Objective:

To develop magnetostrictively actuated devices for use in microgravity and low-temperature research.

The device presented here is a room temperature working demonstration model of a linear translator. Other demonstration devices and prototypes are currently being designed and developed at JPL [1].

What is Magnetostriction?

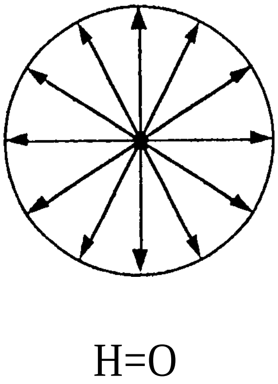
Magnetostriction is a phenomenon in which the magnetic and elastic properties of a crystal are coupled, producing strains in the material when a field is applied, or changing the magnetization of the material in response to strains. In our applications, we seek to induce strains in the material by application of a magnetic field.

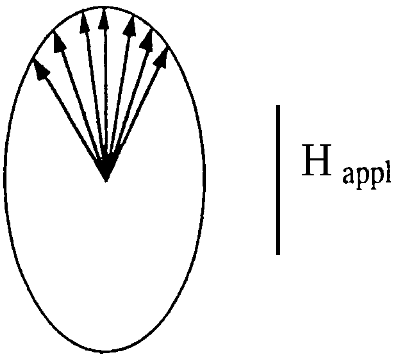
Many materials exhibit magnetostrictive properties, but the most useful of these are soft ferromagnets and ferrimagnets. Nickel and iron both exhibit magnetostrictive properties. The saturation strain ($\Delta l/l$) in conventional magnetostrictors is about 10-5 [2].

Crystals made of Terbium-Dysprosium compounds such as $Tb_{0\,3}Dy_{0\,7}Fe_2$ (commercially called Terfenol-D) can have maximum strain as high as 10-3 at room temperature, and related alloys can display a saturation strain of as much as 10-2 at cryogenic temperatures [3]. The applied field needed to saturate these low-temperature materials is typically only =1000 Oersted.

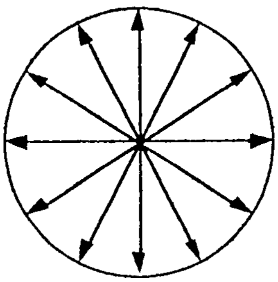
How do magnetostrictors work?

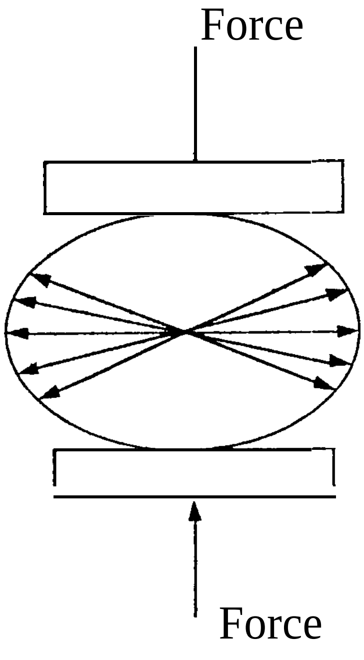
For Joule magnetostriction (the effect we are using), an applied field causes rotation of the magnetic moments in the material to align them with the field. The moments in the material are coupled to the lattice, causing elongation of the lattice, parallel to the applied field, as they rotate.

