

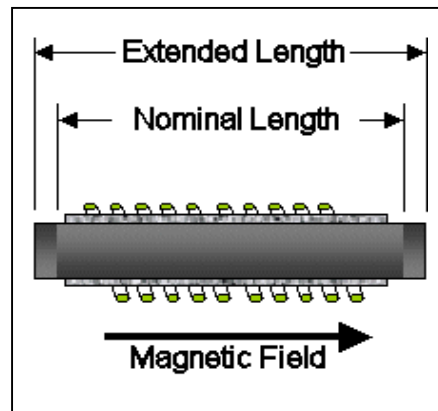
# Magnetic Smart Materials: Magnetostrictor Technology

*Energen is a pioneer in motion control solutions based on magnetic smart materials (MSM), materials that change shape when exposed to magnetic field. This shape change is called magnetostriction. Energen develops and manufactures motion control products including standard and custom actuators, linear stepper motors, valves and other precision systems*

## Magnetic Smart Materials MSMs

Magnetostriction is a dimensional change of a magnetic smart material (MSM) caused by a change in its magnetic state<sup>1</sup> as is illustrated in Figure 1. Magnetostriction arises from a reorientation of the atomic magnetic moments. When the magnetic moments are completely aligned, saturation occurs after which increasing the applied magnetic field will produce no further magnetostriction. The amount of magnetostriction at saturation is the most fundamental measure of MSM material.

Figure 1 – Magnetostrictive strain results from an externally imposed magnetic field. The peak strain occurs when the material reaches saturation.



For applied fields below saturation, the magnetostriction is approximately linear. MSM devices become valuable to industry and science when they can be precisely controlled to repeatedly and reliably position objects within very close tolerances. Their linear behavior is the basis for the development of precision MSM devices including actuators, stepper motors, position sensors, valves and acoustic transducers. One advantage of MSM devices comes from the ability to provide a large force through a small displacement. The force capability of such a device depends on the Young's modulus of the magnetostrictor and its cross sectional area. Another advantage is that a MSM device can provide motion in both directions unlike a solenoid that can only pull and thus

<sup>1</sup>F. V. Hunt, *Electroacoustics, the Analysis of Transduction, and its Historical Background*, Harvard University Press, 1954, in paperback, American Institute of Physics Press, 1982.

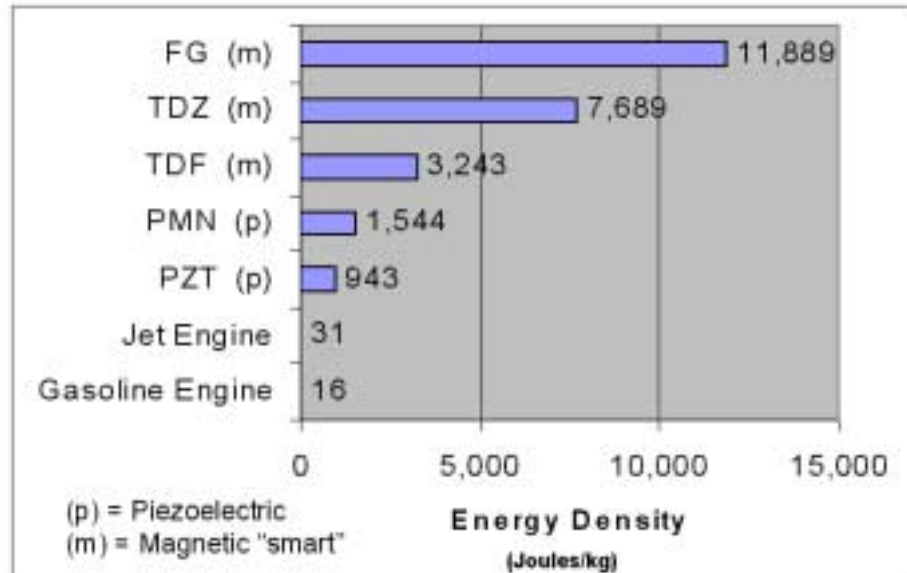
requires a separate return mechanism. Furthermore, having no moving parts, a MSM actuator is inherently a more reliable, and more precise positioning device.

The modern era of magnetostriction began in 1963 when strains approaching 1% were discovered in the rare earth materials, terbium (Tb) and dysprosium (Dy), at cryogenic temperatures. Since then many materials have been shown to exhibit magnetostrictive behavior including several materials at room temperature.

Currently, low temperature MSMs are being tested for a number of space and other low temperature applications. One example is NASA's Next Generation Space Telescope project.

Over the years, advances in magnetostrictive science have led to commercial viability. A new family of magnetic smart materials with high saturation strain and desirable mechanical properties demonstrate excellent performance for both room temperature and cryogenic actuator applications. Energen, Inc. uses these high performance MSMs in its actuators and linear stepper motors.

