber. All mechanical and electrical components of these assemblies must be compatible with vacuum operation.

Focus: The system must provide a Z axis resolution comparable to that of the X and Y axes in order to accurately return a wafer to within ½ wavelength of a position previously established. This requirement necessitates a dual focus methodology that includes a "coarse" focus system for repositioning a wafer and an interferometry - controlled "fine" position system to maintain the position accuracy and stability required.

Positioning bandwidth: The initial requirements for positioning bandwidth (a measure of the positioner's repositioning speed used to indicate wafer throughput capability) are liberal due to the research nature of the tool. A 30 Hz bandwidth was considered acceptable.

System Configuration

The wafer positioning system for the EUVL research tool consists of the maglev stage, two long travel coarse position stages, an electronics rack and a high resolution interferometry
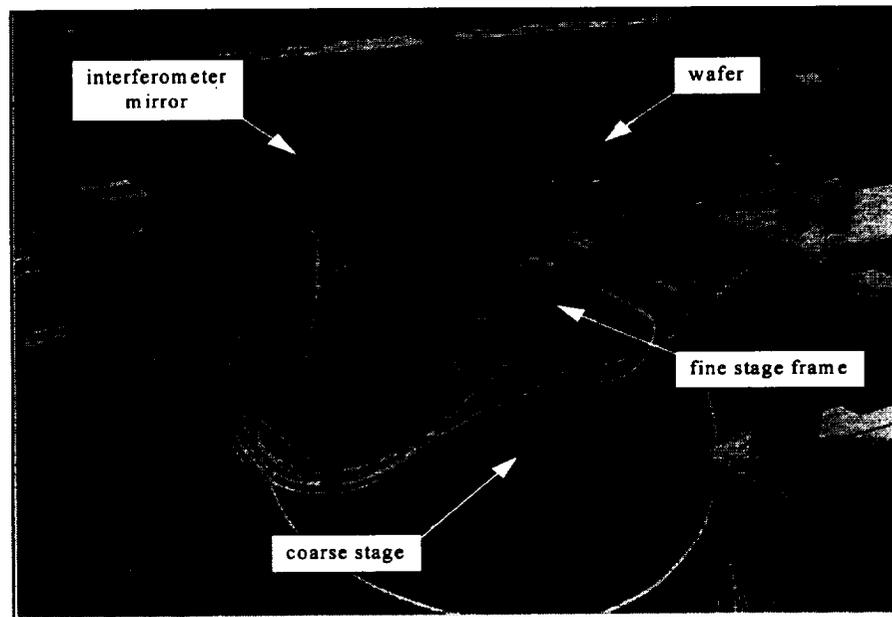

Figure 2: EUVL Stage Assembly

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system. The photograph of Figure 2 shows the stage assembly on a test table prior to installation into the EUVL tool.

Maglev Fine Stage

The design of the maglev fine stage for the EUVL system is essentially unchanged from that originally developed by GCA and MIT. This design was described in a paper presented at the Second International Symposium on Magnetic Suspension Technology in August, 1993[2]. Figure 3 is a photo of the stage. Since 1993, extensive refinements have been applied to the electronics and software used to operate and control the system and to provide interfaces required by the EUVL system.

