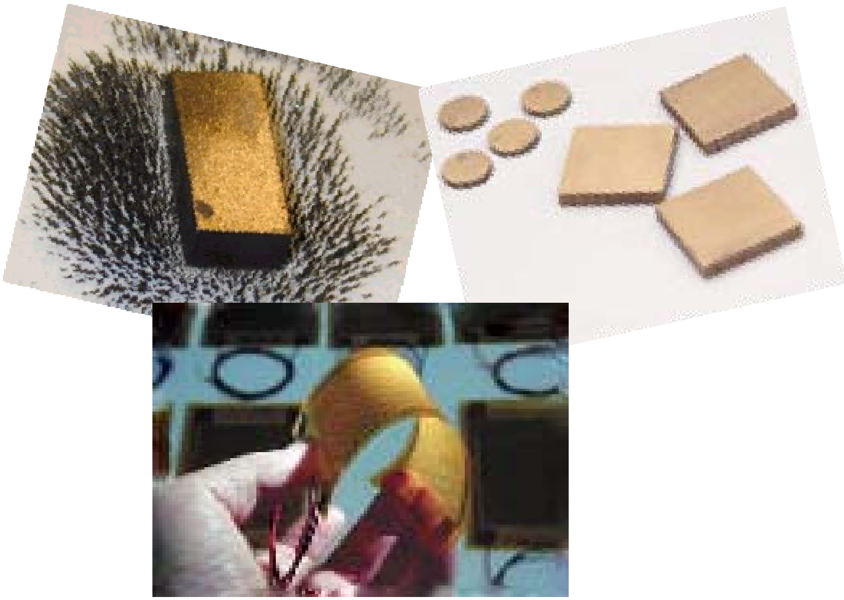
Overview of Smart Materials



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LECTURE 7:

Smart Muscles based on Shape Memory Alloys and Electro-active Polymer

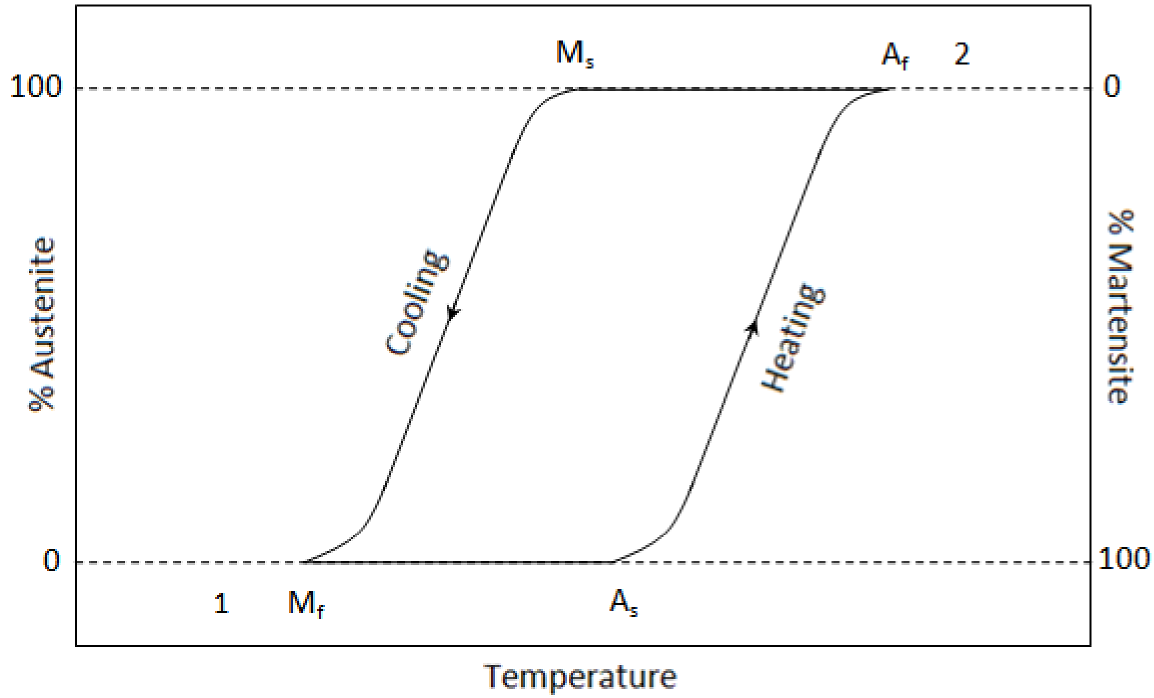
Organization

- What is Shape Memory Effect?
- Metallic alloys that show Shape Memory Effect
- The Constitutive Relationship
- Actuators Developed using SMA
- Sensors Developed using SMA
- Future of SMA

What is Shape Memory Effect?

