MAGNETIC/FLUID-BEARING STAGE FOR ATOMIC-SCALE MOTION CONTROL

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1 INTRODUCTION

This paper briefly describes the design, construction, controller implementation, and performance of a magnetically-suspended six-degree-of-freedom precision motion control stage. The suspended platen (3 kg mass) is floated in oil to support its weight and to provide mechanical damping and high-frequency coupling. Twelve electromagnets and six capacitance probes operate through the resulting oil film to exert control forces and to measure the position of the stage, respectively. Our hybrid approach of magnetic and fluid bearings allows the stage to achieve performance not possible with either approach alone. The magnetic/fluid-bearing stage is designed to ultimately achieve 1 angstrom (.004 μin) resolution in a 100 μm cube of accessible travel. The stage has applications in areas such as scanned probe microscopy, fine motion control for X-ray and optical photolithography, diamond tool machining, and probing and analysis of integrated circuit structures.

At the present time, the stage is operational, with travel of 100 μm and noise under one nanometer peak-to-peak. We have used the stage to provide scanning motions for scanned tunnelling microscopy and have imaged nanometer-scale features with good performance.

2 MECHANICAL DESIGN

Figure 1 shows a cross-section through the center of the stage. In this figure, a 30 cm line is included to indicate the scale. This view shows the platen inside the oil-filled chamber created by the frame. The sample holder is mounted kinematically to the sample holder support column which is bolted to the top of the platen. Three ruby spheres epoxied into pockets in the bottom of the sample holder fit into three corresponding grooves in the sample holder support column. The kinematic mount is preloaded with a permanent magnet. The STM head has three support columns. The foot of each support column is a steel sphere. The steel spheres fit into three grooves in the frame forming a kinematic mount. Each groove is formed by two parallel cylinders which are pressed into pockets located in the frame.

The position of the cylinders is such that the STM tip aligns over the center of the sample holder. This kinematic mount is pre-loaded with three springs. With the platen inside the chamber and the top of the frame bolted in place, the chamber is filled with oil such that the oil level is approximately halfway up the sample holder support column. This ensures that all actuators and capacitance probes are operating in oil. The frame is approximately 30x30x20 cm and is fabricated from aluminum. The platen is approximately 17x17x8 cm and is also fabricated from aluminum. The platen is light-weighted and floated in oil to support its weight and to provide mechanical coupling of high frequency vibrations. The oil-filled capacitance probe sensor gaps form squeeze film dampers which provide viscous damping of the platen motions.

The light-weighted platen is shown in Figure 2. Each of the triangular pockets is vented to the cylindrical hole in the center of the platen which is vented through the sample holder support column to the atmosphere. The platen's mass is tuned to approximately equal the mass of oil that it displaces. The platen and sample holder assembly has a combined mass of 3.09 kg.

Figure 3 shows a 3 dimensional exploded view of the frame and platen as well as the actuator and sensor designs. Each of the electromagnetic actuators is fabricated with 230 turns of 22 gauge copper wire around 50-50 Ni-Fe E-core laminations. The actuators operate with a gap of 300 μm and are capable of producing in excess of 50 N at this gap, though normal operational forces will be less than 5 N. The electromagnetic actuators are potted directly into rectangular pockets in the frame. Each actuator acts on a corresponding I lamination target which is epoxied opposite the actuator in the platen. The capacitance probes are fabricated from brass and designed for operation in the oil with a nominal standoff of 100 μm and a range of ± 50 μm. The capacitance probes are inserted through cylindrical holes in the frame and bolted to the outer side of the frame. Precision ground aluminum pads on the platen act as the capacitance probe targets.

Figure 4 shows the actuator and sensor orientations. In Figure 4, the capacitance probes, C1-C6, and the actuators, E1-E12 (E8 is opposite E11 and not visible in this view), are contained in the frame which is removed in this view. Once the platen is under suspension, due to the kinematic nature of the capacitance probe sensor sub-system, a nominal capacitance probe gap of 100 μm can be achieved by all of the sensors, representing zero position in all degrees of freedom, regardless of fabrication errors. Any fabrication errors show up in the less critical actuator gaps, which are nominally 300 μm.

3 CONTROLLER

The six degree of freedom controller was implemented on a TMS320C30-based DSP. The DSP board resides in a 50 MHz 80486 PC which provides the I/O bus. Also located in the PC's I/O bus are the A/D and D/A boards utilized by the stage controller.