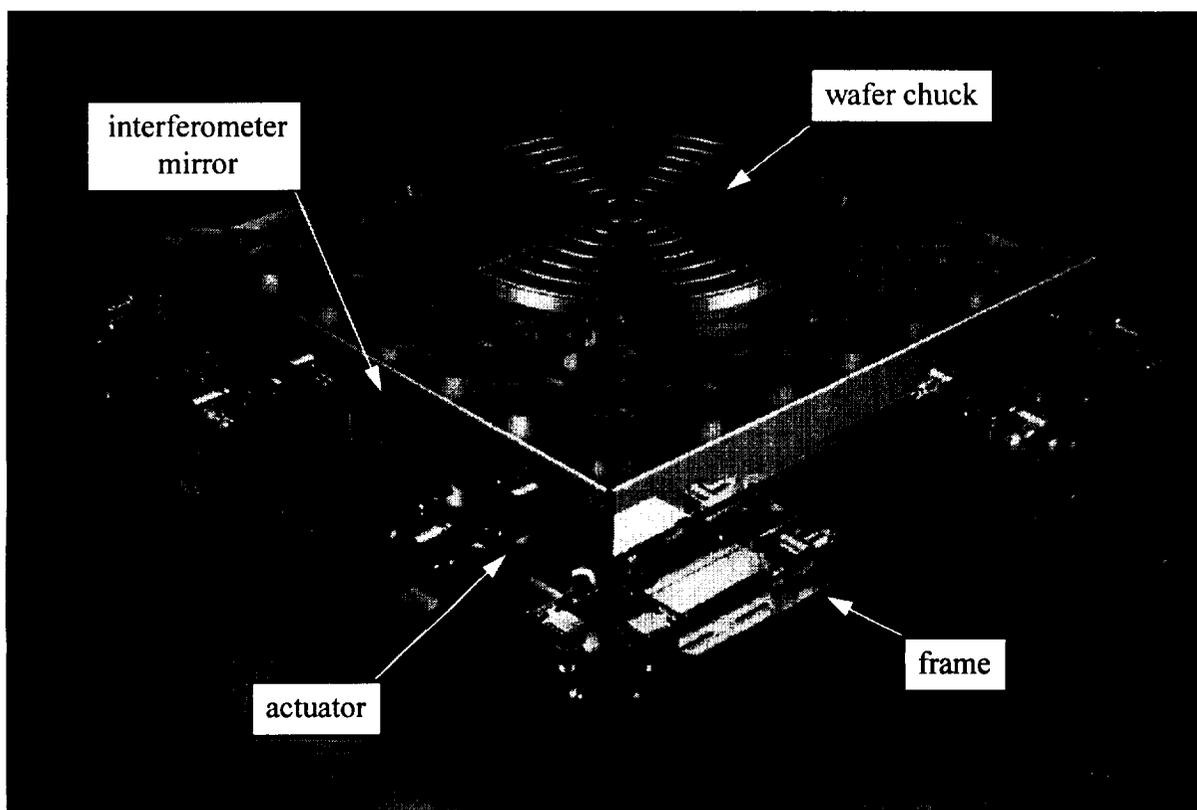Figure 3: Maglev Fine Stage

Coarse Stages

Two Anorad lead screw stages mounted perpendicular to each other are used to provide positioning over the full range of motion. These stages are controlled independently of the fine stage. They include linear encoders for position detection and incorporate rotary encoders in the drive motors for motion stability. These stages have a stated resolution of 0.1μm.

Interferometry

A Hewlett Packard Laser interferometry system consisting of five interferometers, two laser sources, beam benders, optical receivers, and high resolution laser axis boards provide position information in all six degrees of freedom. The interferometry can resolve to 0.625nm in X and Y and 1.25 nm in Z. The Z axis requires that a wafer be in place to provide a reflecting surface for the light beam.

Capacitive "Gap" Sensing

The maglev fine stage utilizes six capacitive sensors for determination of the "gap" between the movable platen and stationary frame. This information is used to linearize the maglev actuator force characteristics for control purposes. The fine stage can be controlled and positioned using only these sensors for feedback, but with less accuracy than that obtainable with

Figure 4: System Block Diagram

the interferometers. Capacitive sensors are used for Z axis measurement and control in the absence of a wafer.

<u>Electronics</u>

Two computers are used in the implementation of the EUVL wafer positioning system. An embedded VME-based 486 PC provides the user interface. The electronics include six TMS320C40 DSPs for data acquisition, manipulation, and control. Figure 4 is a diagram showing the major system elements.

Host computer: The host computer is an embedded PC subsystem that mounts in the VMEbus chassis. It provides a critical interface between the operator and the positioning system. Two methods are available for human interface. A user can access the system using a monitor and keyboard for complete control. This also provides the interface required for development and modification of the system operating characteristics. The second method of interface is via a TCP/IP network served by the executive computer of the EUVL system. This is the interface that is used during normal operation.

DSP computer: The digital signal processing computer consisting of four TMS320C40 DSPs located on a Hydra™ computer board (by Ariel Corp.) and two additional TMS320C40 DSPs on two Ariel CommIO™ interface boards provide the necessary processing power for the positioning system. This is the stage control computer for the system.. Analog-to-digital I/O is used to gather gap information from the capacitive sensors as well as other EUVL system data. Sixteen channels of digital-to-analog I/O control the current amplifiers which drive the electromagnetic actuators.