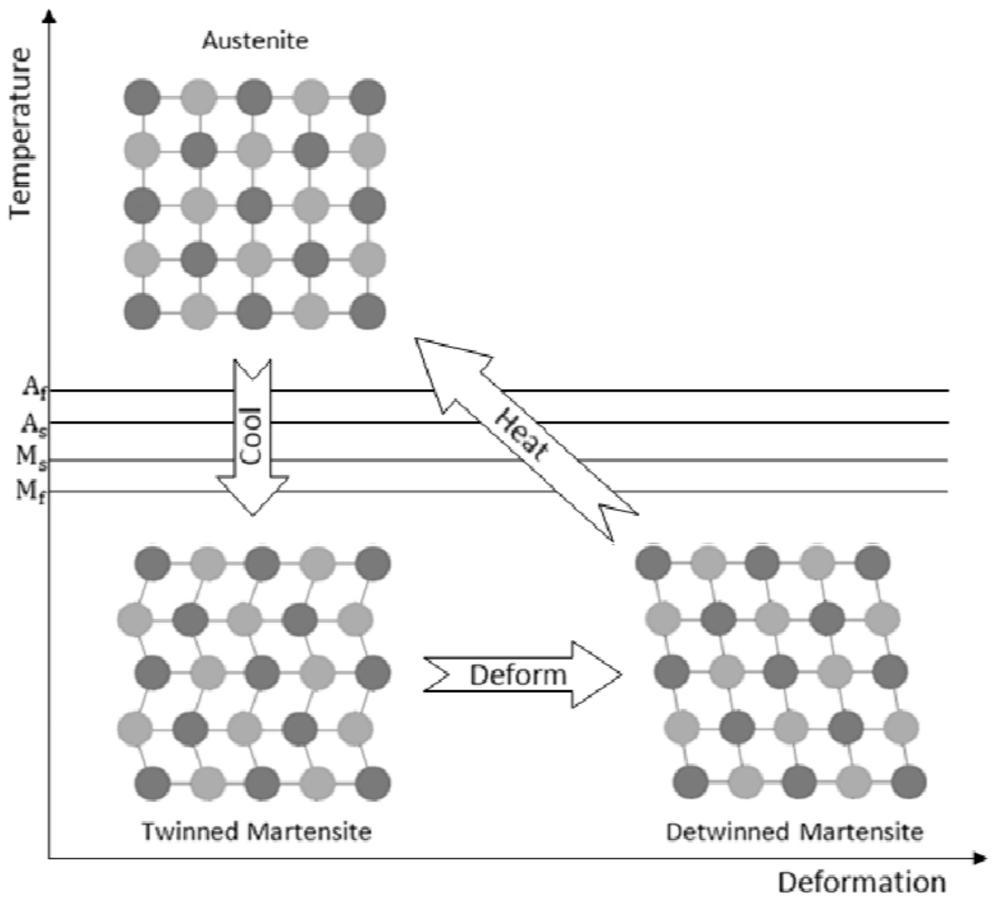
- There are two common shape memory effects - One Way and Two Way effects.
- In the case of One Way effect, the material always remembers the shape at Parent State (Austenite Phase)
- In the case of Two Way effect, the material is trained to remember two shapes, one at the Parent Austenite phase and the other at the Martensite Phase

