1.0   4.5   2.8   2.5

     50   3.2   2.2

     56   3.6   2.0

1.1   6.3   4.0

            1.8

1.25   1.4   1.6

1 of 1

Six Degree of Freedom Fine Motion Positioning Stage Based on Magnetic Levitation*

R. W. Arling
Independent Consultant
Windham, NH

S. M. Kohler
Sandia National Laboratories
Albuquerque, NM

SUMMARY

The design of a magnetically suspended six degree of freedom positioning system capable of nanometer positioning is presented. The sample holder is controlled in six degrees of freedom (DOF) over 300 micrometers of travel in X, Y and Z directions. A design and control summary, and test results indicating stability and power dissipation are included in the paper. The system is vacuum compatible, uses commercially available materials, and requires minimal assembly and setup.

INTRODUCTION

Efforts in the field of single degree of freedom magnetic suspension date back over one hundred years, while multiple degree of freedom systems date back perhaps thirty years. Recent success of multiple degree of freedom efforts provided the impetus for development of a commercially available design based on techniques proposed in [1-2]. The intent of the design is to provide positioning for silicon wafers used in integrated circuit production.

Positioning systems are employed in a variety of end products. High precision fine range positioning stages are often coupled to a larger motion X-Y stages for increased travel. This combination allows utilization of available dynamic range for extension to the nanometer regime. Conventional fine positioning systems employ piezoelectrics, linear motors, or DC motors coupled either directly or through lead screws or friction drives for actuation. Flexures and/or bearings are employed to constrain the motion to the desired degrees of freedom. Performance of these conventional systems is compromised by the requirement of providing six independent degrees of positioning with stacked, reduced degree of freedom systems. The positioning problem becomes difficult due to undesirable couplings between "independent" axes. In addition, the systems suffer performance degradation from friction, backlash, etc. Vacuum compatibility further reduces available options or, at the very least, greatly increases complexity.

Magnetic levitation is an attractive alternative to the conventional positioning systems outlined above. Friction and particle generation are eliminated, and vacuum operation is possible. The nonlinear nature and computational requirements of magnetic positioning have, however, impeded the development of the technology. The advent of high speed processing now allows real time linearization at speeds commensurate with the controller bandwidth requirements. The limitations of stacked stage design are overcome by use of a single body acted on magnetically to provide motion in X, Y, and Z linear axes, as well as rotations about these axes. This system has been constructed, controlled, and tested and represents the subject of this paper.

FUNCTIONAL OVERVIEW

Electromagnetic actuators housed in a fixed frame are employed to provide stabilizing and actuating forces to a 10 kg. sample holder. The unipolar force capability of the actuators requires their arrangement in pairs to provide a quasi push-pull effect. The sample holder is counterbalanced against gravity with permanent magnets to reduce the power expenditure in the electromagnetic actuators. Local position feedback of the suspended sample holder is provided by commercial capacitive based sensors. Absolute position feedback is established with a laser interferometer system. Actuation signals are generated in a DSP based CPU and are based on six modal controllers whose position information is derived from either transformed capacitive sensors or laser interferometer measurements. Real time linearization is provided though application of analytical relationships and empirically determined lookup tables.

The magnetic gaps are adjusted with movable actuators to provide a nominal spacing of 300 microns, with total travel of +/- 150 microns from nominal. Permanent (counterbalancing) magnet gaps are adjustable to provide correct force balance of the sample holder.

SYSTEM DESCRIPTION

Mechanical Assembly

The primary mechanical components are illustrated in Figure 1.

Stage Frame. The stage frame is fixed in position relative to the motion of the sample. It supports 16 electromagnetic actuators arranged in 8 pairs located symmetrically about its periphery. Due to the unipolar force characteristics of the electromagnetic actuators, the pairings effect a quasi push-pull effect. Four pairs provide vertical force, and four pairs provide lateral force. The frame also supports the active portion of capacitive based position sensors for measuring magnetic gaps.