Custom interface: Custom electronics is provided for interfacing the components of the coarse and fine stage to the computer electronics. The chassis includes power supplies, enabling relay circuitry, I/O analog filtering, and interface matching circuitry.

Coarse stage control: The two coarse stages are controlled using a dedicated control computer (Galil DMC1320). This computer is programmed for optimum stage performance and receives commands from the host computer when it is necessary to travel beyond the range of the maglev fine stage.

Actuator amplifiers: Custom current amplifiers are used to supply drive current to the sixteen electromagnetic actuators. They are 1 amp limited, but capable of up to 100 volts output. This provides the inductive magnetic actuator with a fast force response thereby allowing high bandwidth positioning.

Control System Design

Figure 5 is a block diagram of the stage control system. A complete simulation of the system was constructed using the Matlab Simulink® environment. Included in the simulation are the dynamics of the levitated platen, the nonlinearities associated with the actuators, the voltage limitations associated with the transimpedance amplifiers, quantization errors, computational delays associated with the control computer, and changes in the interferometer measurement equations due to displacement of the platen. A simplified model of the coarse stage is also

included. Small motions are assumed, allowing the dynamics and the transformations between the positions and the measurements to be approximated as linear.
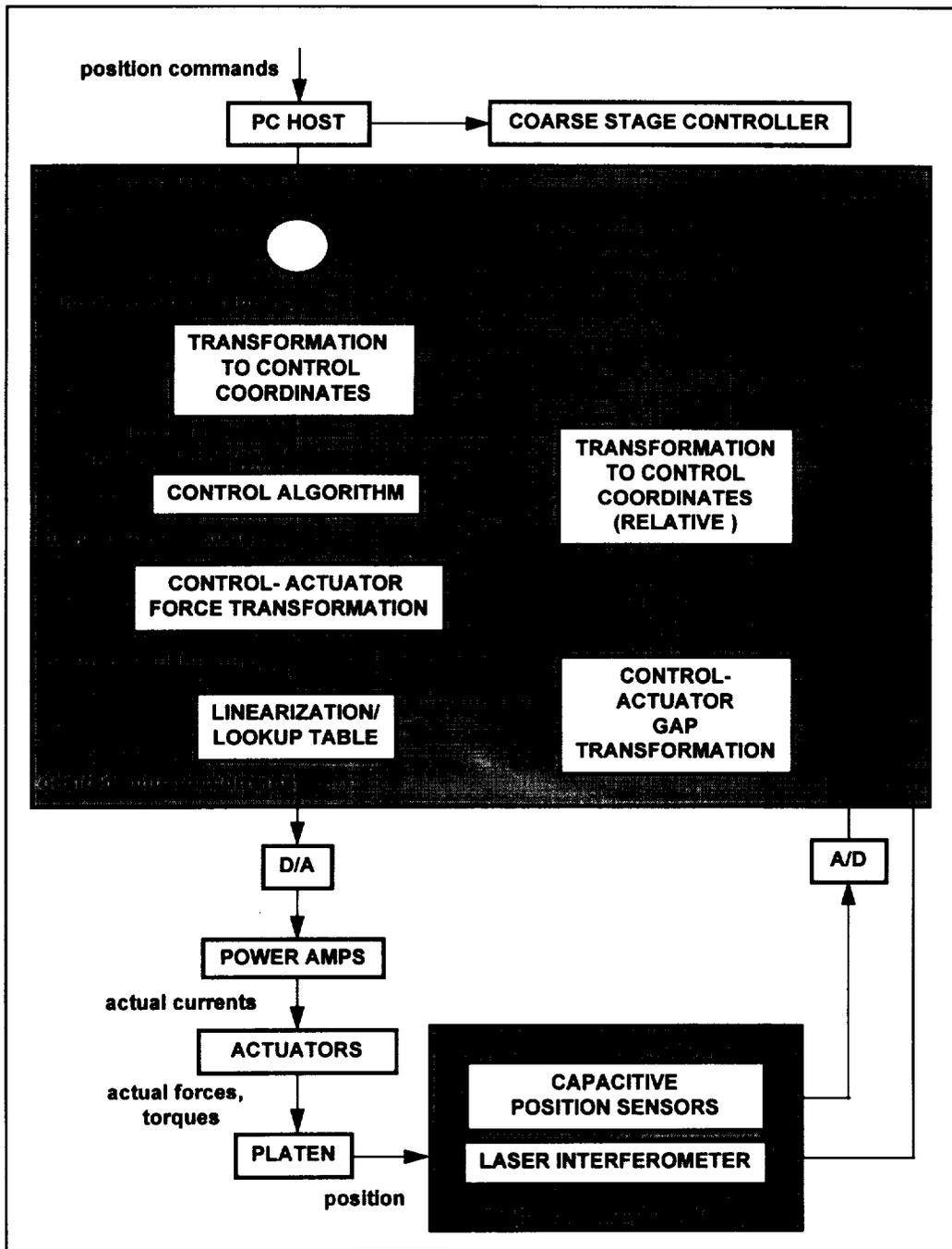