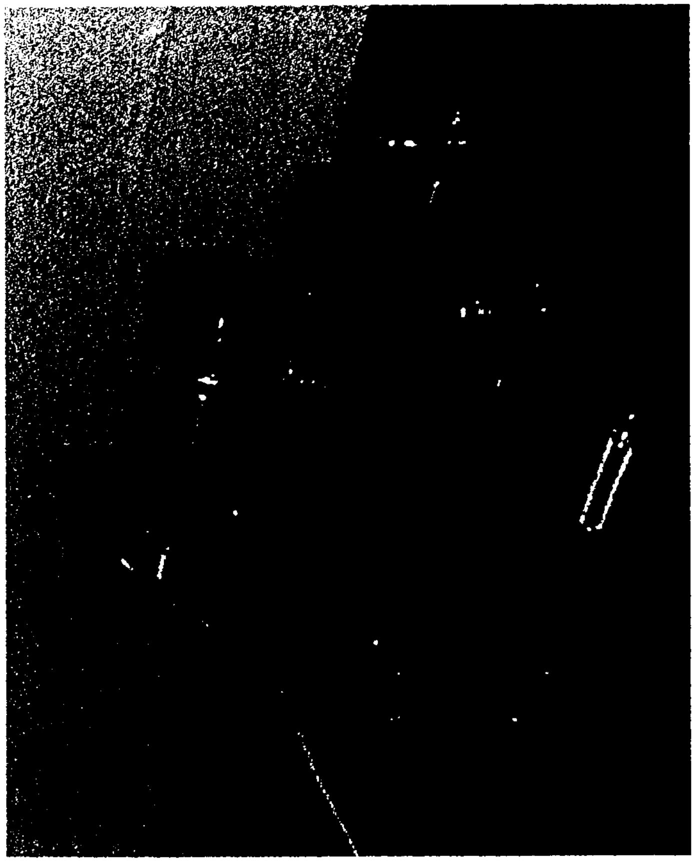


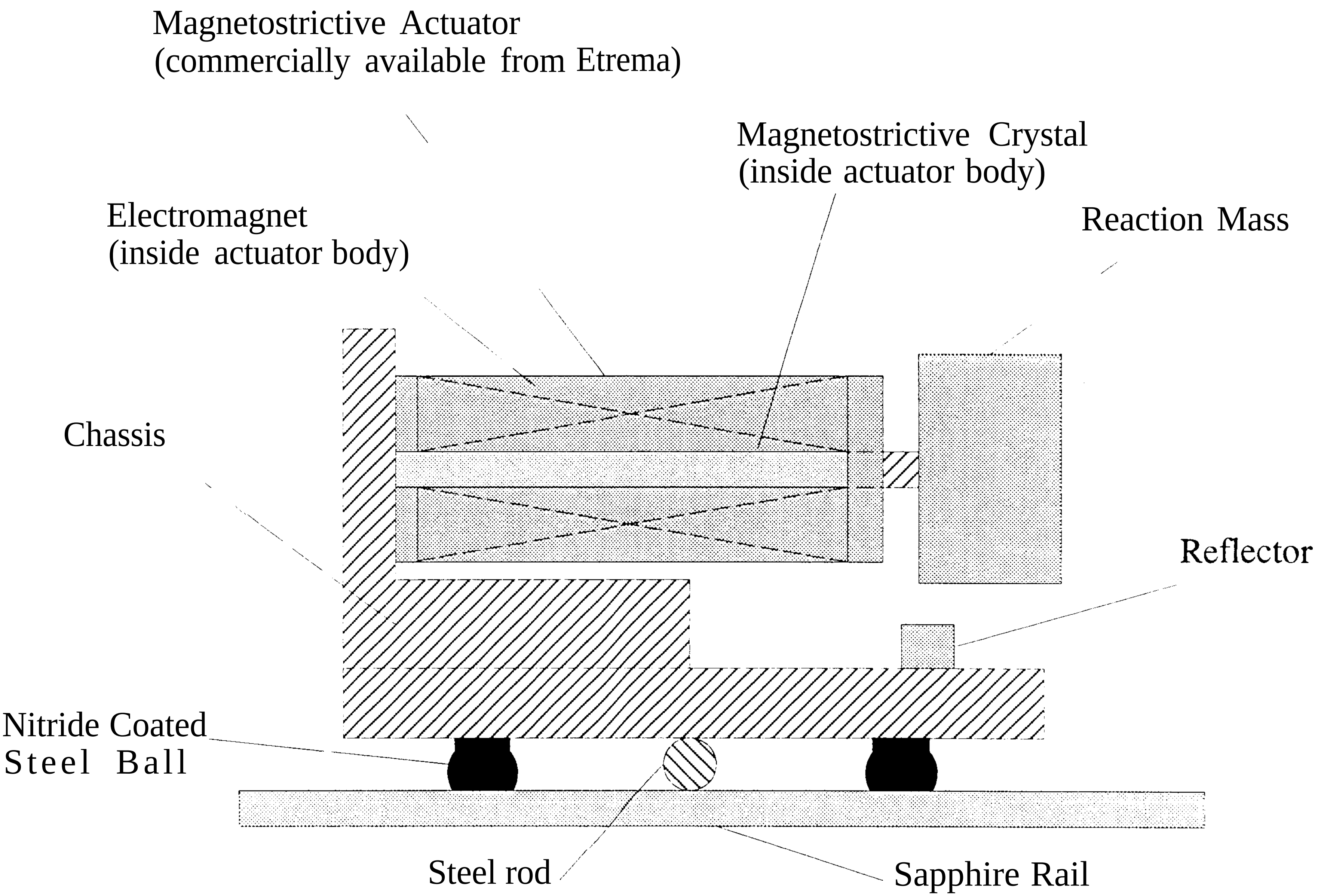


If we first compress the material, the compression rotates some of the moments perpendicular to” the applied stress. When an external field is applied, more moments are then rotated parallel to the field, resulting in larger saturation strains than in an unstressed material [2].



