# Magnetic Shape Memory Alloy Actuator for Nano-Positioning

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## Background

Active or smart materials are substances that can change their properties in response to physical disturbances. Many of these materials are limited to small strains. Most piezoelectric and magnetostrictive materials have a high stiffness, requiring a strong force to induce any strain. Magnetic Shape Memory Alloys (MSMAs) have been gaining attention since they perform better than current active materials used for precision actuators. MSMAs have large strains over 10%, which is a whole order of magnitude better than other active materials. They have lower stiffness, higher bandwidth, higher accuracy and require less power compared to other materials. They require no lubrication and can run at cryogenic temperatures, thus allowing them to function in space for millions of cycles. Since the ferromagnetic material is activated by a magnetic field which easy and fast to apply, MSMAs have a much higher response time. This game-changing technology that will reduce costs by eliminating expensive sensors.

## Material Properties

| | |
|---|---|
| Material | NiMnGa Single Crystal |
| Response | Up to 1 to 2 kHz |
| Force Density | About 2 Mpa |
| Work Output | Max 100 kj/m$^3$ |
| Modulus of Elasticity | 20 – 200 GPa |
| Magnetic Field | <0.8 Tesla |
| Upper Temperature Limit | Transformation from martensitic to austenite at 70$^o$C |

Figure 1: Table of material properties

The theoretical maximum strain is given by the equation:

$$\varepsilon_{max} = 1 - \frac{c}{a}$$

Where c is the short easy axis and a is the long axis.
The typical strain achieved is around 6% but strains over 10% have been seen.
Figure 1 shows the predicted properties of the alloy. Once the material has been tested in the test set-up being developed at Goddard, the specific values will be know.

## Martensitic Structure

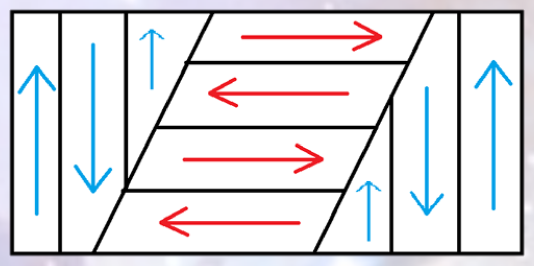

Figure 2: Variants in MSMA

In the martensitic phase, MSMA is composed of different areas with alternating orientations, called the twin variants.

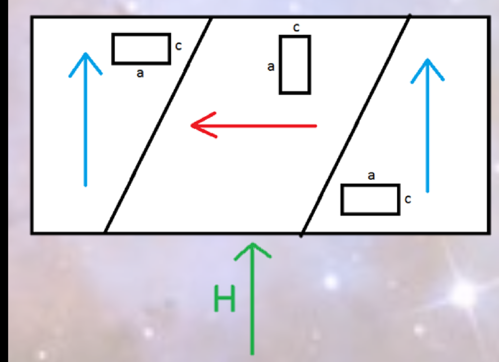


Figure 3: MSMA in small magnetic field

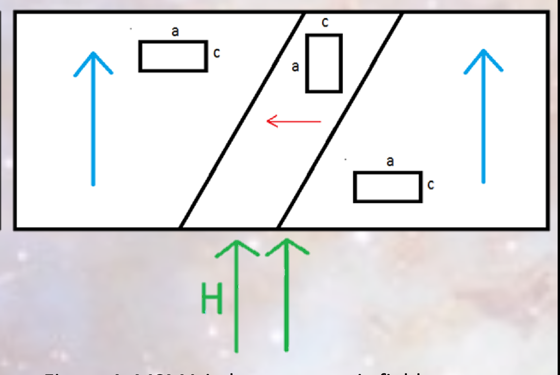


Figure 4: MSMA in large magnetic field

When a small magnetic field is applied to the material, each variant forms a single orientation of the easy axis of magnetization or the shorter c-axis. This boundary between the variants is called the twin boundary.
When a stronger magnetic field is applied to the material, there is growth in the variants aligned with the field. The twin boundaries move causes an overall lengthening of the sample.