Figure 5 : Stage Control System Block Diagram

To allow the use of SISO linear controller design techniques, the system is considered to consist of six independent subsystems, each corresponding to one of the six

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degrees of freedom $(x, y, z, \theta_x, \theta_y, \theta_z)$. In the control computer, the measurements are transformed to give the positions of, and rotations about, the center of mass. These are the quantities that the controller regulates. The outputs of the controller are six resultant forces and torques to be applied to the levitated platen. The control computer then calculates a set of forces that, when applied at the 16 actuators, will produce the desired forces and torques. Since the outputs of the control computer, in conjunction with the transimpedance amplifiers, produce the currents flowing in the actuators, the desired actuator forces must be transformed into representative actuator currents. For small forces, the following equation is a good fit.

$$i = \sqrt{f(a_0 + a_1 g + a_2 g^2)}$$

f is the desired force from a given actuator, g is the gap between the actuator and its associated target, the a_i are constants determined empirically, and i is the current. If the desired forces are large, the actuator will be driven nearer to saturation, and a lookup table is used to compute the needed current given the actuator gap and the desired force.

By using the ideas outlined above, the controller sees six linear, decoupled systems, and any controller design technique can be used. For each of the six axes, we are using a PID (Proportional-Integral-Derivative) controller with an additional high-frequency pole. Because of the compliance of the mechanical structure supporting the interferometers and their reference mirrors, the closed-loop bandwidth was limited to 30Hz to prevent unacceptable excitation of structural noise. The final controller implemented also has notch filters for eight different resonances excited by the control loop.

We verified the behavior of the combined plant and compensator by comparing the response of the system with the simulation. Agreement was excellent.

Software Design

Software Requirements

As might be expected with a research system, the stage control system software requirements are very broad. The throughput of the system must be sufficiently high in order to limit system phase delays. The user interface must be flexible enough to allow easy system development, user control, and system diagnostics. And finally, an interface to the EUVL executive computer is required to give a remote user limited system control and information feedback.

The stage control system software is made up of C and assembly language code written and compiled for use on 486 PC and TMS320C40 DSP processors. Additionally, a text based language is used for programming the Galil motion control board used for controlling the coarse stages. Vendor-supplied board-specific routines are used where possible. Each DSP of the Hydra board executes a distinct program allowing individual processor task tailoring. Controller

timing, controller synchronization, host communications, and system state are controlled by one of the four DSPs on Hydra in a master/slave relationship.

Host Computer Software

The Host PC software is responsible for several aspects of system operation. It handles system startup and initialization sequences, user interface functions, EUVL executive computer communications, coarse stage controller interface, and coordinates system data collection and analysis.

If a coarse move is required a simple command to the Galil motion controller is made by the Host PC. After the coarse stage move is complete, the maglev fine stage makes the required position error corrections.

All data collection and system diagnostics are coordinated by the Host PC. The user, through the user interface, can configure the DSPs on Hydra to capture "snapshots" of real time data of interest. The "snapshot" is triggered by a system command or user input allowing flexible performance monitoring and system diagnostics. The "snapshot" data can then be transferred to the Host PC and written to disk. The user interface screen contains important controller and system data which are updated automatically every second.