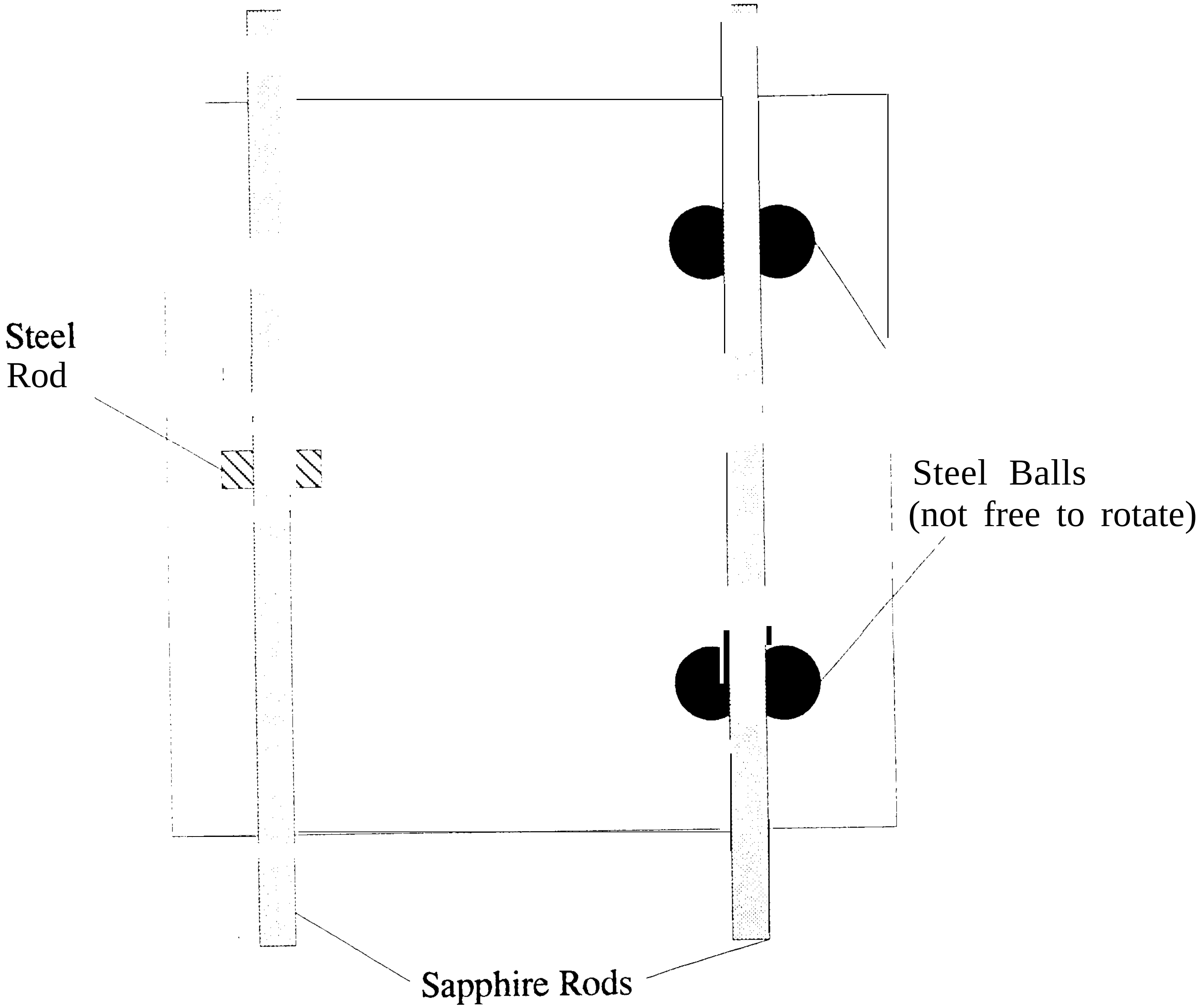






Total Mass: 1.5 kg
Reaction Mass: 0.3 kg

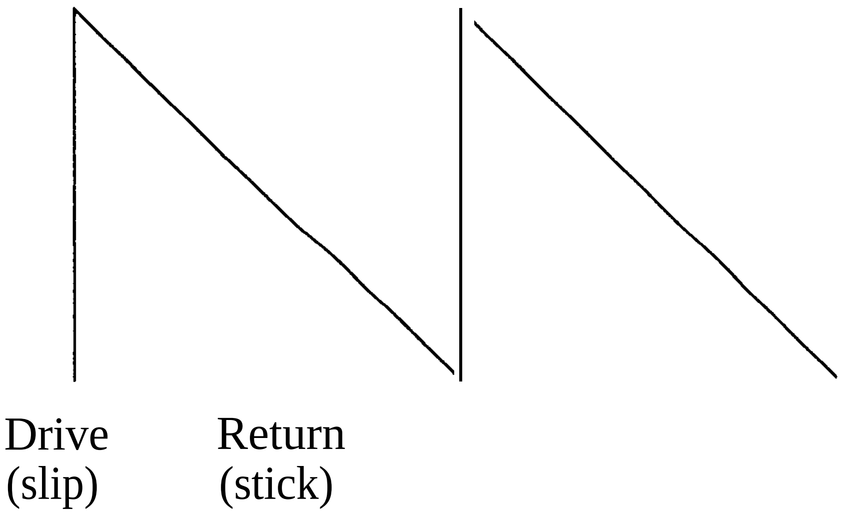
Bottom View of Chassis



How the stepper works:

The device operates by moving the reaction mass rapidly in the direction opposite the desired motion, so that the chassis slips along the rails as momentum is conserved. The reaction mass is then returned to its initial position slowly enough that friction between the bearings and rails keeps the device in place. By adjusting the amplitude of the motion of the reaction mass, we can control the displacement of the chassis.

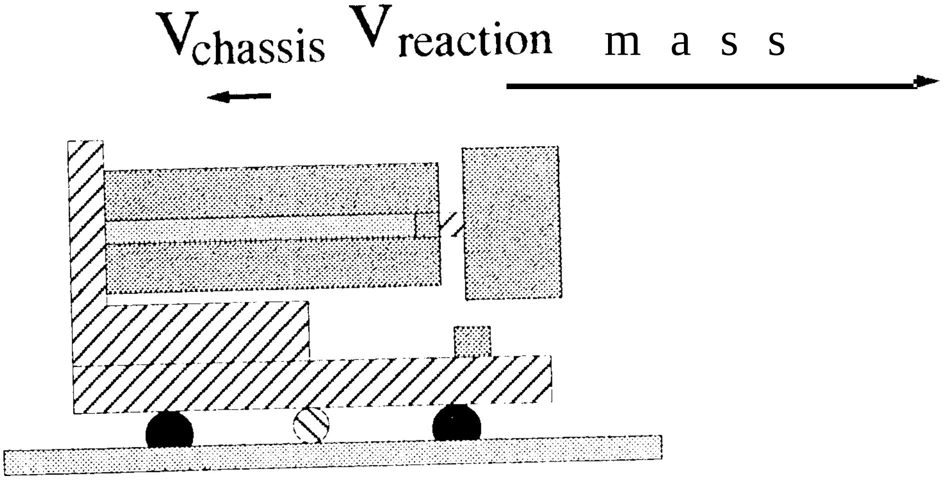
The driving waveform is a simple sawtooth function, which is reversed to change the direction of motion.



Similar devices have been made using piezoelectric actuators for use in scanning-tunneling microscopy [3].

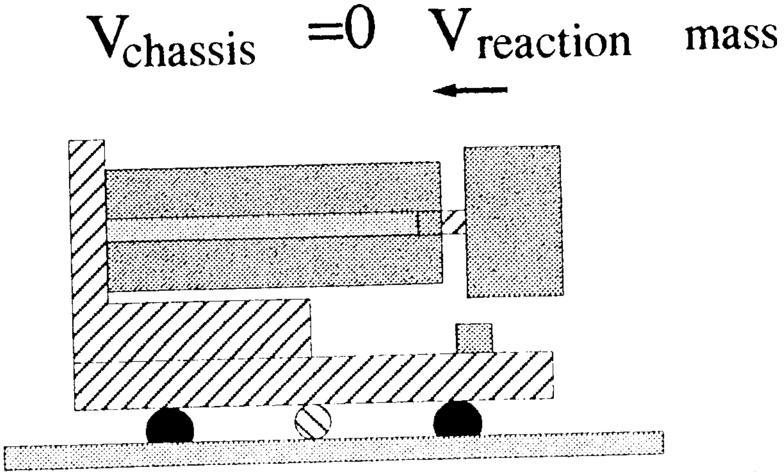
One Cycle of Operation:

Drive:



The current (producing a magnetic field) is applied abruptly, driving the reaction mass rapidly opposite the desired direction of motion. The force required for the rapid acceleration is sufficient to cause the bearings to slip along the rails. Conservation of momentum causes the cart to move slightly in the desired direction.