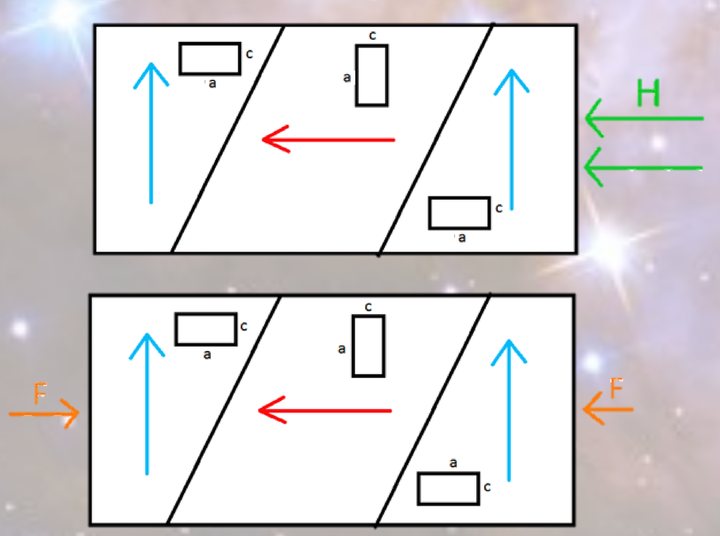


Figure 5 top: MSMA with perpendicular magnetic field
Figure 5 bottom: MSMA with external restoring force applied

When the field is removed, the elongation is self-supported until an external force or magnetic field at 90° to the original field is applied to restore the original shape.

## Actuator Properties

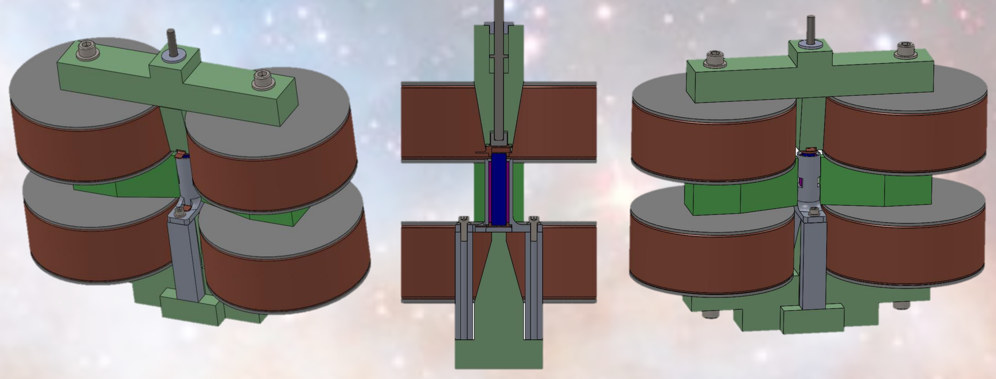

Figure 6: Top, side and bottom view (from left to right) of MSMA actuator

The precision actuator uses four coils to direct magnetic flux through the MSMA sample. This design is inspired by the field-inverting concept.

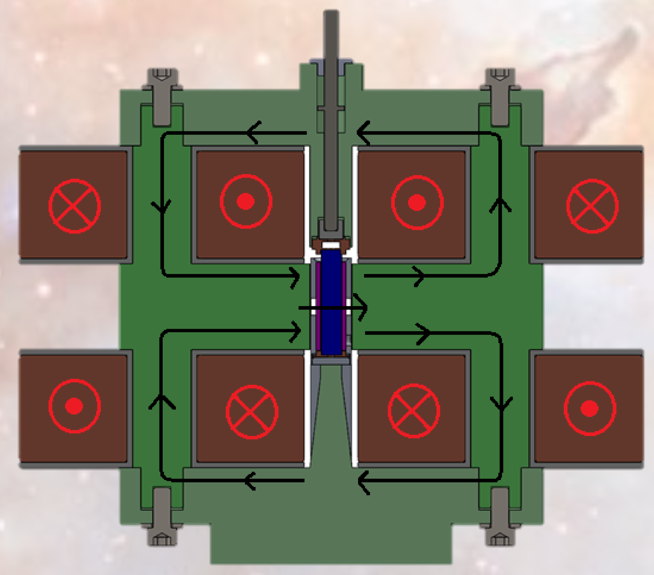

Figure 7: Actuator in elongation field

To elongate the sample, the coils must drive a magnetic field perpendicular to the axis of motion. Figure 7 shows the coil configuration needed to generate this field.

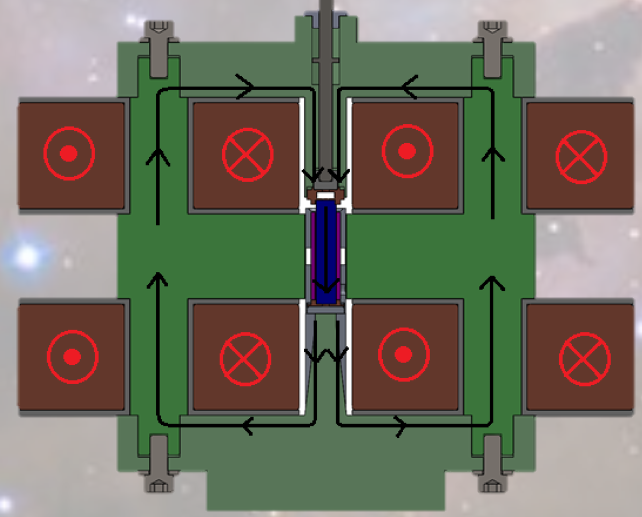

Figure 8: Actuator in contracting field

Figure 8 shows the coil configuration needed to restore the sample. The coils must drive a magnetic field parallel to the axis of motion. generate this field. To do this, two of the coils must be inverted.

