MAGNETICALLY-SUSPENDED STAGE FOR ACCURATE POSITIONING OF LARGE SAMPLES IN SCANNED PROBE MICROSCOPY

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ABSTRACT

This paper describes a magnetically-suspended six-degree-of-freedom precision motion control stage which was built in the Precision Engineering Laboratory at the University of North Carolina at Charlotte (Holmes, 1998). This Long-Range Scanning (LORS) stage has travel in the horizontal plane of 25 mm by 25 mm with 100 μm of vertical travel. Vertical position feedback is provided by three capacitance probe sensors while heterodyne laser interferometry is used for lateral position feedback. The forces to suspend and servo the moving element are provided by four six-phase linear motors. The stage was designed to have a positioning resolution of 0.1 nm, positioning repeatability of 1 nm, and a positioning accuracy of 10 nm. These performance objectives were chosen to match the measurement requirements associated with present and future production needs for devices such as integrated circuits, photo-masks, and micromechanical actuators. The LORS stage is used to position samples beneath a scanning-tunneling microscope (STM). The STM will ultimately be used to characterize the performance of the LORS stage. This paper presents a summary of the final design along with some initial performance characterization data.

MECHANICAL DESIGN

The LORS stage, shown in Figures 1 and 2, consists of a moving element (**platen**), a **machine frame**, and a **metrology head**. The bottom of the platen holds four permanent magnet arrays. A **reference block** is mounted to the top of the platen via three flexures. As in previous work (Holmes and Trumper, 1996), the platen is light-weighted and floated in oil to reduce bias currents in the motors and to provide viscous damping and high-frequency coupling. The stator windings are mounted in the machine frame opposite the magnet arrays. The reference block contains the reference surfaces for the position feedback sensors, namely, target mirrors for the interferometers and a conductor plane which acts as the targets for the capacitance probes. The sample to be imaged is supported by a sample holder which is kinematically mounted to the reference block. The metrology head is kinematically mounted to the top of the machine frame. The metrology head contains the feedback sensors, three interferometers for lateral position feedback and three capacitance probes for vertical position feedback. The metrology head also provides support for the

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scanned probe microscope head. To reduce the effects of thermal drift, the metrology head and the reference block are made of Zerodur, with a coefficient of thermal expansion of 0.05 μm/m/°C. The idea is to control the currents in the motors, thereby controlling the forces exerted on the platen, based on the position feedback from the interferometers and the capacitance probes. We are able to image various samples which are placed on the sample holder. The scanned probe interface mount is designed to support various types of scanned probe microscope heads (i.e., Atomic Force Microscopes (AFM) and Scanning Tunneling Microscopes (STM)).