Stage Platen (Mirror Support Structure). The stage platen, in conjunction with the interferometer mirror and sample holding apparatus, is acted upon as a single body by the actuators located in the frame. The stage platen contains iron targets for completion of the actuator magnetic circuit, as well as one half a

kinematically designed mount for interferometer mirror attachment. The stage platen also houses targets for the capacitive based position sensors.
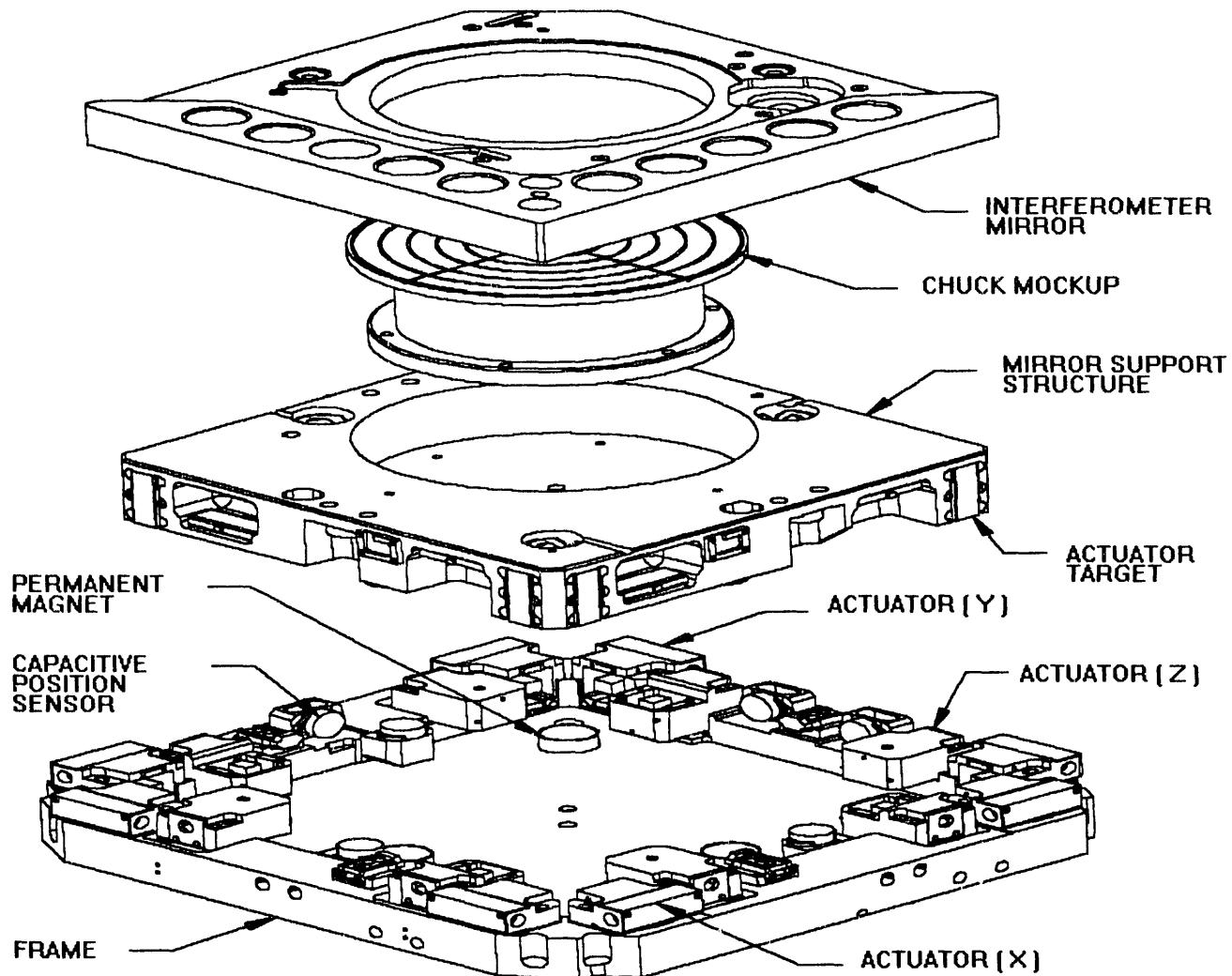

Figure 1. Stage mechanical components.

Interferometer Mirror. The interferometer mirror provides reflective surfaces for a laser interferometer system. In addition, it provides capability for secure attachment of a sample holder to minimize motion to the interferometer measurement points.

Magnetic Actuators. Actuators are individual modules of three types; lateral, vertical (upward), and vertical (downward). All actuators are nominally identical in electrical and force characteristics. The actuator mounts are adjustable to provide null position gap settings.

Chuck Assembly. A solid pedestal and chucking mechanism provides attachment of a sample (silicon wafer).