## Testing Set-up and Procedure

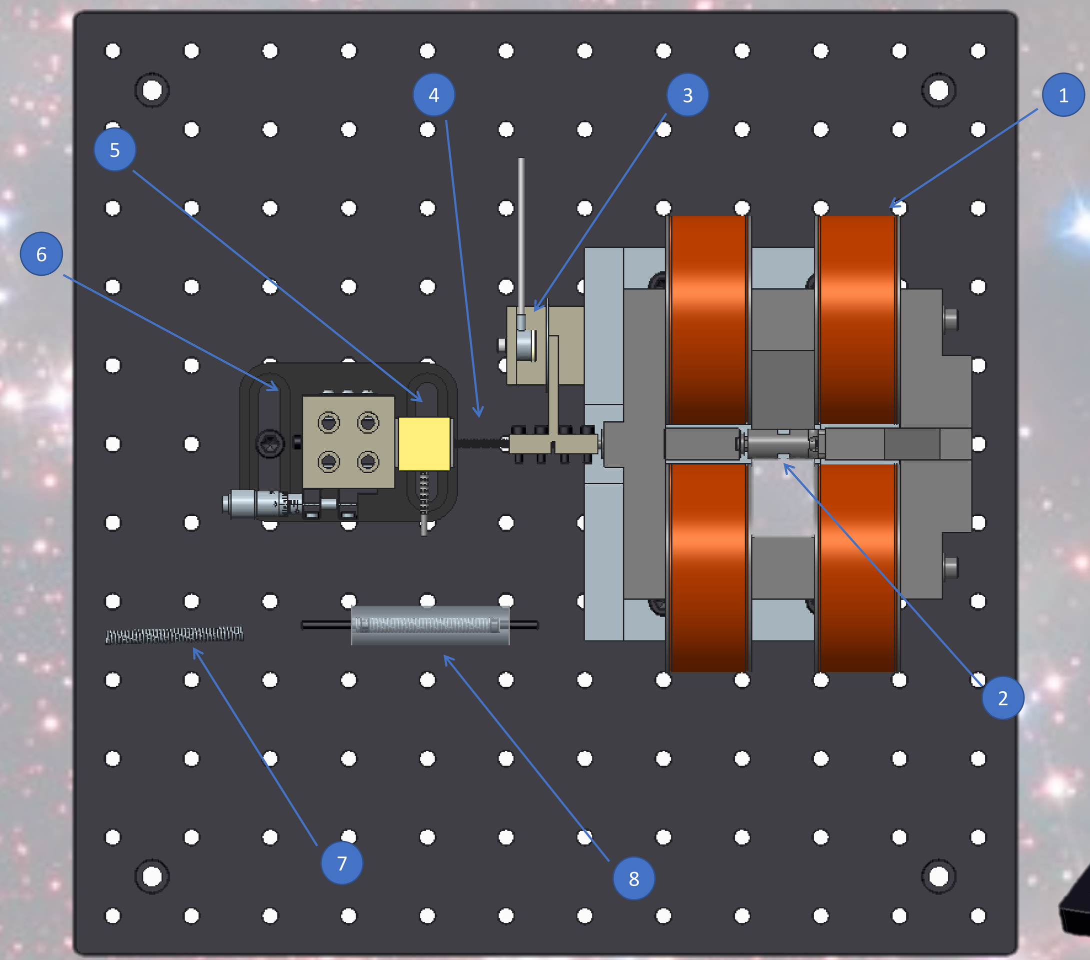

Figure 9: MSMA test stand parts drawing

The MSMA Test Stand:

1. MSMA Actuator
2. Gauss-Meter Probe
3. Eddy Current Displacement Sensor
4. Rigid Link
5. Load Cell
6. Micrometer Stage
7. Tension Spring Link
8. Compression Spring Link