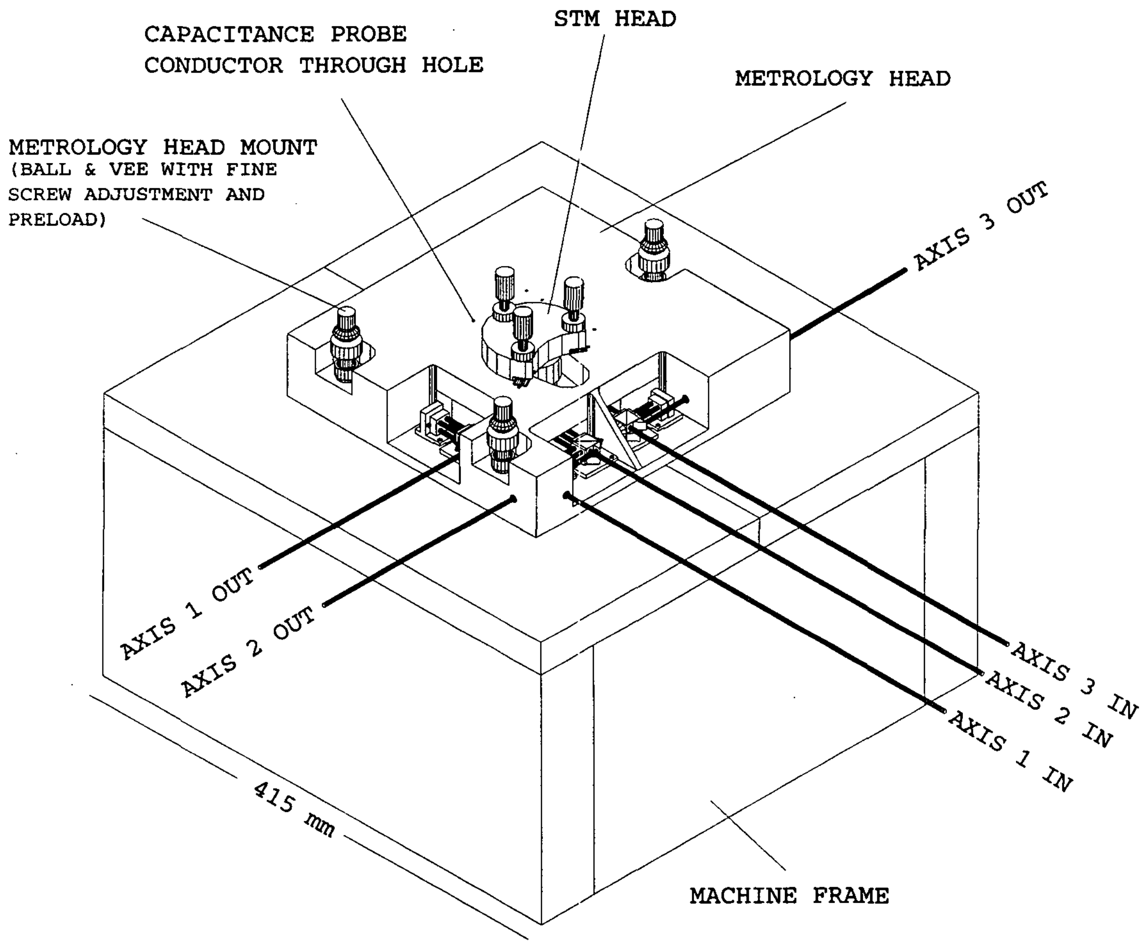


Figure 1: The LORS Stage (External View)

LINEAR MOTOR DESIGN

Four linear motors (Trumper, 1990) of the type shown in Figure 3, are used to suspend and servo the moving element (platen). The design procedure is outlined by