Return:

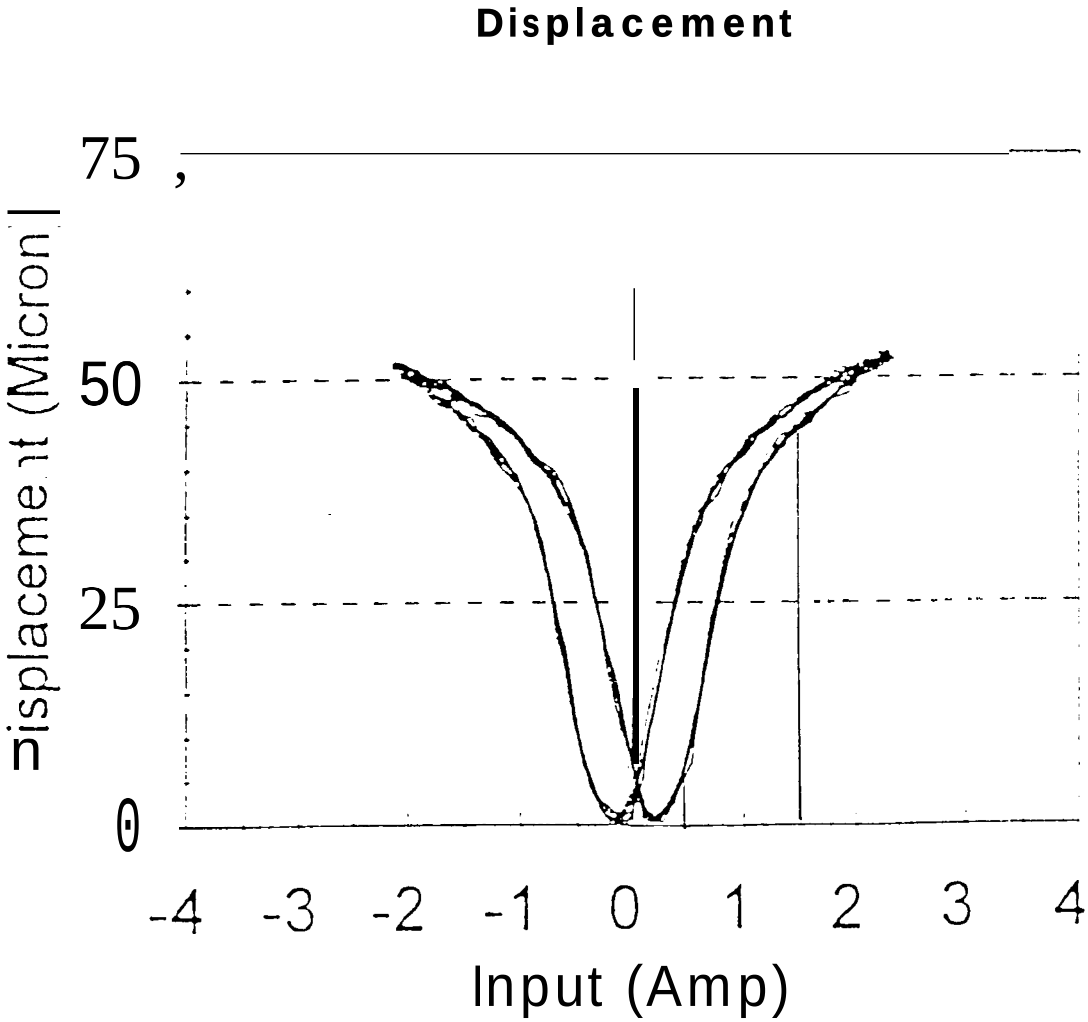


The reaction mass is brought slowly back to its original position. The friction of the bearings on the rails holds the entire assembly in place.

The combination of steel balls and sapphire rods provides a kinematic support, so that the cart’s alignment with the rails will not be affected by temperature changes.

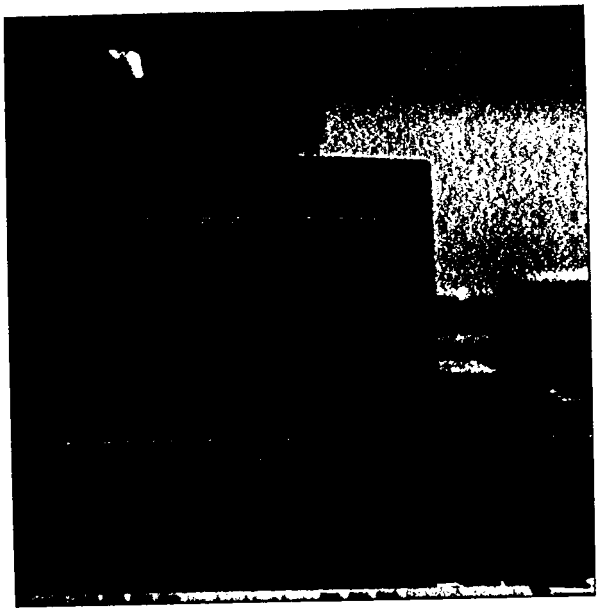
The sapphire rails provide a smooth, low-friction surface on which the balls, which are not allowed to rotate, can slide. Stainless steel rails have also been used, but are unreliable for small step sizes.