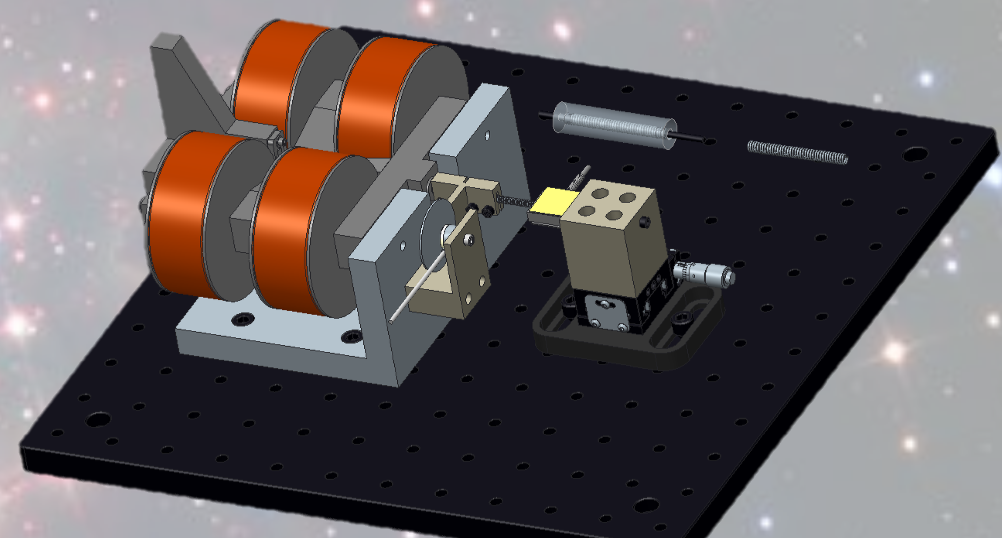

Figure 10: MSMA test stand

### Test Procedure:

1. Force in relation to current and displacement
   A current will be induced to elongate the sample to a specific displacement. The load cell will measure the force created by the sample using either a rigid link, tension spring link or compression spring link. The load cell and micrometer stage can be moved to vary the distance between the alloy and where the force measurement is being taken.
2. Magnetic Field in relation to current and displacement
   A current will be induced to elongate the sample to a specific displacement. The magnetic field will be measure using a Gauss-Meter through the probe access ports on both sides of the sample. Similarly to the force measurement, the load cell and micrometer stage can be moved to vary the distance the actuator moves.
   The theoretical relation between the current used to drive the coils and the magnetic field used for actuation comes from the magnetic-circuit equivalent of Ohm's Law:
   $$\mathrm{MMF} = \Phi R = NI$$
   Since magnetic circuits tend not to be as linear as electrical circuits, the magnetic fields need to be measured to confirm the performance of the magnetic structure.
3. Displacement in relation to time with a constant current and force load
   A load force will be applied to the sample to simulate a typical application the actuator will be used in. The Eddy Current Displacement Sensor will measure the displacement of the sample when a constant current and force load is applied. This will help determine the dynamic properties of the actuator.
4. Displacement in relation to current and temperature
   MSMA exhibits a hysteresis motion cycle similar to the one shown in figure 11. This can create problems when trying to design a controller to drive the actuator. By measuring the hysteretic behavior of the alloy at various temperatures and currents, a better control algorithm can be made. This measurement will also test for the best operating temperature to produce the maximum strain.

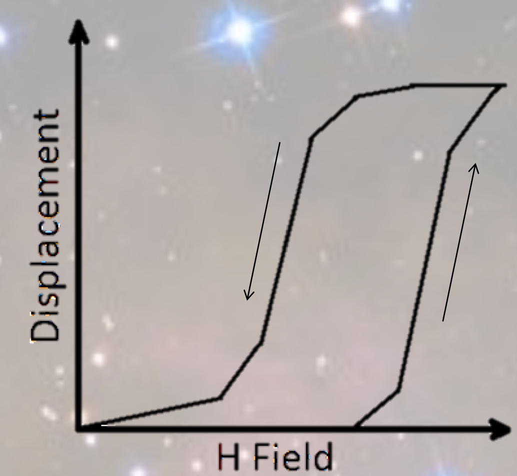


Figure 11: Hysteresis motion cycle of alloy

## Applications

A large strain and fast response time make MSMAs very applicable in range of spaceflight instrumentation supporting all of the science directorates at Goddard. The alloy is versatile and can be used in instruments such as:

- Linear motors
- Beam-steering mechanisms
- Mass spectrometers
- Laser altimeter cavities
- Mircopump systems
- Vibration Isolation
- Sonar devices
- Aero flaps
- Vibration energy harvesters
- Breaker Switch

Potentially, this new alloy could replace current active materials being used in spaceflight instruments.

## Acknowledgements and References

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