Hysteresis Curve of SMA

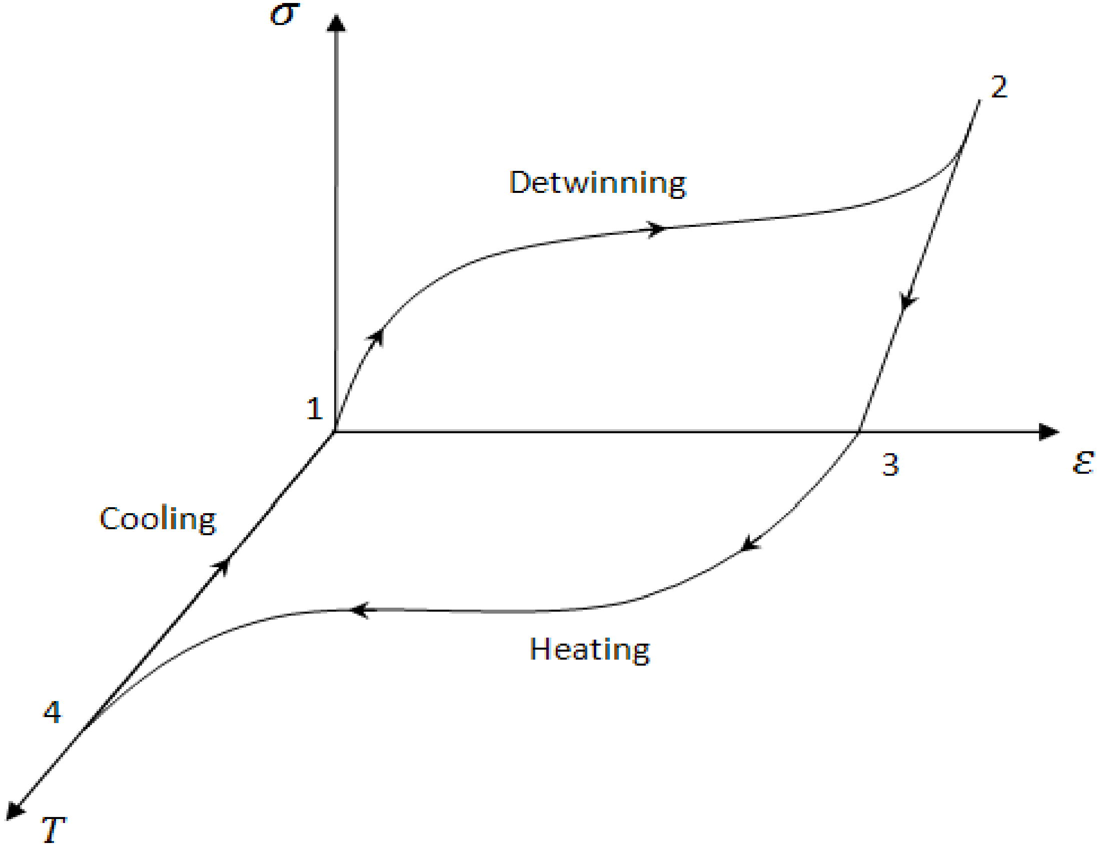


M_s: Martensite start temperature, M_f: Martensite finish temperature, A_s: Austenite start temperature and A_f: Austenite finish temperature