Permanent Magnets. Three pairs of permanent magnets provide a gravity counterbalance for the suspended stage Platen/Mirror assembly. The magnets in the platen and frame are oriented with poles appropriate to provide force to offset the Platen/Mirror weight. This counterbalancing force is necessary to minimize the power expended in the electromagnetic actuators. The mounting system allows adjustment of permanent magnet gaps to balance the Platen/Mirror. The gap adjustment provides a slight downward bias of the suspended assembly to guarantee a stable resting position.

Electrical Components

The electrical system is composed of the following subsystems; digital chassis, power amplifier chassis, power supplies, and user interface.

Digital Chassis. The digital chassis contains the following VME based circuit cards; 32 bit floating point Digital Signal Processing (DSP) microprocessor card, a 32 channel 16 bit analog to digital conversion card, 14 bit digital to analog conversion cards, laser interferometer interface cards, and VME to user interface card.

Power Amplifier Chassis / Power Supplies. The power amplifier chassis contains 16 amplifier cards to provide current to each of the actuators. Linear transconductance amplifiers with scale factors of 100 mA / V are employed. Amplifier bandwidth ranges between 15 kHz and 20 kHz depending on actuator inductance, which varies with magnetic gap. The worst case bandwidth contributes less than two degrees of phase loss at 100 Hz. Linear power supplies provide current at +/- 40 volts to the actuator amplifiers.

User Interface. The user interface is a PC that serves as a development system for the software and provides control inputs, data collection, and display of relevant system information.

Position Sensing

Capacitive Position Sensors. Commercially available capacitive based position sensors measure the position of the stage platen relative to the stage frame (i.e., magnetic gaps). Six sensors are located in the frame, with corresponding targets located in the stage platen. Three sensors measure laterally (X, Y, Θ_z), and three measure vertically (Z, Θ_x, Θ_y).

Laser Interferometer. A laser interferometer measures absolute position of the laser interferometer mirror with respect to the machine frame. Recall that the fine stage is, for practical uses, coupled to a coarse positioning stage for larger travel capabilities. The actual coordination of the various position measuring systems is discussed later in the paper. The laser interferometer system provides measurement of X, Y, Θ_z, Θ_x, and Θ_z. The stated resolution of the system is $\lambda/128$ (λ = 633 nm for HeNe laser), or approximately 5 nm linear.


Laminated "E" Core

Coil Winding

Laminated "I" Core Target
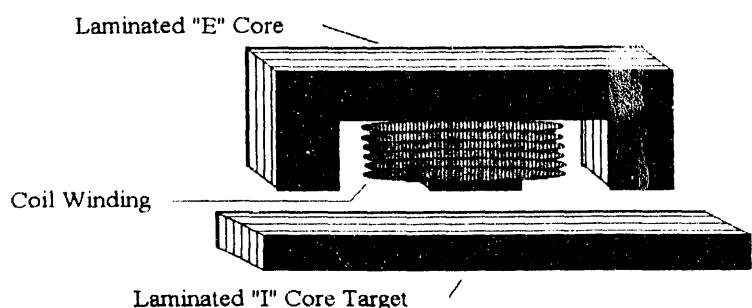
Figure 2. Schematic actuator / target representation.

The actuators employed in this system are represented schematically in Figure 2. Material, geometry, and electrical coils are designed to maximize frequency response and force, and minimize packaging volume and power dissipation.

The actuator core and target are constructed of commercially available 0.15 mm laminations of Superperm 49. The laminations are stacked to a thickness of approximately 12 mm and clamped in the actuator housings. A free standing coil of 550 turns of #26 copper wire is fitted over the center section of the lamination "E" and the entire assembly is potted in epoxy. The face of the actuator is ground to provide a uniform surface. A similar construction process is used in the construction of the targets. The target assemblies are potted into the stage platen, and the sides are ground flat. When current is passed through the electrical coil in the "E" structure. a force that seeks to reduce the distance between "E" and "I" is developed. The force produced is a highly nonlinear function of both gap and applied current. Linearization of the force - gap - current relationship is required for implementation of effective control technique. A specialized test fixture is employed for the actuator characterization [3]. Information is obtained by incrementing and recording the gap throughout the expected range of travel. At each gap setting, the current is discretely increased and, for each point, a force value is recorded. The data obtained is represented as a curve of force versus current. parametric on gap. This information is translated into a three dimensional look-up table for use by the controller. Figure 3 is a representative curve of the uncompensated actuator characteristics.