DSP Computer Software

The DSP software is primarily responsible for executing the fine stage controller tasks. These tasks include gathering position sensor data, executing controller algorithms, and outputting to actuators. Other responsibilities of the DSP software are to initialize hardware under its control at startup, handle error situations, and deliver data to the Host PC when commanded.

During system startup, the DSP software handles initialization of the fine stage controller subsystems. These subsystems include the CommIOs and their A/D and D/A modules, the laser interferometer cards, and the multifunction card which controls the custom interface chassis.

After the system has been initialized, the DSP software begins executing the control loop. The controller sequence is simplified by breaking it into seven sequential tasks:
1. Gather sensor data (capacitive pickoffs and laser interferometers).
2. Calculate stage relative position and actuator gaps.
3. Calculate stage absolute position and form modal errors.
4. Execute controller difference equations to determine required modal force outputs.
5. Resolve modal forces into actuator forces.
6. Linearize actuator output based on present actuator gap and required output force (either linearization algorithm or lookup table).
7. Output actuator voltage (apply forces).

The capacitive pickoff sensor data are collected by sampling six A/Ds on CommIO boards. The laser interferometer data are collected by triggering and then reading position registers in the laser axis boards via the VME bus.

As part of the process for determining the desired force at a given actuator, linearization is performed. When the desired actuator current data are available, they are written out the sixteen D/As on the CommIO which controls the actuators.

The controller tasks are distributed among the four DSPs on the Hydra card to maximize system throughput. Much of the previously described sequence occurs in parallel.

The control loop timing is generated by an internal timer of the master DSP. The timer generates an interrupt to the master DSP at a programmable rate. When the master DSP services the interrupt, it transmits commands over the communication ports to the other DSPs on Hydra signaling the beginning of a cycle thus synchronizing the four processors. All controller data are passed between processors via the C40 communication ports which give complete interconnectivity between the four processors.

The control loop has three states in which it can execute: the X-Y-Z capacitive pickoff feedback state, the X-Y laser, Z capacitive pickoff feedback state, and the X-Y-Z laser feedback state. The three possible system states determine which instruments are being used to measure the position of the stage. During the control cycle, several sensor status checks are made. Any sensor errors cause system state changes which prevent hardware damage.

Performance Testing Results

The original performance requirement for image stability was, as given earlier in this paper, 10nm peak-to-peak with high probability. Figure 6 shows a plot of the laser interferometer data for the x-axis. As can be seen, this has a peak-to-peak displacement of less than 10nm. The corresponding Y axis data had less than 9nm peak-to-peak displacement. From the figure, it can be seen that a large component of the displacement is low frequency (about 5Hz). The clean room is located on an isolated slab that has a mode near 5Hz, and the isolated table that holds this system has a mode at 5Hz. The commercial isolated table we are using has active vibration damping that should provide better suppression of this 5Hz mode when the equipment is working properly, which we anticipate in the near future. This could reduce the peak-to-peak displacements by several nm.