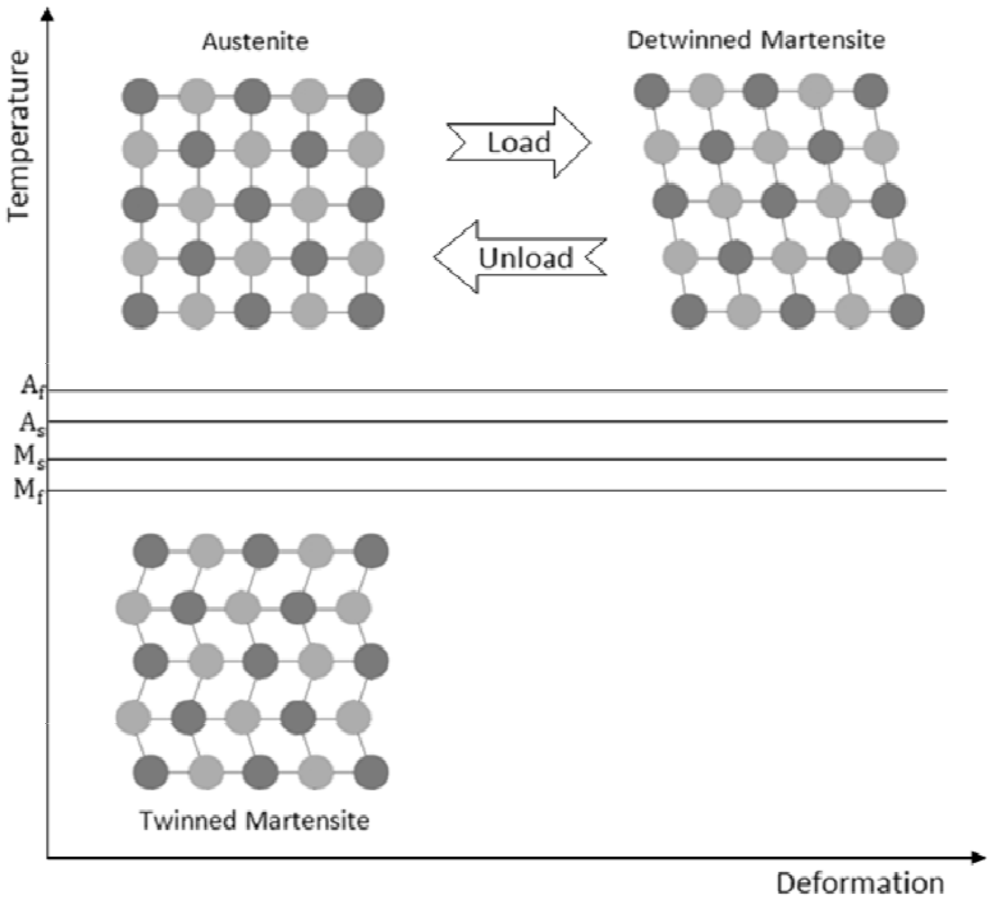
Crystal Structure Depicting SME



One-Way SME



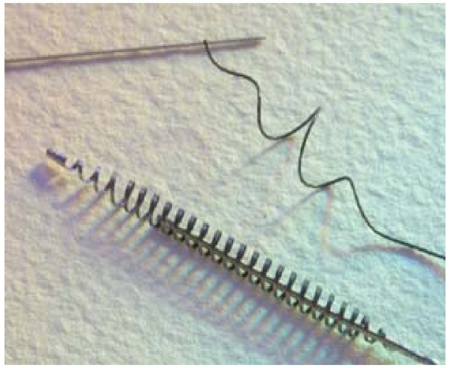
Pseudo-elasticity



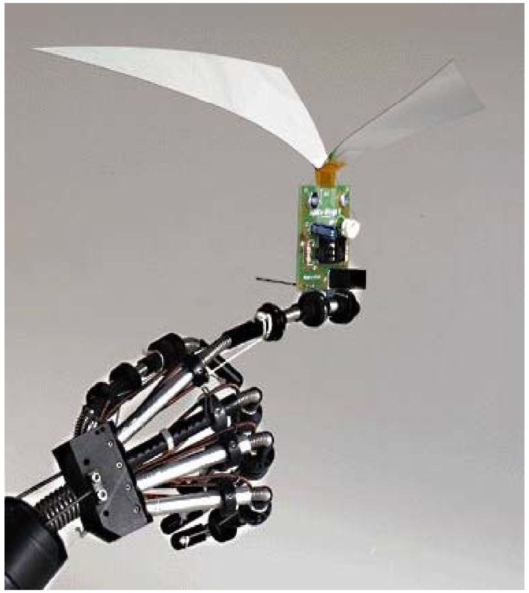
Metallic Alloys that show SME

- SME was first observed in 1932 in Silver Cadmium Alloy
- Three types of SMA are currently popular
  - Cu Zn Al
  - Cu Al Ni and
  - Ni Ti
- The last one is commercially available as NiTiNOL (NOL – Naval Ordinance Laboratory)

Space Application of SMA:



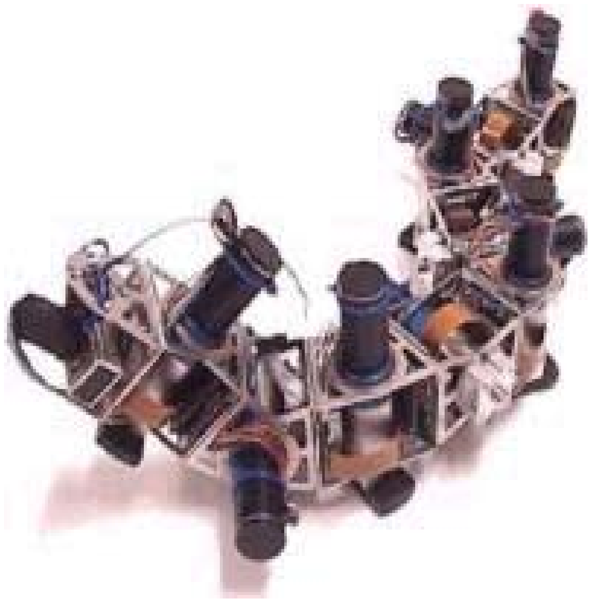
- Control of aerodynamic surfaces
- Micro-coils for vibration isolation
- Grasping by robotic fingers
- Space exploration: rock splitting by ESA
- Nitinol filter
- Deployment of Solar Array Hinges (EMC)