The lookup table is employed for large force commands. For small force commands, as for stabilization about an operating point, the force relationship is approximated as [2];
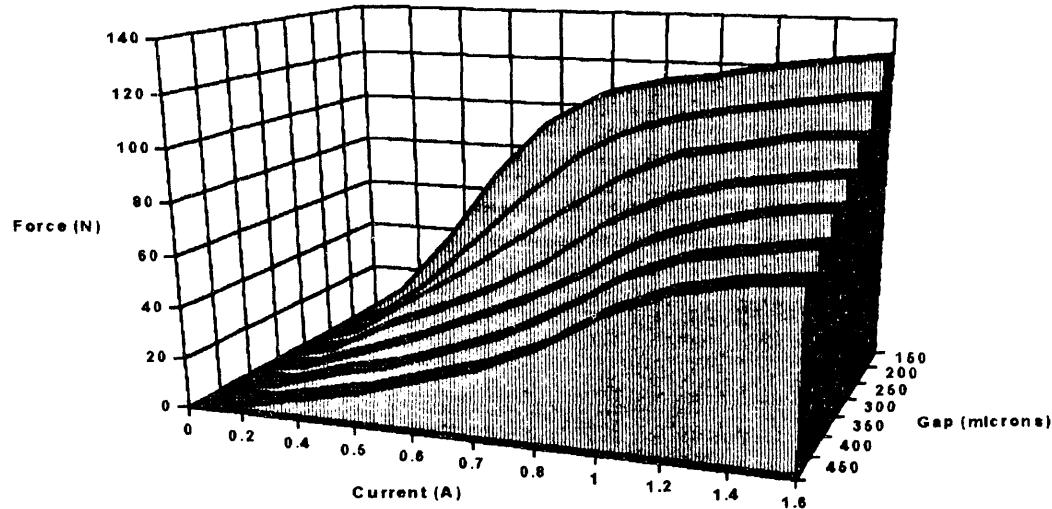

Figure 3. Uncompensated actuator force curve.

$$F \propto (i \ / \ g)^2 , \tag{1}$$

where f is desired force, g is measured gap, and i is required current.

STRUCTURAL CONSIDERATIONS

High controller bandwidth is a requirement of the positioning system described in this paper. To achieve high bandwidths, effort is made to design for high stiffness in the mechanical parts and couplings. The goal of this initial design is to utilize common, machinable materials in the construction. Given this constraint, geometric optimization of the parts is undertaken as a means of providing stiffness. Finite element analysis is employed prior to design of the parts, with verification of the predictions provided by modal testing. Knowledge of the modal frequencies proved invaluable in controller efforts as well as system troubleshooting. Most of the optimization involves the interferometer mirror, as the effects of distortions in this component are readily apparent as positioning error. Material for the mirror is Zerodur; selected for its suitability for extreme temperature stability in mirror surface fabrication. Stage platen, frame, and actuator housings are nickel plated aluminum.

The stage platen to interferometer mirror mounting receives attention due to the dissimilar coefficients of thermal expansion between the two materials. A kinematic mount of three hemispherical steel balls and V-grooves is employed in the coupling. A magnetic preload increases the loading between the ball and groove. A vertical adjustment scheme is incorporated into the mount to provide for interferometer mirror leveling with respect to measurement laser beams.

CONTROL SYSTEM

Digital control of the system is desirable due to the geometrical transforms required between sensors and actuators and the linearization of 16 independent actuators. The overall control strategy is outlined in Figure 4.