The step size as a function of current can vary with time, but manual or automatic feedback can be used to control the step size.



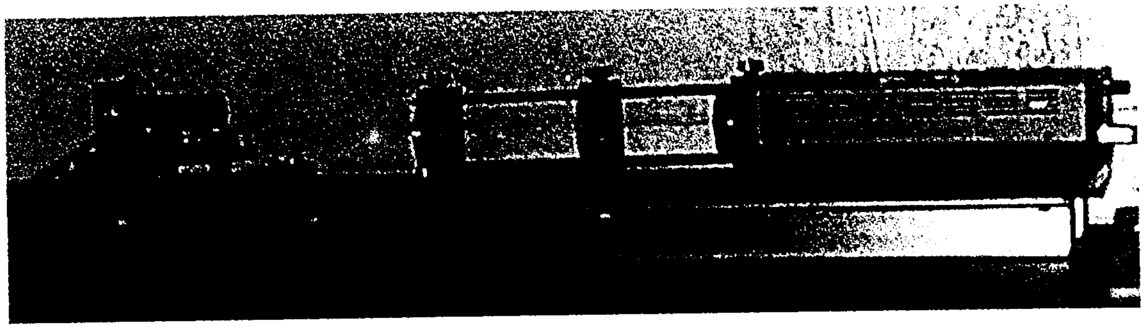
This plot shows the length change of the Terfenol-D crystal in the actuator as a function of applied current at room temperature. (supplied by Etrema)

Because the magnetostrictive crystal has a roughly linear response to applied field only over a limited range of operation. In the demonstration device we apply a 0.5 Ampere dc offset, and drive the actuator mostly in the linear region of its operation. The typical range of currents during operation of the stepper is indicated by the red lines.

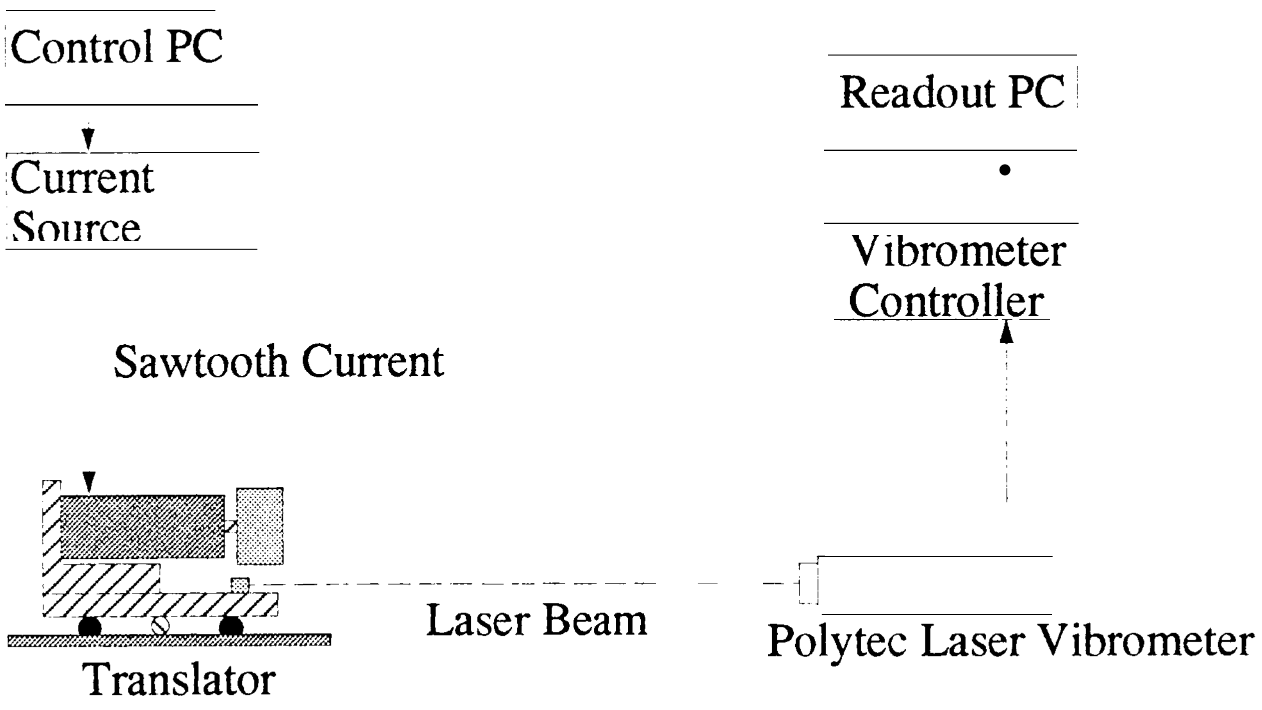


Y: 19 μm/div 3A
X: ~~10s~~ 1s/div

This photograph shows length change as a function of time for an actuator identical in physical dimensions to that used in the demonstration device, but with two 0.75 inch long pieces of TbDy (placed end to end) substituted for the Terfenol-D crystal, and cooled to 77 K. The horizontal axis shows time, with 996 ins/division. The vertical axis shows length change, with 19 pm/division. The drive signal is a O-3 amp ramp, at 10 Hz, with a short period of no drive between each ramp up, followed by abrupt reduction of the current to zero. The total length change of the crystal is ~180 μm **($0.5x10^{-2}$** strain) Terfenol-D shows very little magnetostriction at 77K