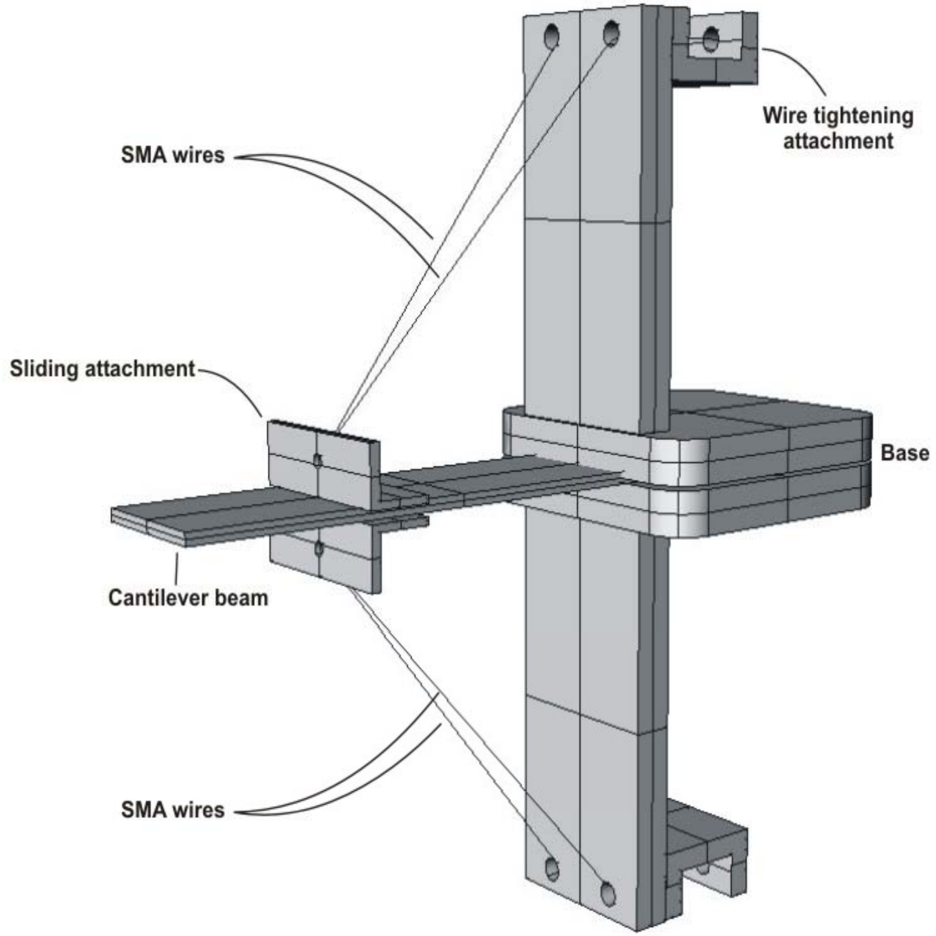
Reconfigurable Systems:

Reconfigurable systems composed of modular units have been investigated intensively for their versatility, flexibility, and fault-tolerance.

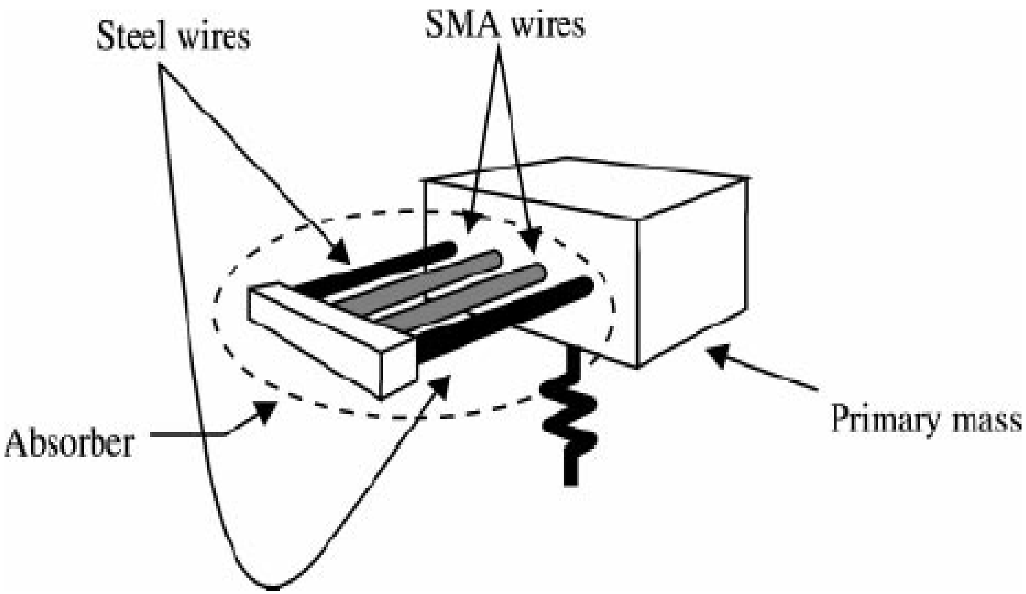
Conventional electric motors used in these studies impose a limitation on miniaturization of the size of the system, due to their poor power/weight ratio