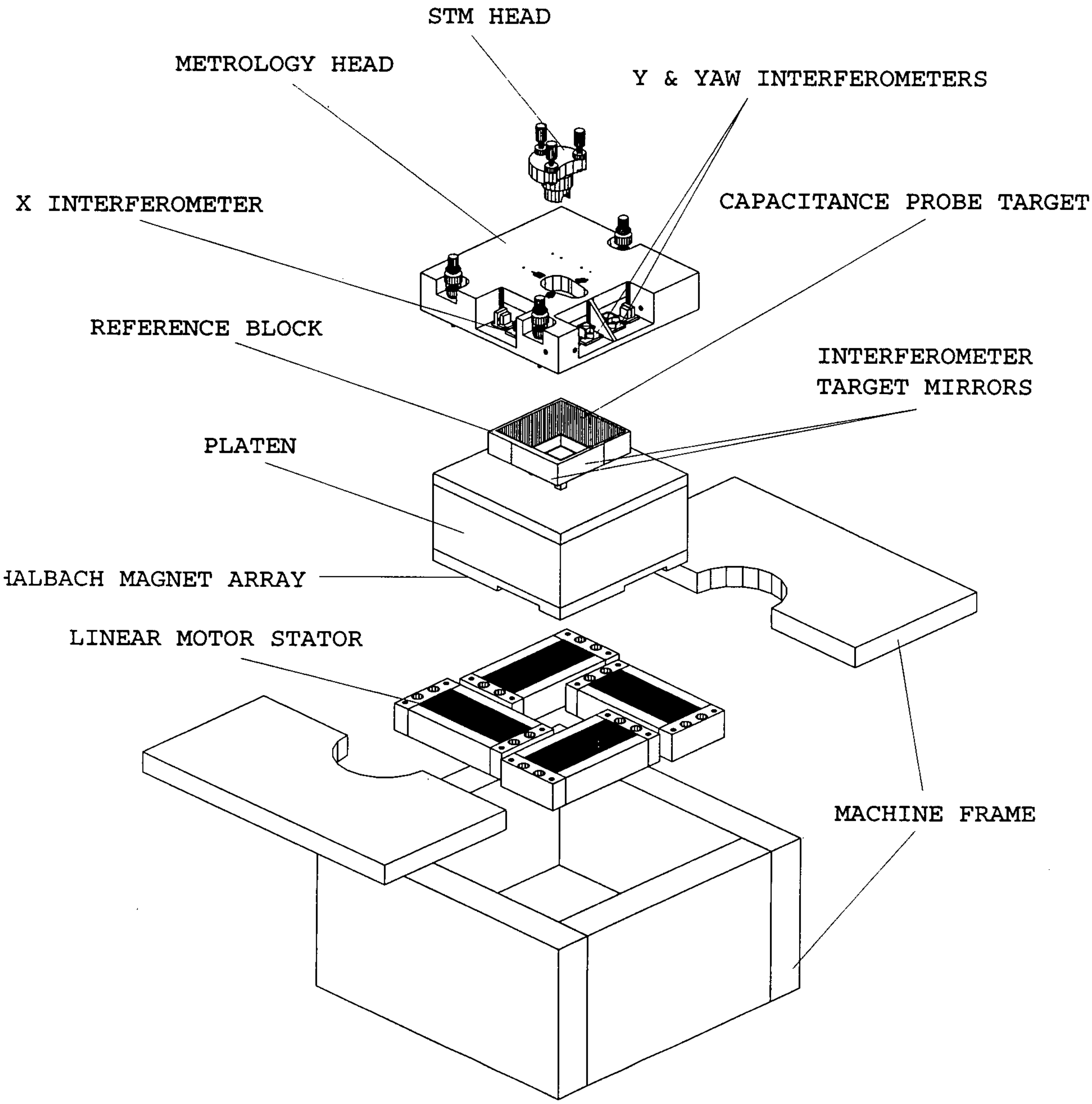


Figure 2: The LORS Stage (Exploded View)

(Trumper, Williams, and Nguyen, 1993) where the design of a two phase linear motor is presented. For the sake of brevity, only the key features of the LORS Stage linear motors are presented here, the reader is referred to the reference for a detailed treatment of linear motor design.

Each of the linear motors consist of a stator and a permanent magnet array. The permanent magnet array consists of 16 NdFeB permanent magnets arranged in the Halbach configuration (Halbach, 1980). Positioned 300 μm directly beneath the magnet array is the stator (in Figure 3 the gap between the magnet array and the stator is exaggerated for clarity). The stator consists of 66 coils each of which contains 10-turns of 18 gauge wire. Every sixth coil is connected in anti-series to make a six-phase linear motor. The motor phase resistance is 0.4Ω and the phase inductance is calculated to be approximately 30 μH (Trumper, Kim, and Williams, 1996). The linear motor shown is capable of exerting bidirectional vertical and horizontal forces Fz and Fx as indicated. This motor is designed for a gain of approximately 6 N/A with nominal operational forces of less than 1 N. The combined power dissipation of the four motors when the platen is suspended and driven with a lateral velocity of 1 mm/sec is calculated to be approximately 30 mW.

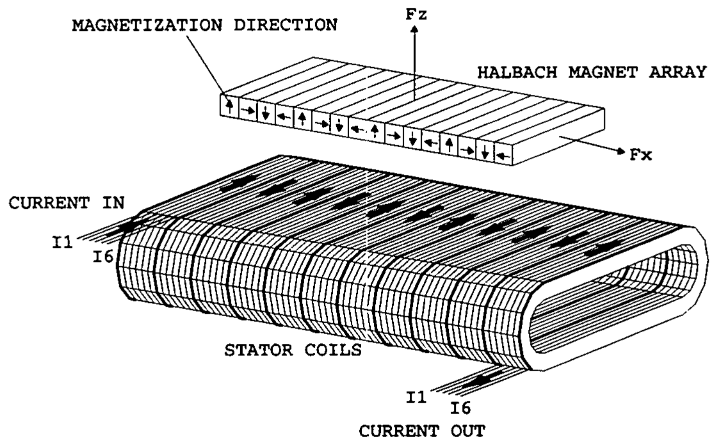


Figure 3: LORS Stage Linear Motor Configuration

SOME INITIAL PERFORMANCE DATA

The LORS stage positioning noise is shown in figure 4. The lateral position noise (X and Y) is less than 1 nm peak-to-peak. The vertical position noise is about 2.5 nm peak-to-peak. The corresponding position noise spectrums are given in figure 5. Note that the significant peaks occur at about 12 Hz. The source of the 12 Hz oscillation has not yet been determined.

Figure 6 shows a 10 nm step in X. Note that although the noise is below 1 nm, there is still structure to the noise. Figure 7 shows a 1 nm step in X with the platen at $Z = -45$ μm. Other 1 nm steps taken at $Z = 0$ μm demonstrate no appreciable increase in noise.