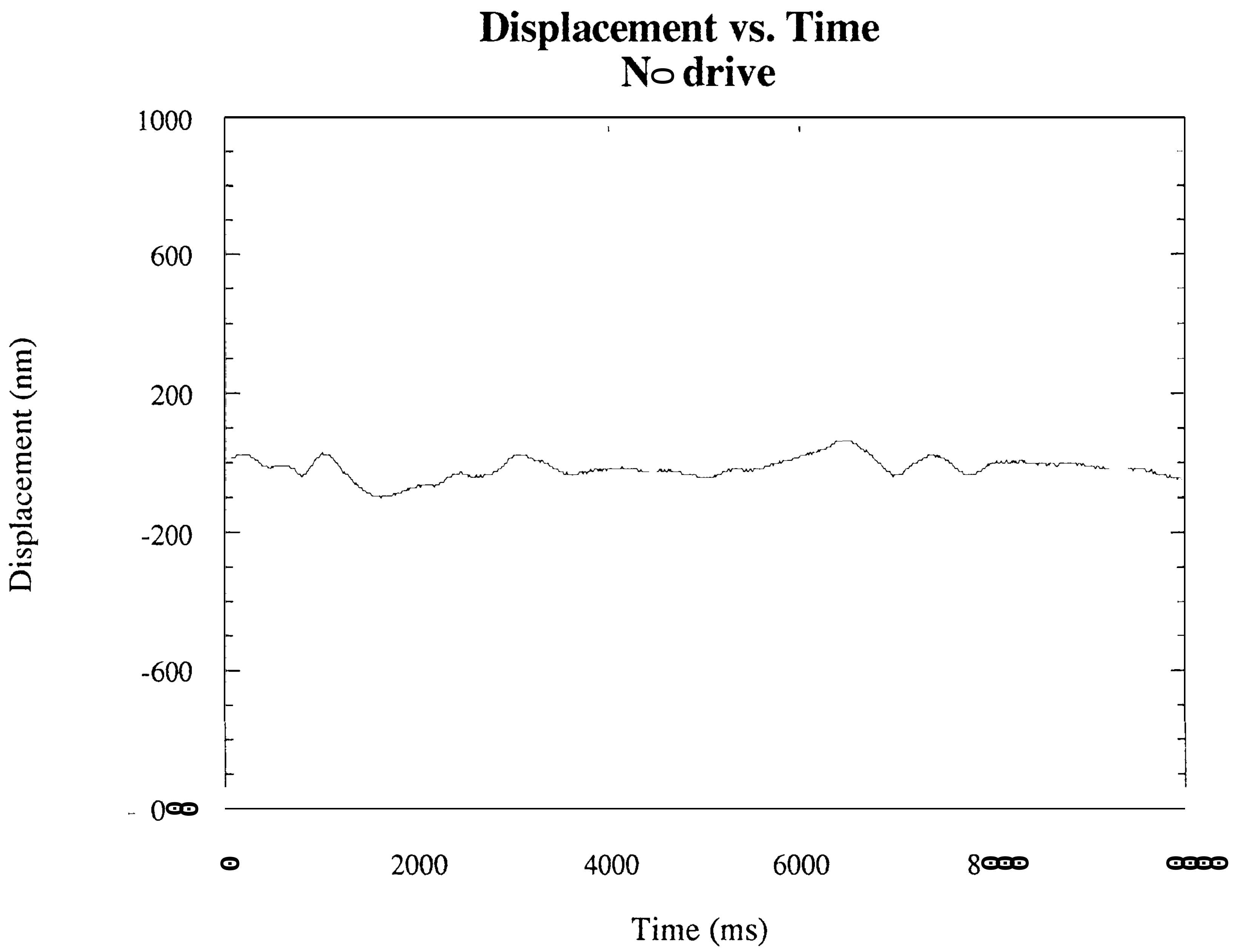


Measurement System

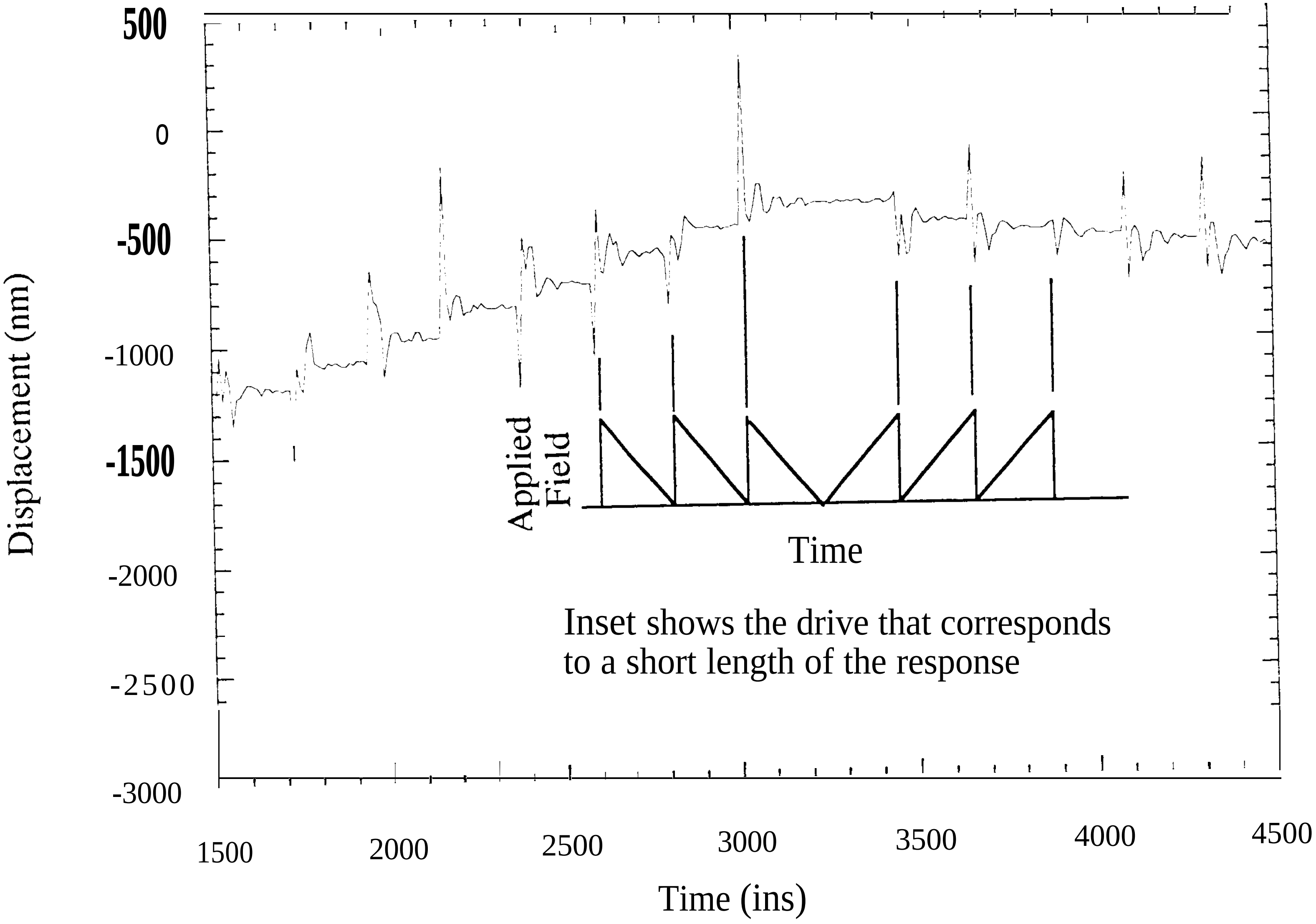

Control PC
Current
Source
Sawtooth Current
Readout PC
Vibrometer
Controller
Translator
Laser Beam
Polytec Laser Vibrometer

The driving current is delivered by a programmable current source, controlled by a computer running Labview. We detect the motion