Vibration generation using SMA wires



SMA based Tuned Mass Damper



SMA Constitutive Relationship

- *Phenomenological Model*
- *Based on experimentally observed phase kinetics of SMA*
- *First model developed by Tanaka, later modified by Rogers et al. and finally by Brinson (1993)*
- *Constitutive relation*

$$\sigma - \sigma_0 = D(\xi)\varepsilon - D(\xi_0)\varepsilon_0 + \Omega(\xi)\xi_s - \Omega(\xi_0)\xi_{s0} + \Theta(T - T_0)$$

$$D(\xi) = D_M + (1 - \xi)D_A = Elastic\,Modulus$$
$$\Omega(\xi) = -\varepsilon_L D(\xi) = Transformation\,Modulus$$
$$\Theta = Elastic\,Thermal\,Coefficient$$

Brinson Model

- *Phase Kinetics*
- *Reverse Transformation: Conversion of Martensite to Austenite*

  for $T > A_s$ *and* $C_a\left(T - A_f\right) < \sigma < C_a\left(T - A_s\right)$

$$\xi = \frac{\xi_0}{2}\left\{\cos\left[\frac{\pi}{A_f - A_s}\left(T - A_s - \frac{\sigma}{C_a}\right)\right]\right\}$$

$$\xi_s = \xi_{s0} - \frac{\xi_{s0}}{\xi_0}\left(\xi_0 - \xi\right)$$

- *Forward Transformation: Conversion of Austenite to Martensite*

  for $T > M_s$ *and* $\sigma_s^{cr} + C_m(T - M_s) < \sigma < \sigma_f^{cr} + C_m(T - M_s)$

$$\xi_s = \frac{\left(1 - \xi_{s0}\right)}{2}\cos\left\{\frac{\pi}{\sigma_s^{cr} - \sigma_f^{cr}}\left[\sigma - \sigma_f^{cr} - C_m\left(T - M_s\right)\right]\right\} + \frac{\left(1 + \xi_{s0}\right)}{2}$$

$$\xi_t = \xi_{t0} - \frac{\xi_{t0}}{1 - \xi_{s0}}\left(\xi_s - \xi_{s0}\right)$$

Beam and SMA Specifications

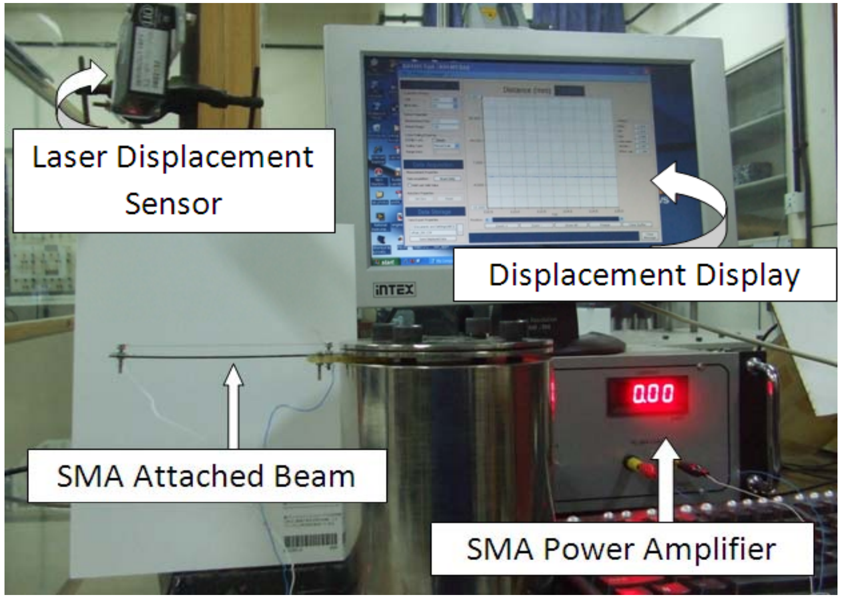
SMA: Flexinol 125µm from Dynalloy Inc.