The electromagnetic actuators, as previously mentioned, are located in the fixed frame and act upon iron targets imbedded in the (suspended) Mirror / Platen assembly. The sensors, both capacitive and interferometer based, measure points of the suspended body different from the actuation points. It is therefore required to transform the measurement and actuation points to modal coordinates for controller operation. These operations require knowledge of geometry and center of gravity of the suspended mass, which are readily available from the CAD models. Command positions and controller design are based on six modal controllers operating simultaneously in the DSP. The interferometer provides position feedback for all modal controllers with the exception of Z. Capacitive sensors provide magnetic gap information for lookup table reference, as well as position feedback for Z motion.
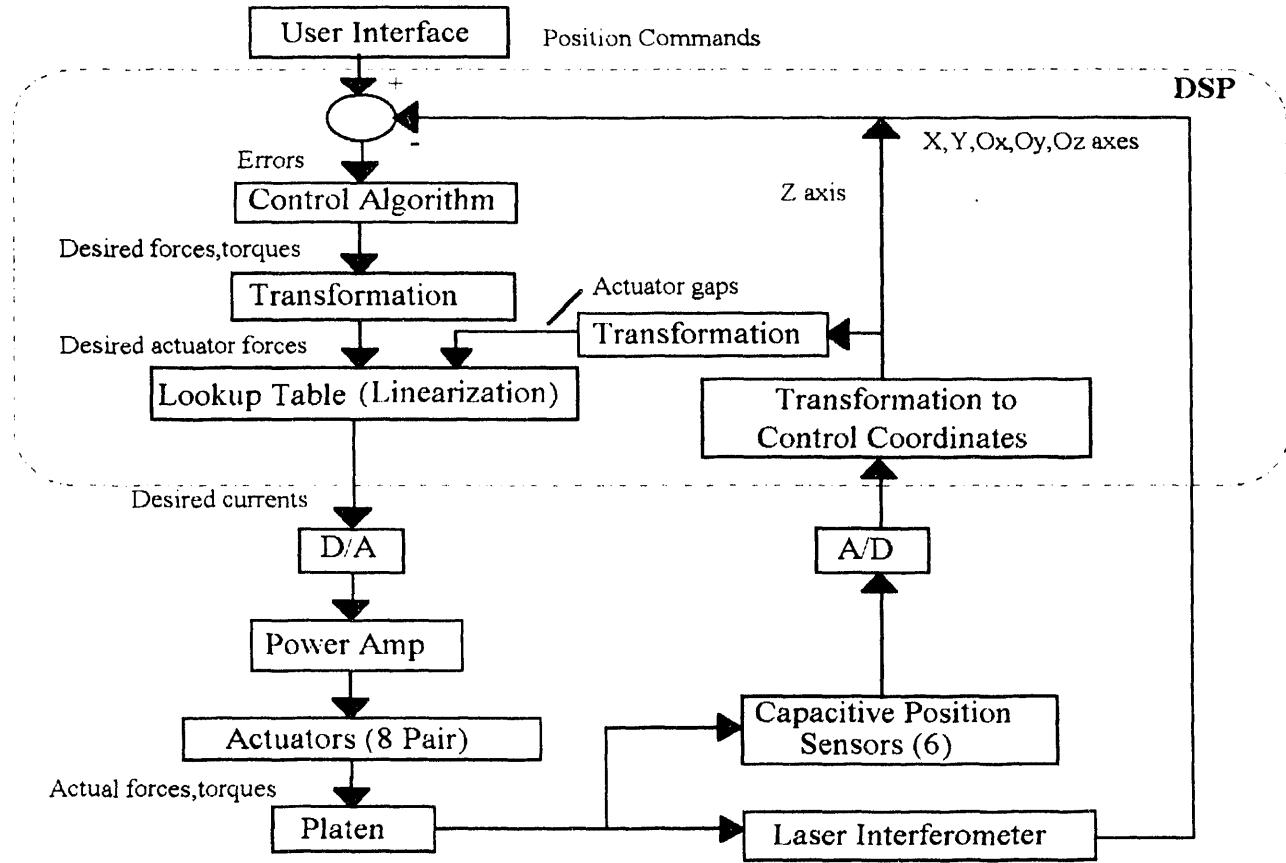
Figure 4. Control approach.

A PID (Proportional - Integral - Derivative) control algorithm is employed for each of the six modal controllers. Gains are selected to provide a critically damped, 30 Hz. gain crossover system in each axis at the 2500 Hz sampling rate. The 30 Hz. gain crossover is selected to avoid excitation of known structural resonances. A higher order controller would address structural issues, but processor limitations precluded implementation. A digital notch filter is employed to filter a predicted structural resonance set up by the kinematic mount between stage platen and interferometer mirror, but extension of this technique to all structural resonances is limited again by processor capabilities. Effort is in progress to address the bandwidth limitations imposed by structural resonance through mechanical and electrical filtering means, and additional computational capability. Part of the difficulty encountered in designing a controller for a fully suspended system is the inability to observe system behavior until levitation is achieved. Numerical simulation is relied on heavily to carry out controller development.

Positioning Stability

Stability Detractors

Positioning stability of the system is dependent on a number of factors. Floor vibration, varying laser interferometer environment, and sensor noise all contribute negatively to the system's intrinsic stability potential. With this in mind, brief descriptions of the Test Setup and stability detractors external to the stage system are included below.