SOME INITIAL STM IMAGES

A reference sample was designed consisting of two grids of 15 μm tall by 15 μm wide crosses. The eight-by-eight fine grid of crosses is centered in the eight-by-eight coarse grid of crosses. The linewidth of the crosses is 1 μm. The sample is chrome on quartz. The cross patterns were etched into the chrome. The sample grid was manufactured by Hewlett-Packard Photomask[1]. The original drawing of the sample grid is presented in figure 8.

[1]Hewlett-Packard Photomask, 5301 Stevens Creek Blvd., Santa Clara, CA 95052-8059.

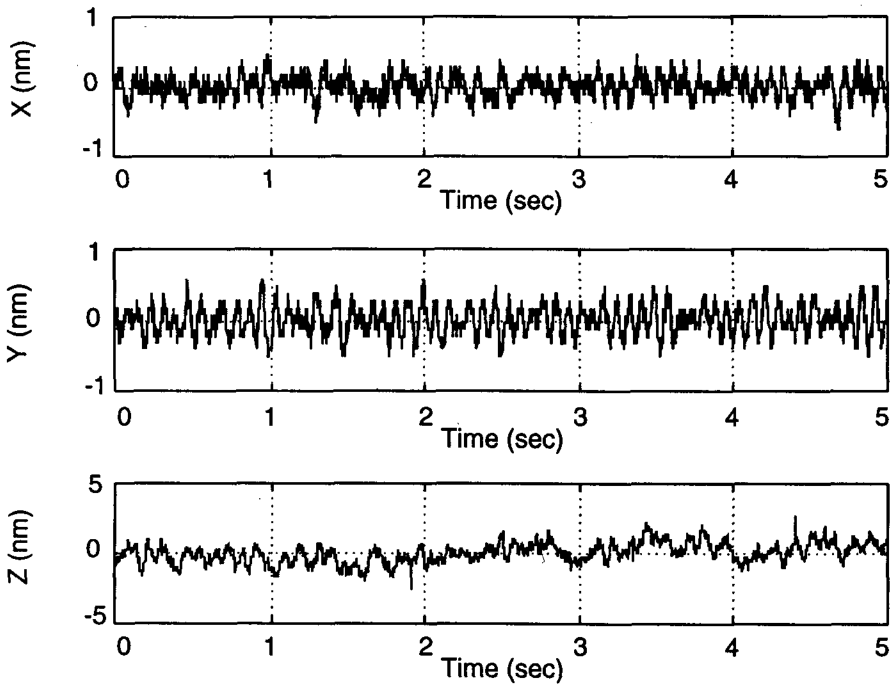


Figure 4: Position Feedback Signals