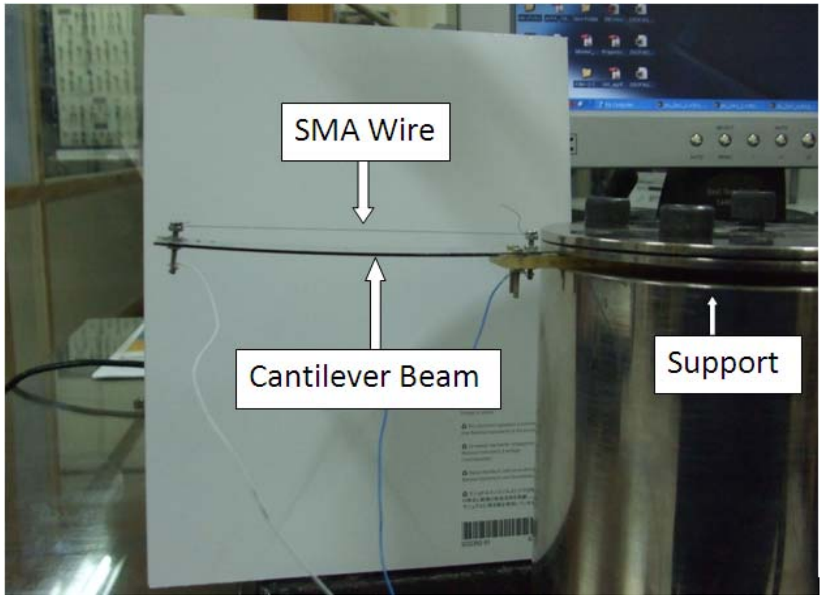
Moduli	Transformation Temperature	Transformation Constants	Maximum residual strain
$D_a = 75GPa$ $D_m = 28GPa$ $\Theta = 0.55MPa/^oC$	$M_s = 44.99^oC$ $M_f = 25.08^oC$ $A_s = 65.73^oC$ $A_f = 83.50^oC$	$c_m = 20MPa/^oC$ $c_a = 28MPa/^oC$ $\sigma_s^{cr} = 70MPa$ $\sigma_f^{cr} = 170MPa$	$\varepsilon_L = 0.06$

Beam Properties

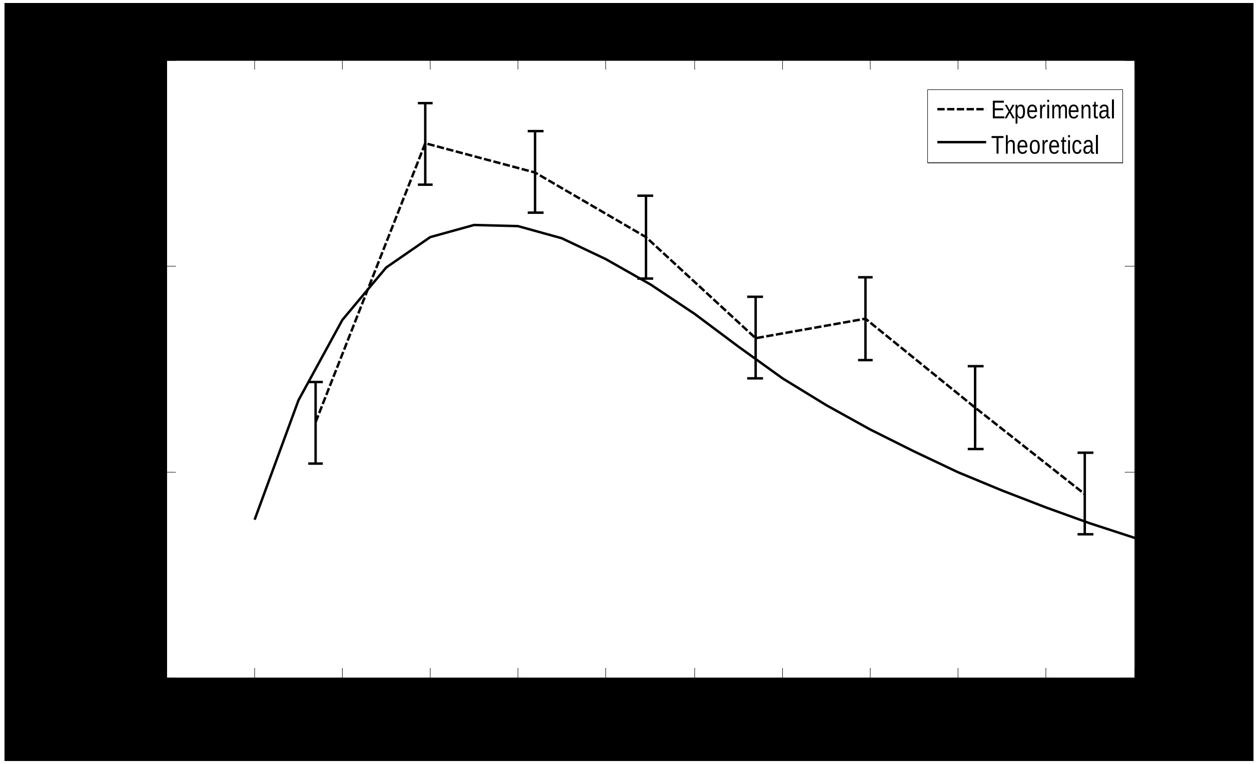
No.	Beam Material	Elastic Modulus	Beam Thickness	Beam Width	Flexural Rigidity
1	Acrylic	1.78	1.1	15.5	$3.06e^{3}$
2	Acrylic	2.38	1.8	10	$1.16e^{4}$
3	Acrylic	2.38	1.8	18	$2.08e^{4}$
4	Acrylic	2.38	2.8	11	$4.78e^{4}$