of the cart using a Polytec laser vibrometer. The vibrometer is based on a Mach-Zehnder interferometer and is capable of providing 8 nm resolution in a non-contact measurement.

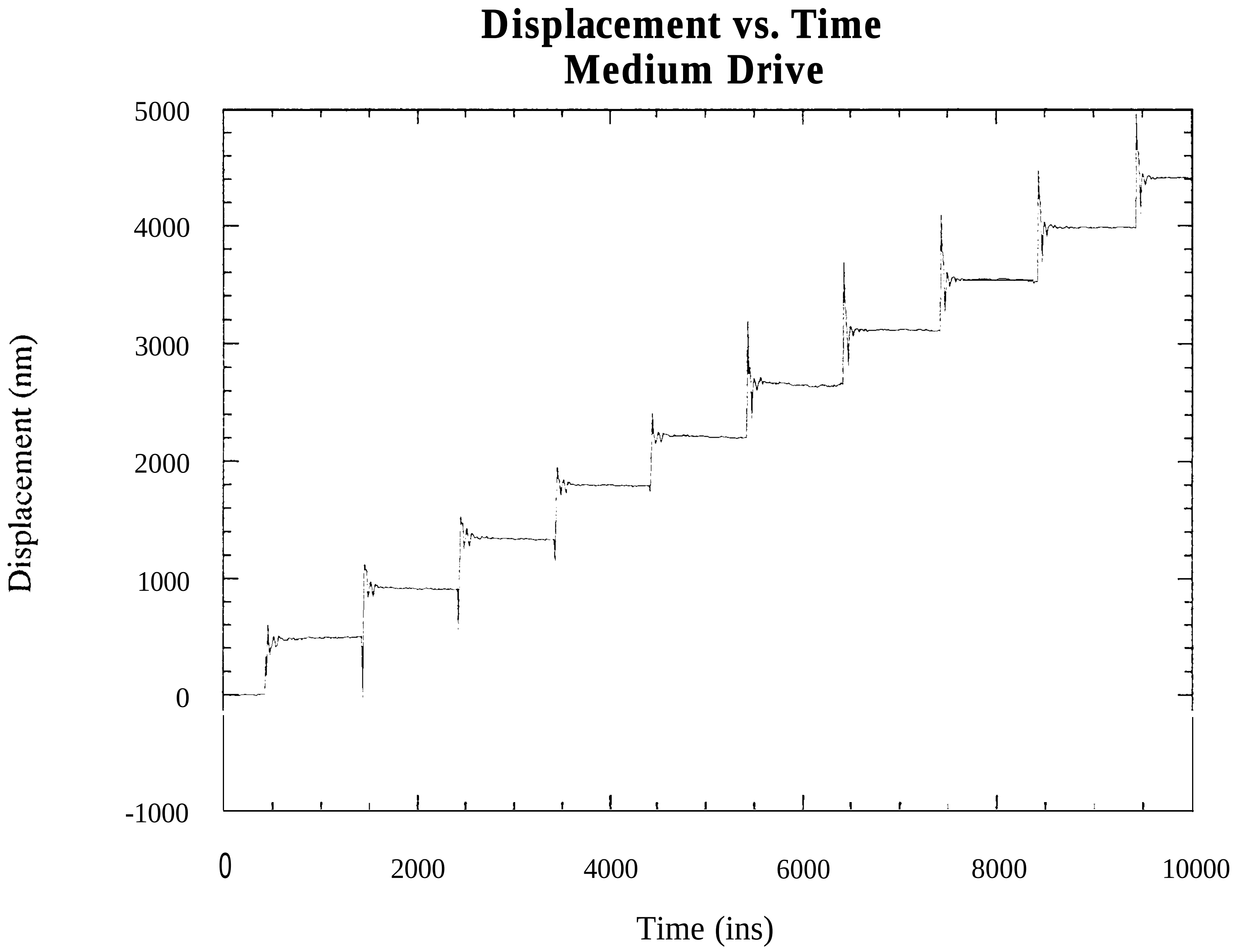
Observed Stepper Motion


Displacement vs. Time
No drive
1000
600
200
-200
-600
-1000
Displacement (nm)
0
2000
4000
6000
8000
10000
Time (ms)