Test Setup. The entire fine stage system is mounted to a coarse X-Y stage system which, in turn, is mounted to a 1m x 1m x 0.5m (l,w,h) cast iron base. Also attached to the base is a bridge of similar dimension mounted above the stage structure to support the laser interferometer optics. The entire structure is encased in a Plexiglas shell (not shown). The structure is mounted on 4 vertical posts resting on a concrete floor. Elastomer isolation pads approximately one inch thick are located between the structure and top of the posts. The Setup is shown in Figure 5.

Floor Vibration. The concrete floor supporting the test setup also supports various pumps and other rotating machinery used in building HVAC. Measurement of environmental vibration levels in the cast iron base indicates substantial 28 to 31 Hz. energy in the Z direction [Table 1]. This frequency range is of particular concern due to the 30 Hz. gain crossover frequency. Vibration below this frequency is tracked out by the control system, while those significantly above this frequency are attenuated by the isolation, structure, and controller. The large Z motions can be attributed to a rigid body resonant frequency of 30 Hz. determined by supported mass and isolation stiffness. The discrepancy in X and Y versus Z is due to non-uniform isolator stiffness in these directions.

Laser Interferometer Environmental Stability. The stability of a laser interferometer is, in part, affected by changes in the beam wavelength due to variations in the density of the medium through which the beam passes. Density (of air in this case) is a function of temperature, relative humidity, and barometric pre ,sure. The laser wavelength in air will change 1 part per million (PPM) for; a 1° C change in temperature, a 2.5 mm of Hg change in pressure, or a 30% change in relative humidity. Of these three, the air temperature is the least controlled. The Plexiglas shield encasing the test setup provides some stability, and the short term variations are expected to be minimal. Since the system stability test data relies on the interferometer, no extension is made beyond the Test Setup's reference frame.

Capacitive Sensor Noise. Capacitive based sensors measure magnetic gaps for look up table reference and provide the sole source of position feedback for Z axis motion. The ability to accurately measure gaps is far less critical to the ultimate positioning as is actual position feedback. Noise has been reduced to 50 nm p-p on the capacitive sensors and cables, but still represents an obvious limitation to performance.
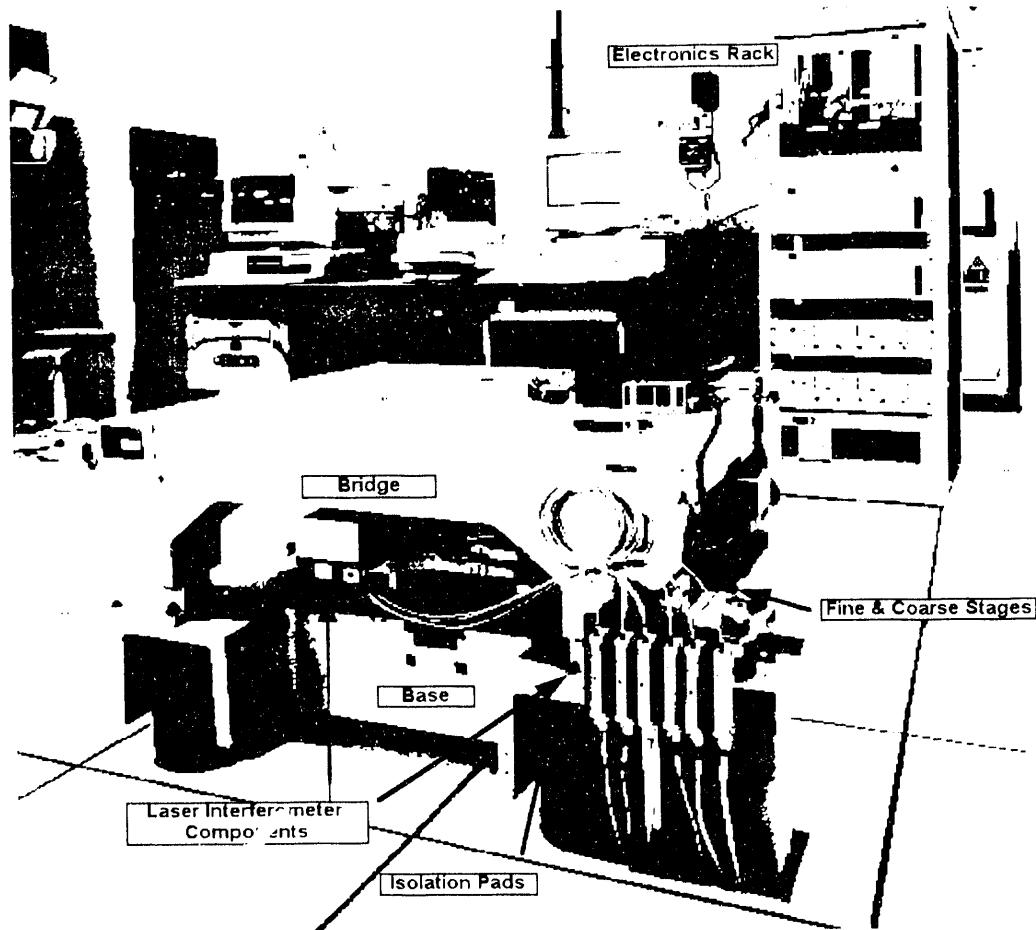
Figure 5. System Test Setup.