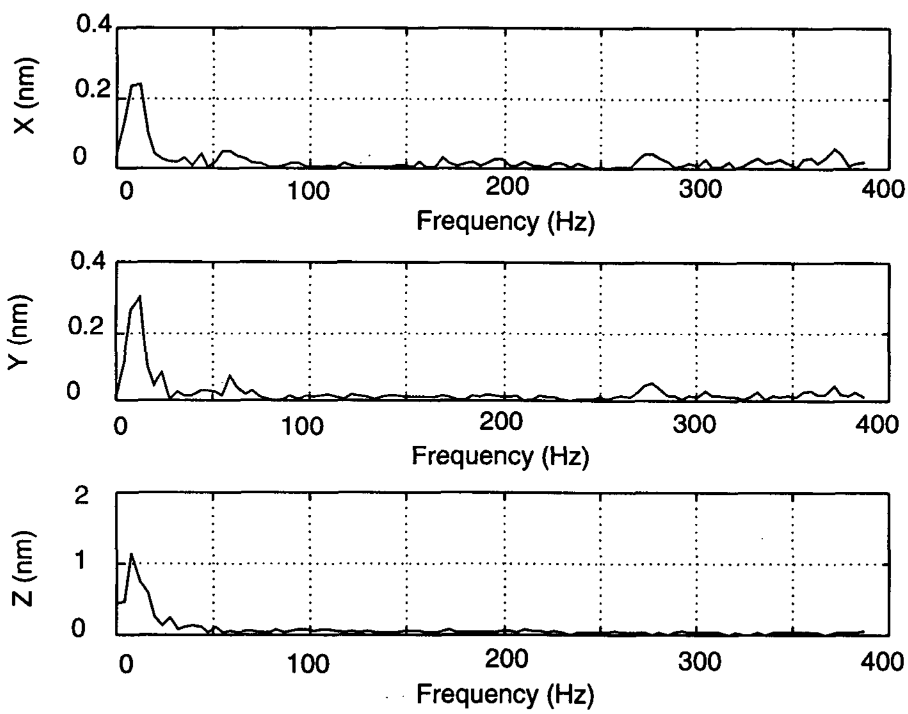


Figure 5: Position Feedback Signal Noise Spectrums

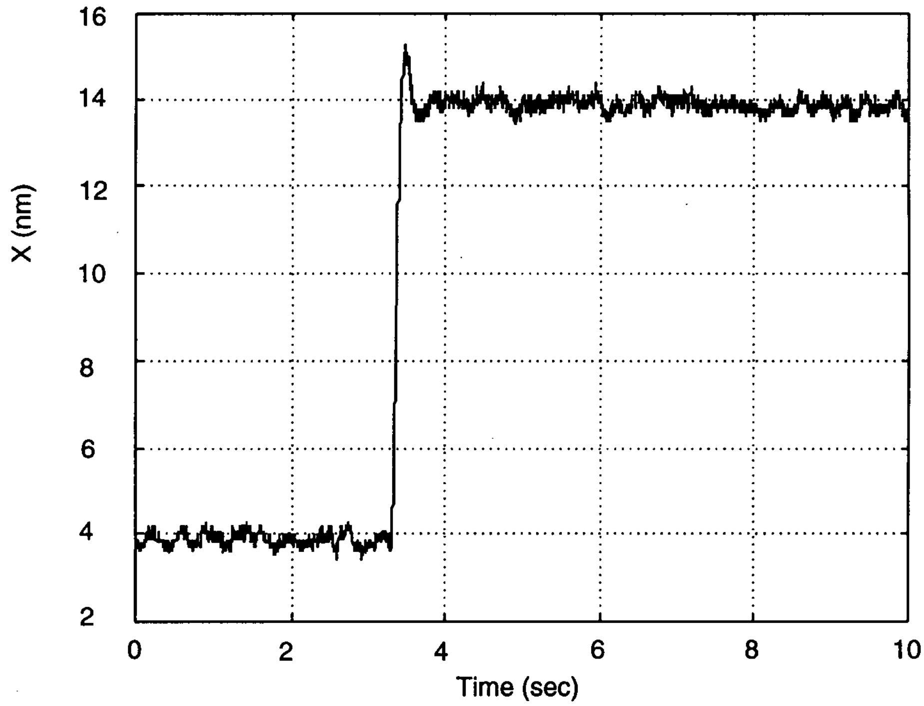


Figure 6: 10 nm Step response in X

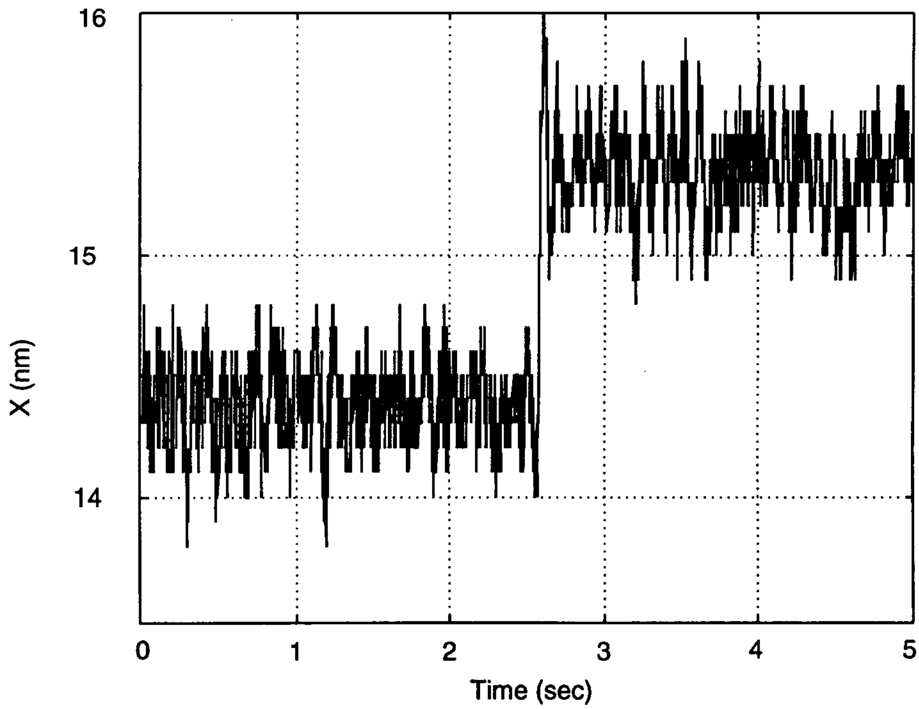


Figure 7: 1 nm Step in X

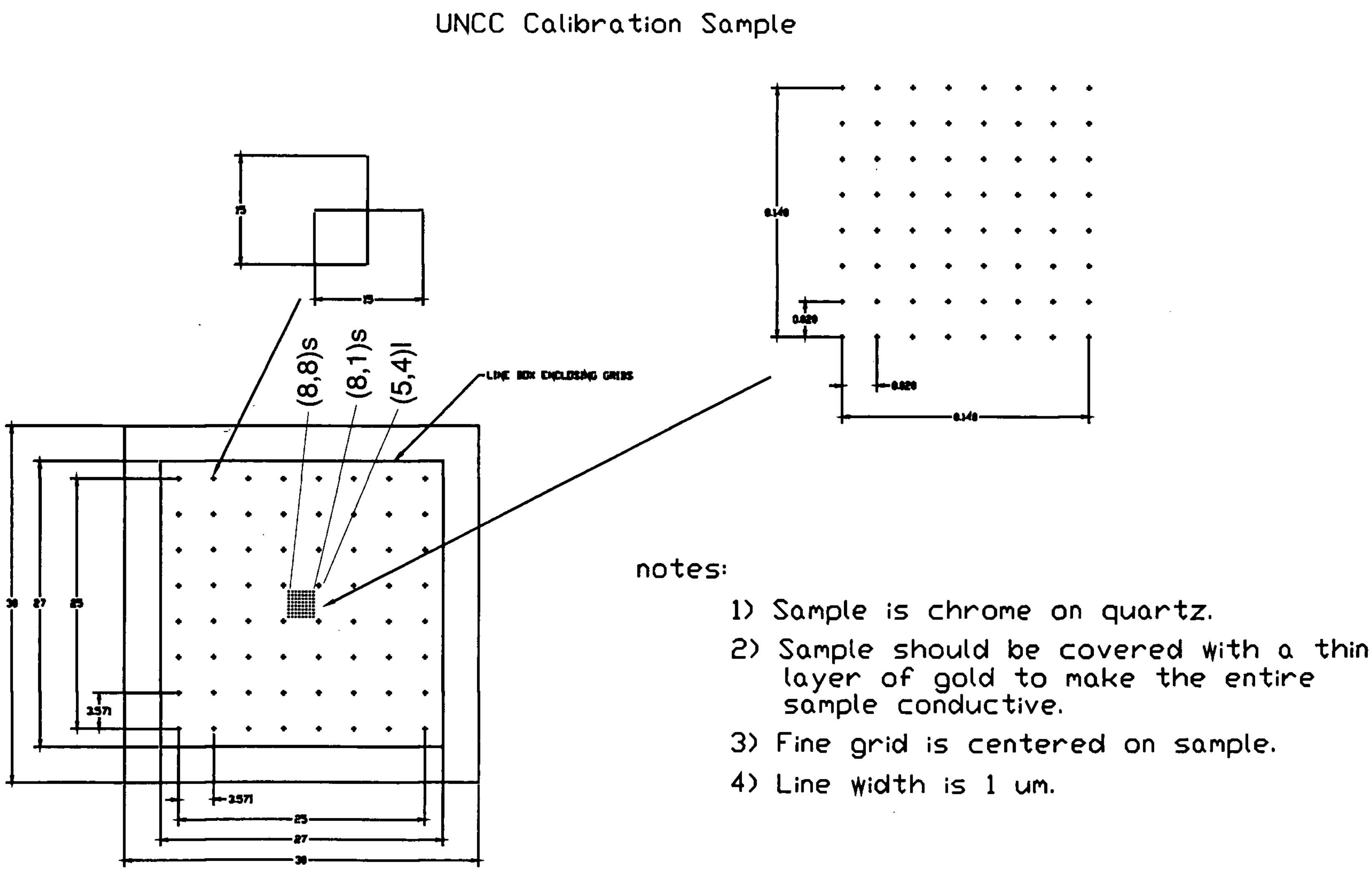
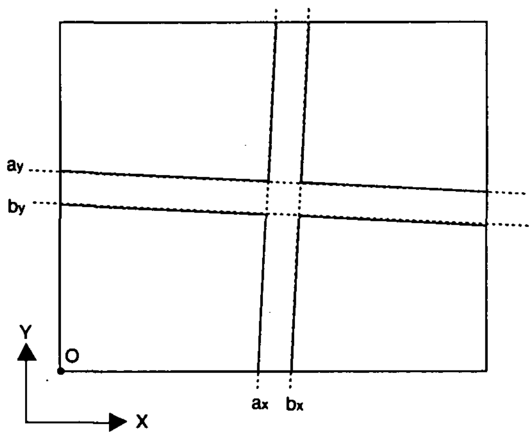