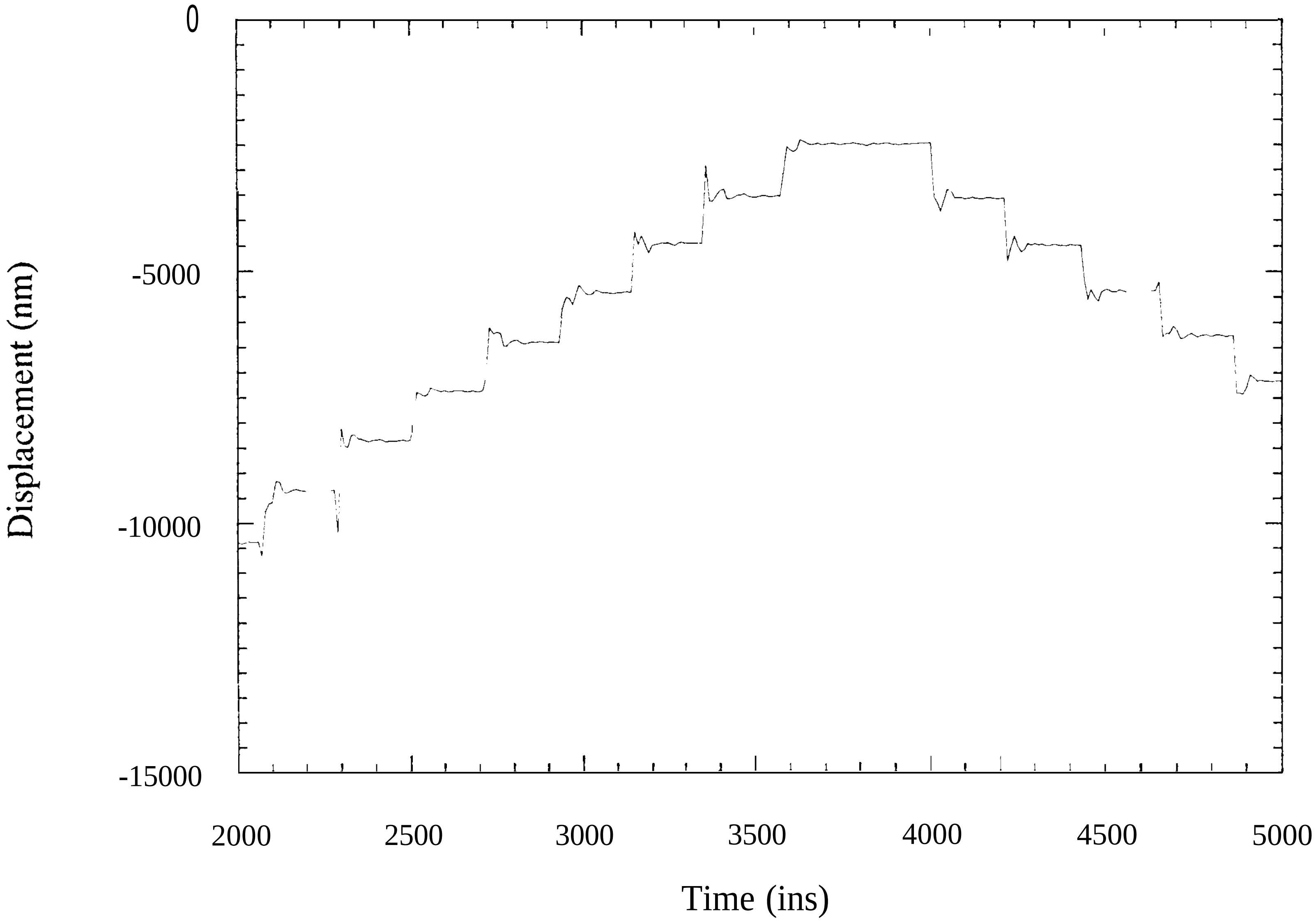
Displacement vs. Time
Low Drive, with reversal



Inset shows the drive that corresponds to a short length of the response


Displacement vs. Time
Medium Drive
5000
4000
3000
2000
1000
0
-1000
Displacement (nm)
0
2000
4000
6000
8000
10000
Time (ins)

Displacement vs. Time
High Drive



Future Work:

- Demonstrate a flight version for moving optical elements in space experiments,-using a magnet to provide force to hold the stepper against the rails.

- Replace room-temperature crystal with a lower-temperature, higher-performance Tb_xDy_{1-x} crystal, allowing reduction in size with increased large-step performance.

- Develop a magnetostrictively actuated cryogenic valve for superfluid helium applications [1].

- Develop a magnetostrictively-actuated optical filter wheel for low-cost space missions.

- Use the existing cryogenic dilatometer setup at JPL in collaboration with materials researchers to develop high performance magnetostrictive materials [5].

References

[1] Inseob Hahn, M. Barmatz, A. Clark, “A New Liquid Helium Low Temperature Valve Using a Magnetostrictive Actuator,” Mat. Res. Sot. Symp. Proc. 360, 253 (1995).

[2] E. du Tremolet de Lacheisserie, “Magnetostriction: Theory and Applications of Magnetoelasticity,” (CRC Press, Ann Arbor, 1993).

[3] A. E. Clark, M. Wun-Fogle, J. B. Restorff, and J. F. Lindberg, “Magnetostriction and Magnetomechanical Coupling of Grain Oriented $Tb_{0.6}Dy_{0.4}$ Sheet,” IEEE Trans. Magn. 29, 3511 (1993).

[4] R. Curtis, C. Pearson, P. Gaard, and E. Ganz, “A compact micropositioner for use in ultrahigh vacuum,” Rev. Sci. Instrum. 64,2687 (1993).

[5] R. G. Chave, T. A. J. Wiseman, M. B. Barmatz, and Inseob Hahn, “A Facility for Interferometric Measurement of Linear Displacement in Actuators and Calibration of Sensors at Cryogenic Temperatures Between 4.2 K and 77 K,” SPIE Proc. 2865-10, 41st Annual Meeting (1996).