Table 1. The energy density of MSMs exceeds other available materials, delivering force per unit weight that exceeds that of jet engines.



Products based on the unique properties of MSMs can be used to solve problems simply, reliably, and at lower cost than was possible in the past. This applies to room temperature and also to uniquely harsh environments such as space.

The critical factors in creating useful MSM devices are:

- ◇ The overall quality and characteristics of the magnetic smart material.  
Today's MSM materials are crystals grown in a fashion very similar to electronic semiconductors. Careful manufacturing controls must be employed to produce the desired material suitable for the environment in which the MSM device is to be used.
- ◇ The manufacturing process.  
MSM devices must be manufactured to careful tolerances in order to achieve the desired levels of accuracy in the finished product. The shell, MSM rod, and magnetic coils must all be precisely fit to achieve an accurate device.
- ◇ The electronic controller.

It is critical to match the design of the electronic controller to the MSM rod material, geometry, and the working environment of the device to assure proper operation of the MSM device.

MSMs are used in products that include:

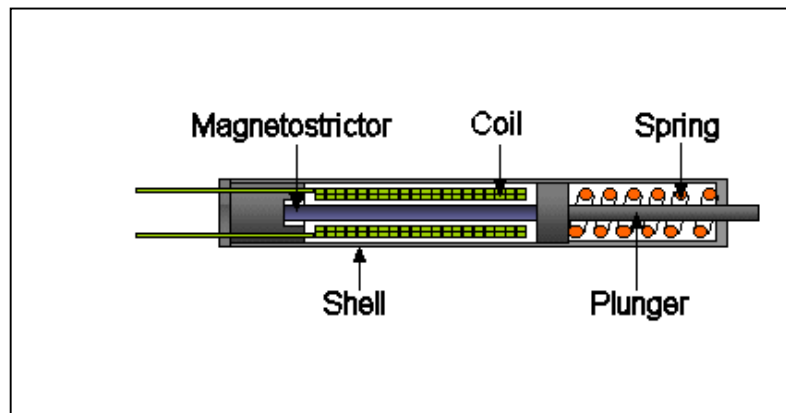
- ◇ Actuators that provide extremely precise change in length with high force and light weight.
- ◇ Linear Stepper Motors that deliver bi-directional, large range of motion with high force.
- ◇ Sensors that measure magnetic fields and stress take advantage of MSM's ability to produce magnetic changes under pressure.

## Linear Actuators

The ability to deliver extremely precise change in length with high force and light weight makes MSMs excellent component from which to build actuators. Properly manufactured and prepared these materials can precisely and repeatedly position actuators with a resolution as small as tens of nanometers. The basic design of a linear actuator based on MSM technology is shown in Figure 2. The actuator consists of a rod of MSM surrounded by a coil. The coil and rod are enclosed in a shell that protects them from damage and concentrates the coil's magnetic flux onto the MSM rod. At one end a spring holds a plunger in contact with the MSM rod. When the coil is energized, the MSM rod elongates, pushing the plunger. The elongation and, hence, position of the actuator is proportional to the current passing through the coil.

Depending on the temperature characteristics of the application, Energen products use coils wound from copper, conventional metallic (NbTi and Nb<sub>3</sub>Sn) as well as the newer ceramic "high temperature" superconductors.

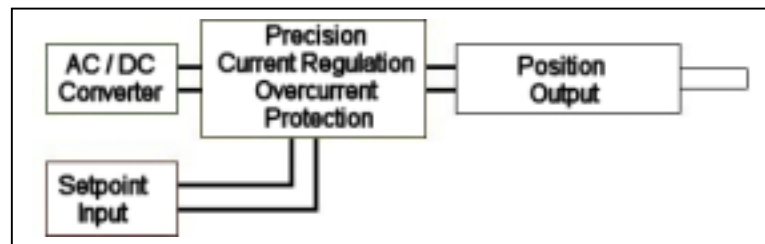
Figure 2 - Linear actuator geometry



## Actuator Electronics

Precision control of the drive current is critical to achieving precision positioning with the actuator. The drive electronics block diagram, shown in Figure 3, consists of a current source containing an internal feedback mechanism to stabilize the current at a given setpoint. A current sense element measures the current flowing through the coil and provides a feedback signal to a current regulator. The high forward path gain ensures current regulation within 10 ppm. The setpoint can be adjusted manually with an external signal or through an computer controlled interface.

Figure 3 – Linear actuator drive electronics.