4 PERFORMANCE

Figure 5 is a scaled trace of the STM Z piezo voltage during a one nanometer step of the platen in the positive Z direction. In order to characterize the lowest possible noise performance of the stage, the viscous damping of the platen motions was increased by pulling the platen into the capacitance probe sensors thereby increasing the squeeze film damping of each damper. This step response was taken with capacitance probe sensor gaps of 55 μm. The rise time is approximately 0.5 seconds which indicates a bandwidth of approximately 1 Hz. The vibration of the platen is approximately 3 angstroms peak-to-peak at this gap.

5 NOISE SOURCES

The present level of stage noise does not allow atomic-scale features to be imaged. However, the present limits to performance are not fundamental; these are dominated by the 16-bit analog-to-digital converter noise and by the finite resolution of the 12-bit digital-to-analog converter which interface the control computer with the stage. The noise level of the capacitance probes is also a limit, but is of less significance at the present time than the converter noise. These noise sources will be corrected in the second pass through the design which is currently in planning.

6 CONCLUSIONS

We have designed and constructed a stage which achieves a noise level as low as 0.3 nm. To ultimately reach the level where atomic scale imaging is possible, this noise must be reduced by a factor of three. However, even at the present noise level, this stage offers a promising alternative to piezo-electric-based motion control systems for precision tasks such as scanned probe microscopy.

7 ACKNOWLEDGEMENTS

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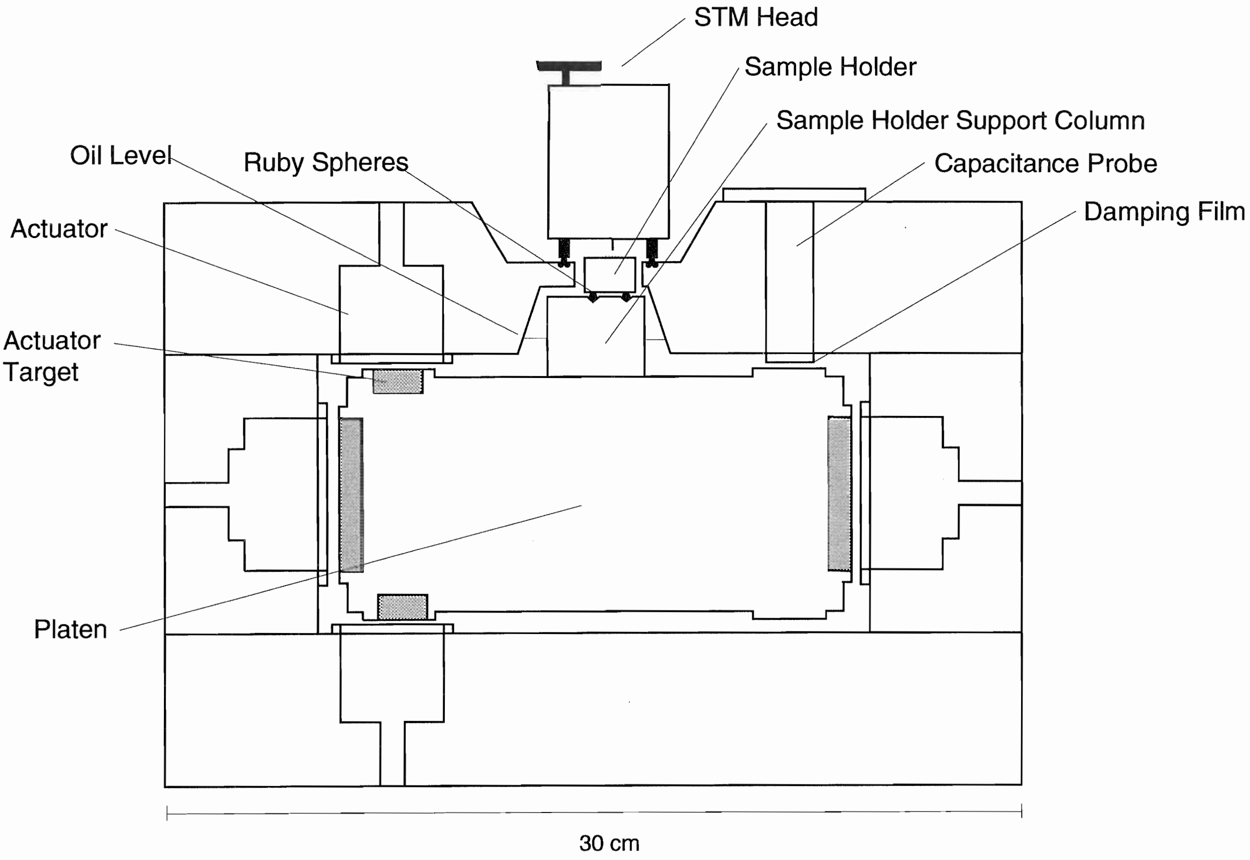