Figure 8: Calibration Sample (Compliments of HP-Photomask)

DRIFT

The first efforts involving the STM were to simply record the location of a single cross over a period of approximately 30 minutes. The "location" of the cross was defined as illustrated in figure 9. Utilizing the STM software, the edges of the cross were located in the STM field of view as shown. The table at the bottom of figure 9 gives the X and Y coordinates of the points shown. The data presented for each corresponding time not only locate the cross, but also provides a measure of its line widths in X and Y. Note that drift of the cross is not monotonic. Further, the width of the cross lines vary by as much as 228 nm over the approximate 38 minute duration of the experiment. The six images corresponding to the data given in figure 9 are shown in figure 10. It is clear from the drift data that the current STM system is not able to provide any characteristic data for the performance of the LORS stage.



Data Buffer	X (nm)		Y (nm)		time	Cross width (nm)	
	a_x	b_x	a_y	b_y	(sec)	Δx	Δy
1	6532	7117	4615	5265	0	585	650
2	6500	7085	4940	5557	381	585	617
3	6402	6922	5005	5525	761	520	520
4	6532	7020	4940	5427	1523	488	487
5	6402	6857	5037	5622	1903	455	585
6	6240	6792	5200	5622	2284	552	422

Figure 9: STM Image Cross Measurement Technique

FUTURE WORK

At the present time the LORS positioning noise is dominated by the system disturbances. Perhaps the simplest means of improving the stage's disturbance rejection is by increasing the system bandwidth.

In order to use the STM to characterize the lateral error motions of the LORS stage, a metrology STM head must be built in which the position of the tip relative to the machine