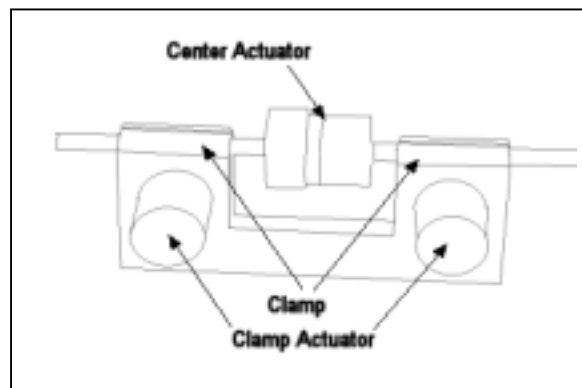
## Stepper Motor

MSMs allow the manufacture of linear stepper motors that provide bi-directional, large range of motion with high force. Their backlash and vibration-free operation can be used to hold position even when power is removed.

The linear stepper motor uses a set of three MSM actuators that enable it to move a rod forward or backward in a stepwise fashion. This motor can provide a large stroke of several millimeters. Variations on this design can yield an actuator with a stroke limited only by the length of the translating rod.

Figure 4 show an assembly drawing of the linear stepper motor. The rod is comprised of three segments assembled end to end. The center section is a MSM rod and is surrounded by a coil. Clamps on each side of the coil grab onto the rod. These clamps contain a MSM rod and a coil that when energized will cause the clamp to release its hold on the rod.

Figure 4 - Linear stepper motor.

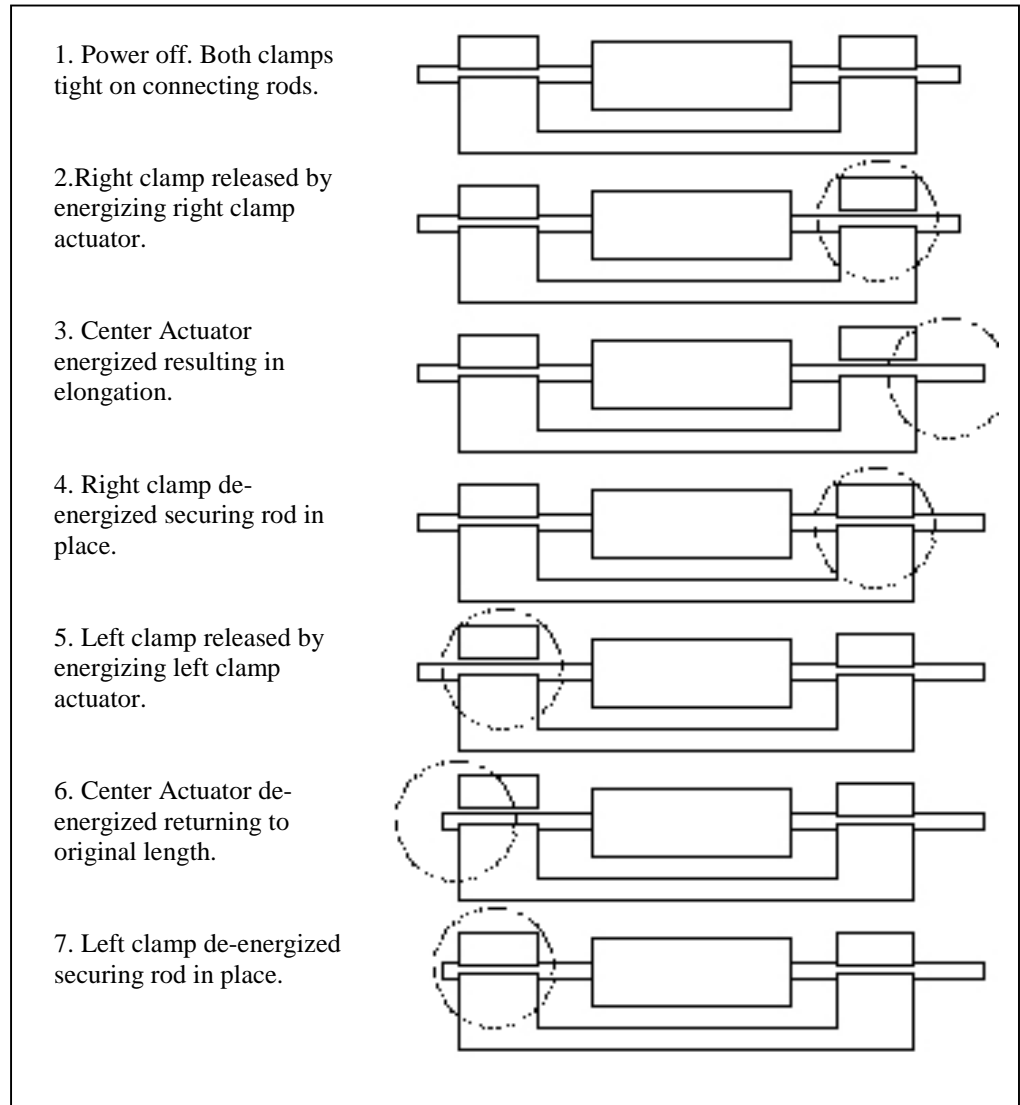


The linear stepper motor can be operated in one of two modes – in *stepper mode* or *fine tune mode*. *Stepper mode* operation is described in Figure 5. *Fine tune mode* operation

provides high positioning resolution. In this mode, the forward actuator is energized to release and the current in the center actuator is modulated thereby moving the forward end of the shaft proportionally. Under this operating mode, the positioning resolution is limited by the current regulation as in the shape control actuator.