Figure 1: Cross Section of the Oil-Floated Stage

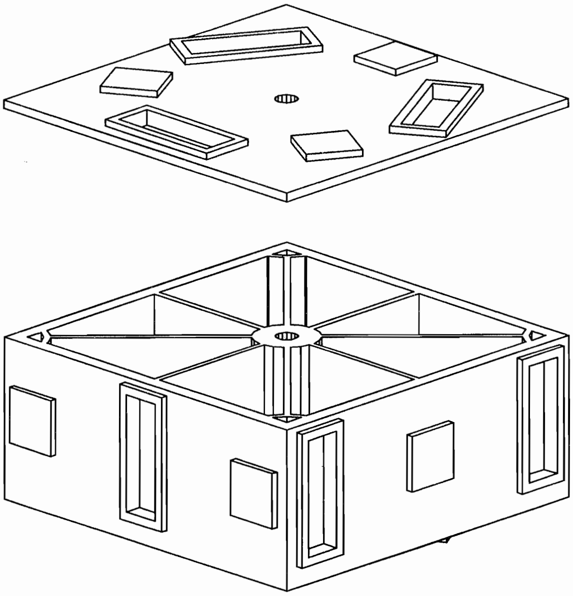


Figure 2: Light-Weighted Platen

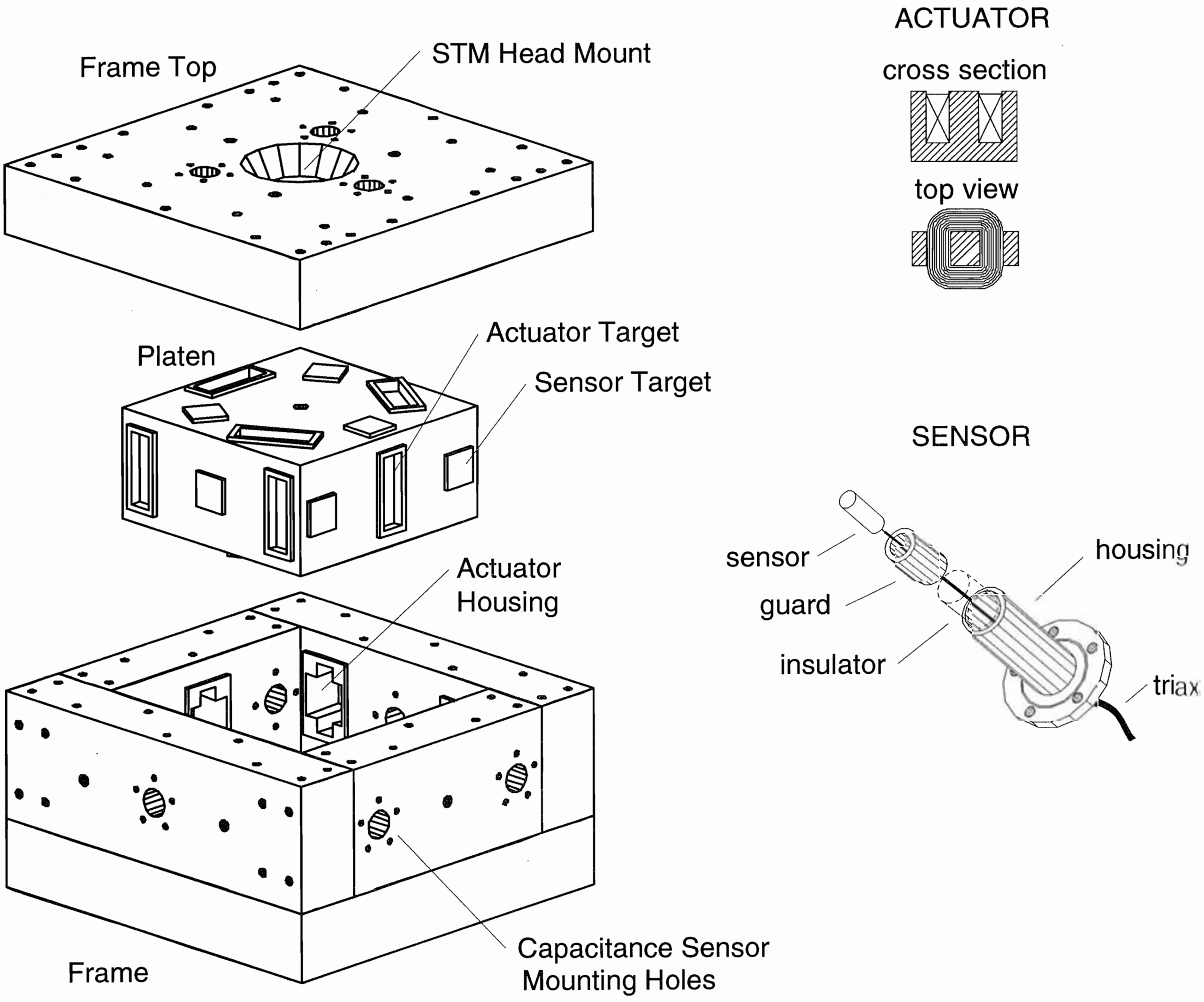
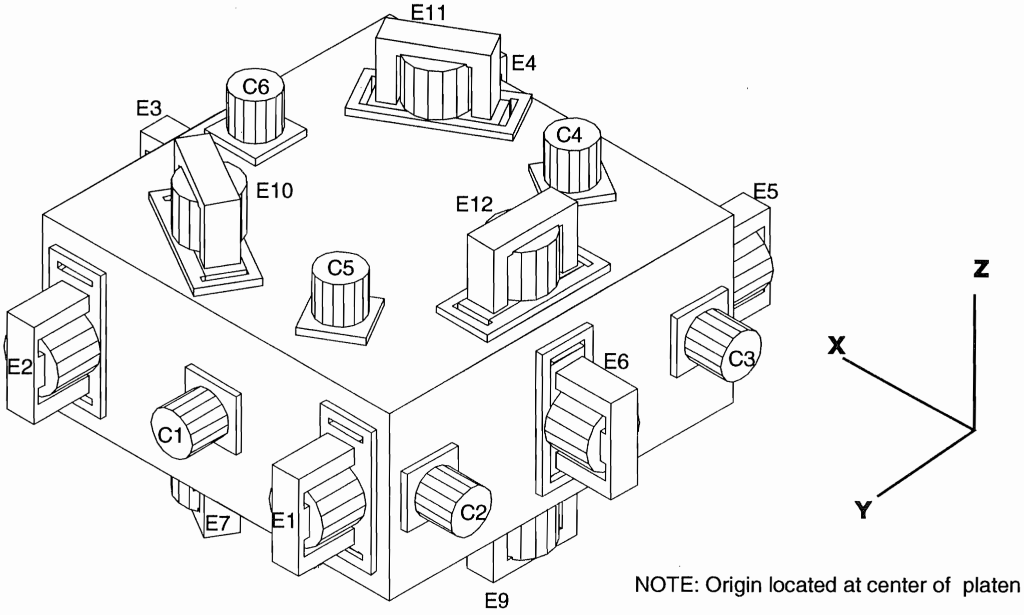