Stability Results

Measured stability of the system is indicated in Table 1. The large discrepancy in stability between axes is attributable to both lack of vibration isolation and sensor/cable noise in the Z axis.

Table 1. Floor Induced Motion and Positioning Stability

Axis	Input Motion @ Base (nm p-p)		Stability (nm p-p)
	Wide Band	28-31 Hz	Stability (nm p-p)
X	308	22	20
Y	482	44	25
Z	390	348	100

The system responds to inputs as expected for a 30 Hz. system. Figures 6 and 7 indicate the results from a test to command position changes in (X, Y, Z), and (Θ_x, Θ_y, and Θ_z) simultaneously. Discrepancies in the responses for a given group are predicted by simulation and result from differences in the degree of saturation among the various actuators. A large, multi-axis move produces large variations in actuator force demands. Actuators that are heavily saturated exhibit inductive lags in output relative to lightly loaded actuators. The momentary force imbalances appear as crosstalk of linear responses and angular responses.

microns

Time (seconds)
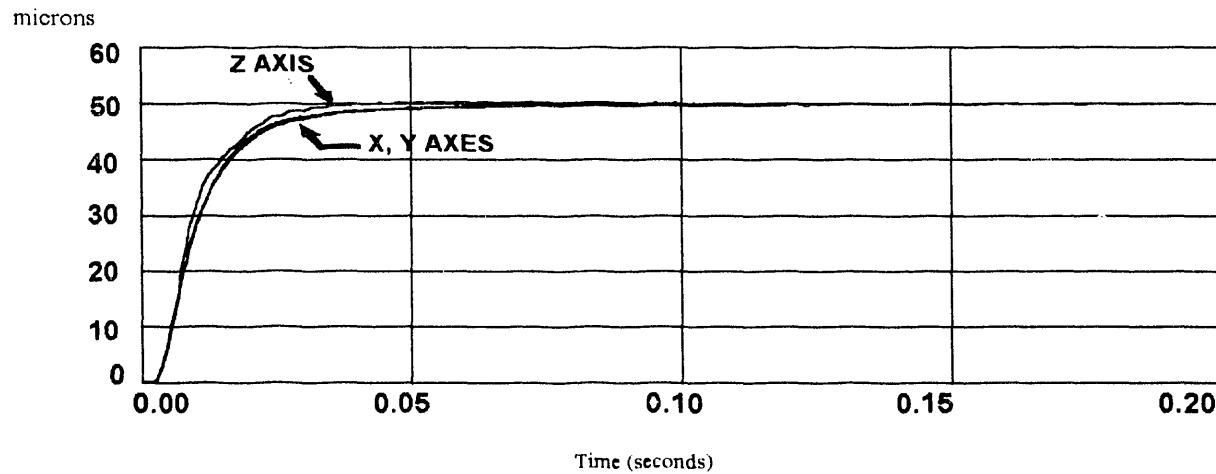
Figure 6. Linear step response.