The data shown in Figure 6 are typical for times when there is no activity in the clean room. The standard deviation of the distance of the image from the desired location on the wafer surface is less than 2.5nm ($\sigma < 2.5$nm). During exposures, when there is generally more activity in the clean room and more equipment running, 3nm $< \sigma <$ 4nm. The EUVL project team was able to demonstrate 0.1 micron lithographic-quality features with operational positioning stability of $\sigma \approx 4$ nm.
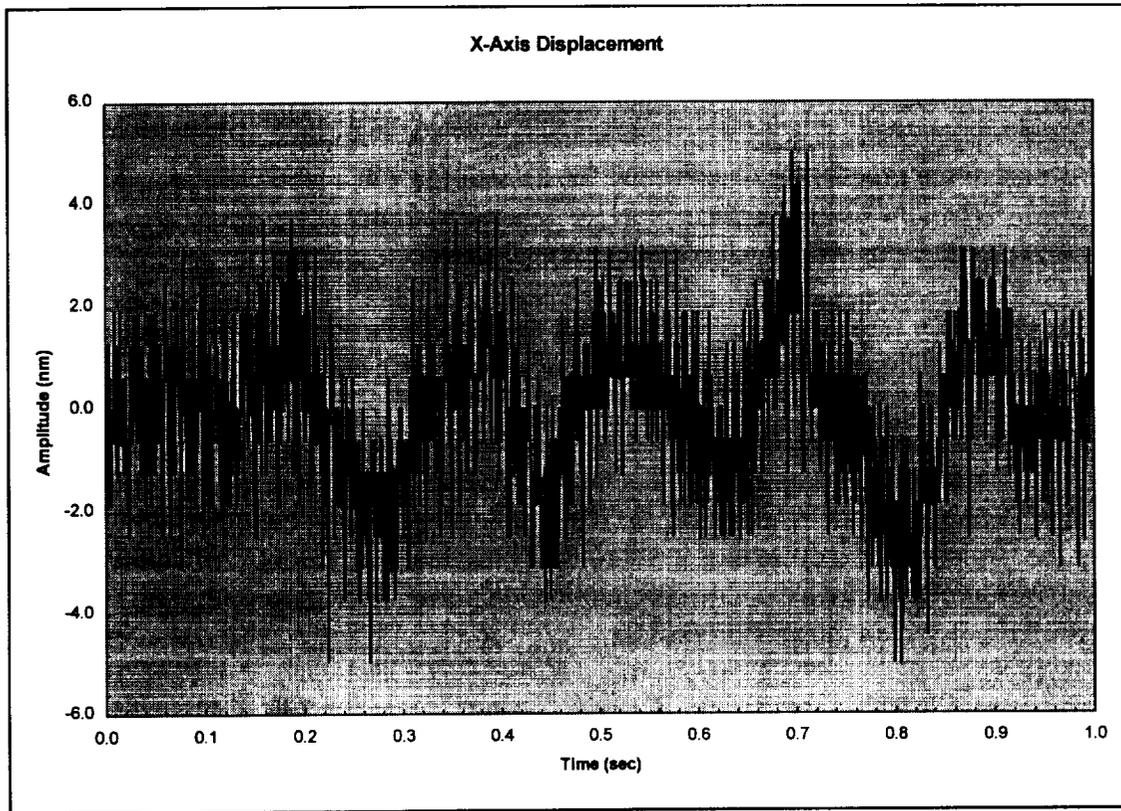
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Figure 6: Laser interferometer data

We have not yet determined the overall system accuracy. The next set of experiments on the EUVL project will entail overlaying one exposure on top of another. The absolute positioning accuracy will be very important for these experiments.

Future Enhancements

System enhancements that are being implemented on a follow-on project include optimization of the electronics for faster data input and output, greater compression of the software by redistribution of tasks and additional use of assembly language, and coordination of target moves between the coarse and fine stages for enhanced response. Progress to date includes the implementation of optimized IIR filter routines written in assembly code which has greatly decreased controller computing time. The IIR filter routines can be used for filtering sensors, filtering controller outputs, and performing controller compensation tasks. Other software enhancements included targeting time consuming system tasks written in C and rewriting them in assembly utilizing the DSP hardware circular buffering, zero overhead looping, and single-cycle parallel instructions where possible. The final area of software improvements is improved task distribution among processors which creates more communication overhead and system complication but has greatly increased system throughput. At present, the follow-on system throughput is over three times faster than the EUVL system.

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1. Tichenor, G. D. Kubiak, S. J. Haney, R. P. Nissen, K. W. Berger, R. W. Arling, A. K. Ray-Chaudhuri, K. B. Nguyen, R. H. Stulen, J. B. Wronosky, J. D. Jordan, T. G. Smith, J. R. Darnold, P. M. Kahle, A. A. Jojola, S. M. Kohler, R. S. Urenda, D. R. Wheeler, J. E. Bjorkholm, O. R. Wood, II, G. N. Taylor, and R. S. Hutton, "Recent results in the development of an integrated EUVL laboratory tool," **Proc. of the SPIE Symp. on Electron-Beam, X-Ray, and Ion-Beam Submicrometer Lithographies for Manufacturing V**, vol. 2437, 292 (1995).

2. R. W. Arling, S. M. Kohler: "Six Degree of Freedom Fine Motion Positioning Stage Based on Magnetic Levitation", Second Annual Symposium on Magnetic Suspension Technology, Seattle, WA., August 11-13, 1993.