Thus, this actuator is capable of providing a long stroke with high positioning resolution. It is capable of holding position with zero power dissipation since the clamp holds when no current is applied.

Figure 5 - The linear stepper motor uses a pair of clamps and a linear actuator to move a shaft in precision steps.

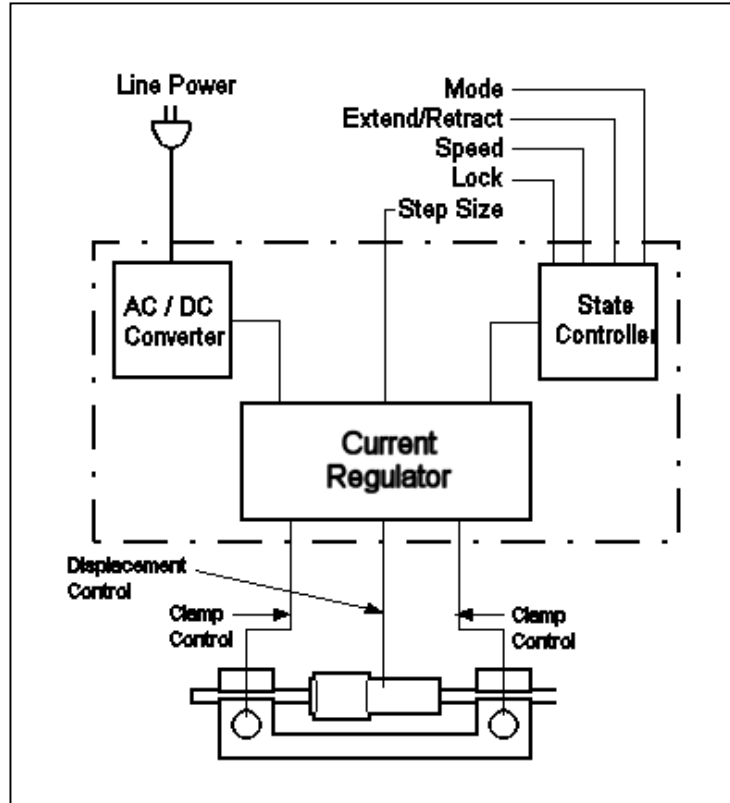


## Drive Electronics

Energen's electronics for the position control actuator includes a digital state control circuit that allows a wide range of operational flexibility. In addition to setting the operating mode (stepper or fine tune), the direction of motion, the step size and stepping frequency can be adjusted.

To achieve accurate stepping and fine-tuning, the current flowing through the center actuator is tightly regulated. The current regulator for the center actuator has an internal feedback loop that provides 10 ppm current regulation relative to a setpoint.

Figure 6 - The linear stepper motor is driven by electronics that gives precision positioning over a long range.



## Products

Energen's products consist of a family of standard actuators, custom stepper motors and electronic controllers for both. In addition the company engineers custom products that utilize magnetic smart materials. These include valves, precision optical devices, heat switches, and more.

Figure 7 - Energen linear actuators can be sized to the job, from miniature dimensions for use in lightweight arrays to actuators that can displace several tons.



Products built with MSMs solve some tough engineering problems with smaller and lighter devices than those built with piezoelectric materials. They also, uniquely, function at extreme environmental conditions. With their smaller size and weight, they open up new avenues of systems design in a number of areas such as the applications below:

- ◇ Active vibration control of low frequencies that, with other technology, require huge, heavy devices
- ◇ Vibration control in clean rooms that lubricants could contaminate
- ◇ Precision machining to reduce the vibration of the machine tool to arrive at finer tolerances
- ◇ Semiconductor lithography for dampening of vibration can increase throughput
- ◇ Airframe vibration control to increase vehicle life and reduce maintenance
- ◇ Precision flow metering for very fine control reducing fluctuations in the saturation or temperature
- ◇ Optical lens manufacture to eliminate final, manual steps necessary because of machine vibration
- ◇ Deliver motion control, especially in extreme environments
- ◇ Noise dampening for applications such as vehicle noise, increasing passenger comfort and safety