micro radians

Time (seconds)
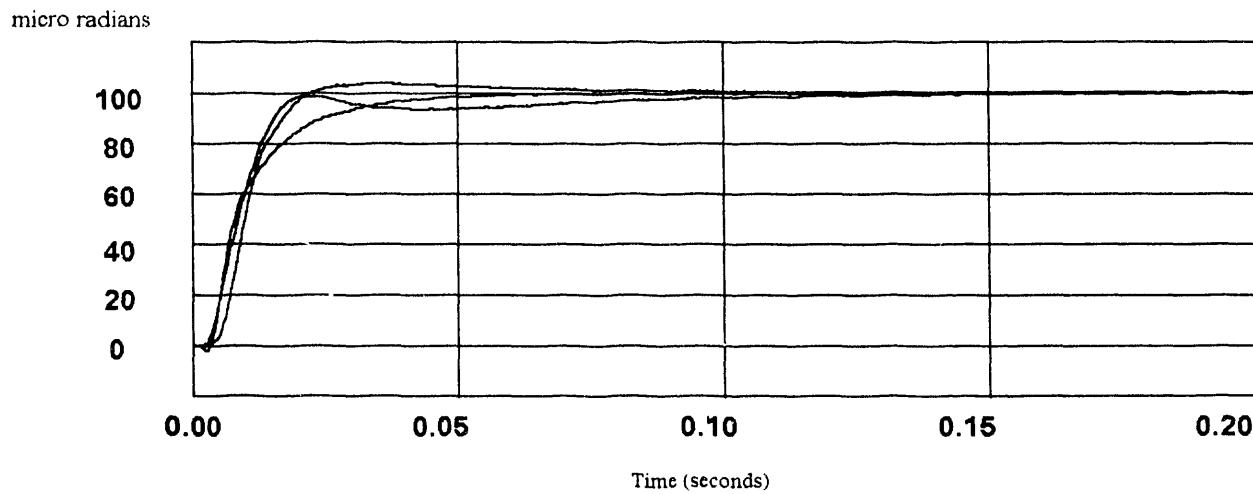
Figure 7. Angular step response.

Power Dissipation

Power dissipation for the positioning system is broken down into two categories; quiescent and peak. Quiescent dissipation refers to the rms power dissipated in the actuators while maintaining position. This value is dependent on such parameters as the effectiveness of the permanent magnet counterbalance, external disturbances, etc. The peak value indicates the peak power dissipated in the actuators during the simultaneous 50μm linear, 100μrad angular move demonstrated above.

Table 2. Power Dissipation

	Vertical	Lateral	Total
Quiescent			
Peak			

In relation to power dissipation, it should be noted that the actuators are mounted in the stage frame to provide a conductive path for heat transfer. In addition, the suspended Platen/Mirror assembly is effectively isolated thermally due to the air gaps. These features are particularly useful in vacuum applications where cooling is problematic.

CONCLUSIONS

This paper has outlined the successful development of a fully suspended and controlled positioning system based on magnetic levitation. Results have confirmed the acceptability of this technology to a wide variety of positioning applications requiring extreme repeatability and accuracy. The test data, though some of the earliest taken with the system, shows performance to be within the capabilities of associated hardware. Extension of the system's stability to the resolution of the laser interferometer system is achievable with modest design modifications. Development is continuing specifically to improve the vibration isolation of the test setup and address the bandwidth and structural resonance issues.

Improvement in the vibration isolation of the Test Setup is possible with the addition of a commercially available system designed for this purpose. Such systems will have the effect of lowering the Test System rigid body modes to the vicinity of two to three Hertz, providing greater attenuation at frequencies critical to the controller.

The addition of processing capability will allow increased controller bandwidth, thus increasing the speed of response and disturbance rejection. The saturation affects associated with actuator inductance can be addressed by an increase in the amplifier voltage rails beyond the +/- 40 volts employed in the initial effort. Commercially available hardware is available to satisfy both of these requirements.

ACKNOWLEDGMENTS

The authors are indebted to a number of persons for the success of this program; Dr. David L. Trumper of the University of North Carolina - Charlotte, Steven Tracy and Paul Lustiber of GCA, and J. Wilcoxen, P. Kahle, J. Wronosky, J. Darnold, and D. Jordan all of Sandia National Labs. The authors are also indebted to SEMATECH for providing funding and opportunity to pursue this program.

REFERENCES

1. Trumper, D.L.: *Magnetic Suspension Techniques for Precision Motion Control.* Ph.D. Thesis, Dept. of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Mass, September 1990.

2. Trumper, David L.; Sanders, James C.; Nguyen, Tiep H.; Queen, Michael A.; *Experimental results in Nonlinear Compensation of a One-Degree-of-Freedom Magnetic Suspension,* International Symposium on Magnetic Suspension Technology, NASA Langley Research Center, Hampton, VA., August 1991.

3. Poovey, Tony; Holmes, Mike; Trumper, David: *A Kinematically Coupled Magnetic Bearing Test Fixture.* Proceedings of ASPE 1992 Annual Meeting.

DISCLAIMER

DATE
FILMED
10 / 14 / 93

END