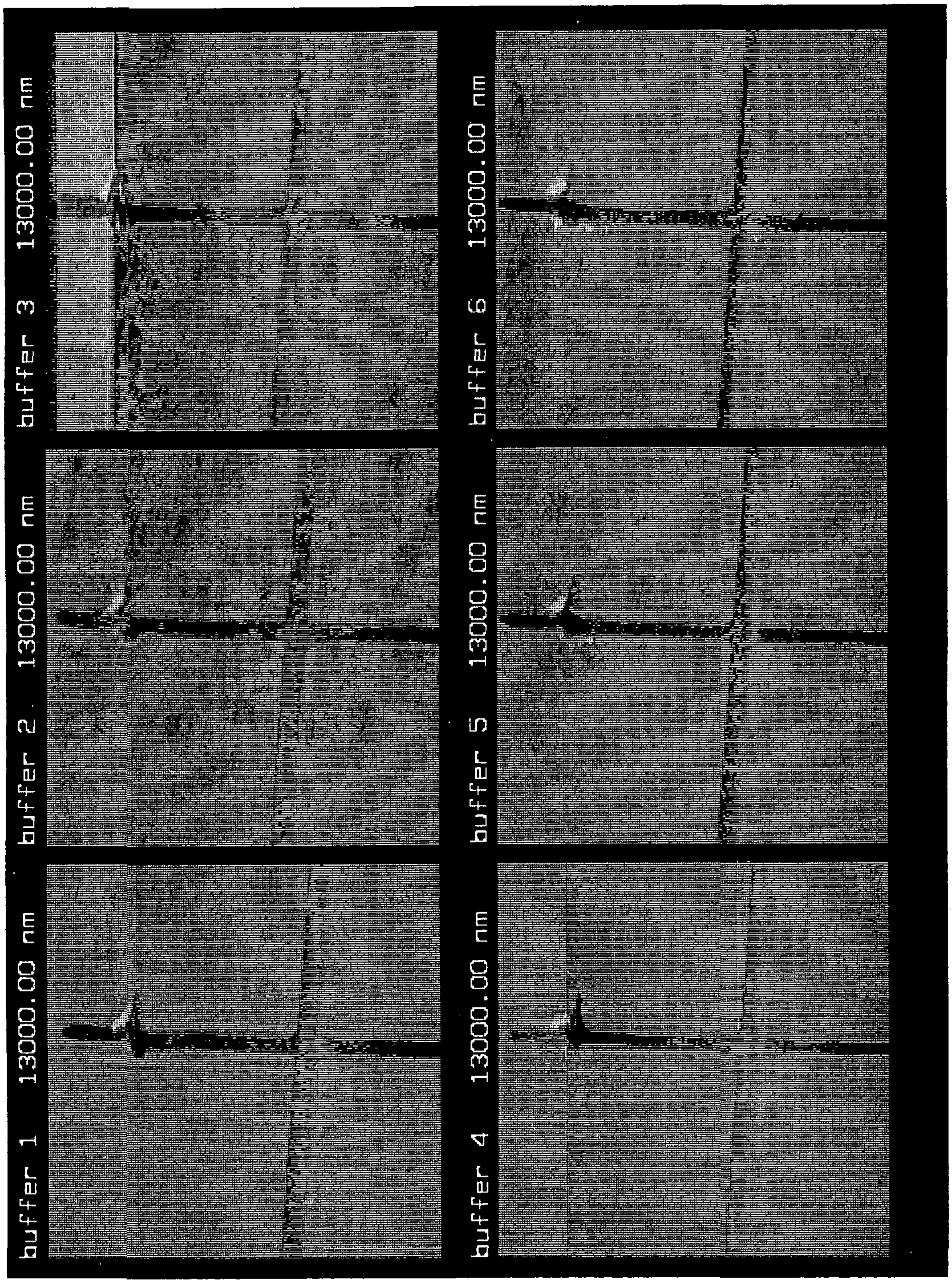


Figure 10: STM Drift Test. Images are 13 μm by 13 μm. The legs of the cross are 1 μm wide.

frame is stable and known. Further, more careful techniques must be employed to ensure the integrity of the image. The changing linewidths illustrated in the drift data suggests errors in the imaging process. Perhaps the tip is picking up trash from the sample surface which is resulting in changing or even multiple tunneling paths from the tip to the surface.

ACKNOWLEDGEMENTS

This research was funded by the National Science Foundation under grant DMI-9414778. The ADE Corporation provided the capacitive gaging electronics and Zygo Corporation assisted with the metrology head and reference block fabrication. Hewlett-Packard Photomask fabricated the sample grid which will ultimately be used for performance characterization. The relative locations of the crosses on the sample grid have been measured by Physikalisch Technische Bundesanstalt. It is our intent to use their results as a comparison rule. Dr. Gerald Blessing of the National Institute of Standards and Technology did some initial experiments to determine the feasibility of using ultra-sonic probes to measure the initial position of the platen in the silicone oil. Also, Won-jong Kim at the Massachusetts Institute of Technology developed the theory underlying the linear motor design and provided the impetus for using the chosen coil configuration.

REFERENCES

Halbach, K., "Design of Permanent Multipole Magnets with Oriented Rare Earth Cobalt Material," Nuclear Instruments and Methods, 169, 1980, pp.1-10.

Holmes, M.L., "Analysis and Design of a Long Range Scanning Stage," Ph.D. Thesis, Department of Electrical Engineering, UNC-Charlotte, Charlotte, North Carolina, May, 1998.

Holmes, M.L., and Trumper, D.L., "Magnetic/fluid-bearing stage for atomic-scale motion control (the Angstrom stage)," *Precision Eng.*, vol. 18, no. 1, pp. 38-49, 1996.

Trumper, D.L., "Magnetic Suspension Techniques for Precision Motion Control," Ph.D. Thesis, Dept. of Elec. Eng. and Comp. Sci., M.I.T., Camb., Mass., Sept., 1990.

Trumper, D.L., Williams, M.E., and Nguyen, T.H., "Magnet Arrays for Synchronous Machines," in *Proc. IEEE IAS 28th Annu. Meet.*, Oct. 1993, pp.9-18.

Trumper, D.L., Kim, W.J., and Williams, M.E., "Design and Analysis Framework for Linear Permanent-Magnet Machines," in press, *IEEE Trans. Ind. Applic.*, vol. 32, no. 2, Mar/Apr 1996.