Figure 3: Oil-Floated Stage Exploded View



NOTE: Origin located at center of platen

Figure 4: Actuator and Sensor Orientations

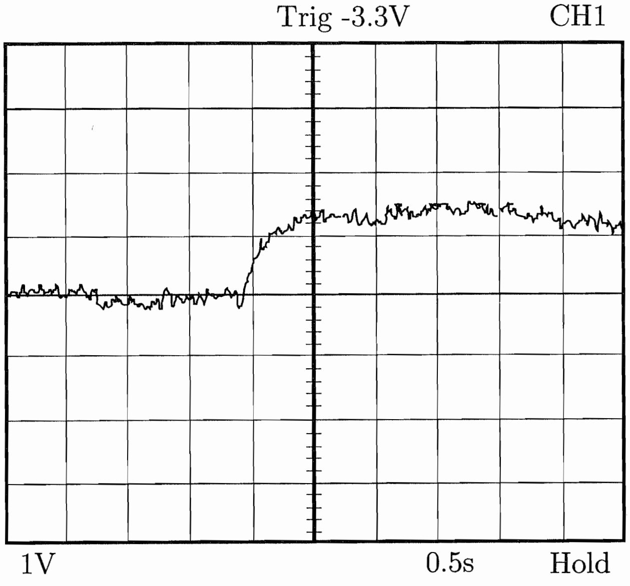


Figure 5: 1 nm Step Response