Experimental Setup



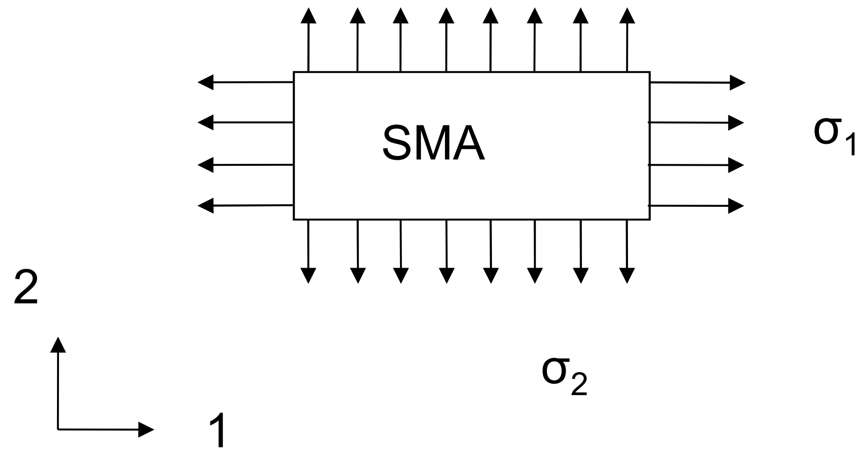


The effect of change of offset distance on deflection by an SMA wire



Variation of end deflection with offset for Beam-2 : [redacted]

Ref: A. Banerjee, J. Badothiya, B. Bhattacharya and A. K. Mallik, "Optimum discrete location of Shape memory alloy wire for enhanced actuation of slender fixed-free beam", ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 2008.



➢Engineering Model of SMA (Equivalent Coefficient of Thermal Expansion / **ECTE**) is recently developed by Turner based upon Nonlinear Thermo-Elasticity.

➢The most fundamental feature of ECTE model of SMA is the axial constitutive relation for SMA in which non-mechanical strain is represented by effective thermal strain.

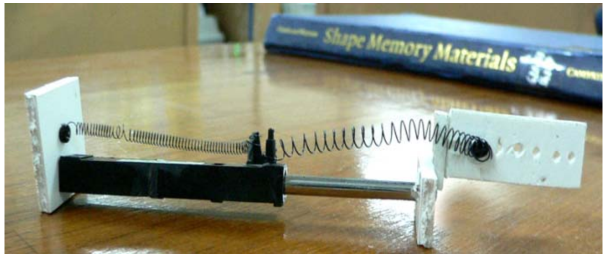
The fundamental equation developed for the SMA element in the longitudinal direction is:

$$\sigma_1 = E_1(T)\left[\varepsilon_1 - \int_{To}^{T} \alpha_1(T)dT\right]$$

Here, σ_1 is the stress induced in SMA, E_1 is the Young's modulus, ε_1 is total axial strain in SMA and α_1 is the effective coefficient of thermal expansion (ECTE).

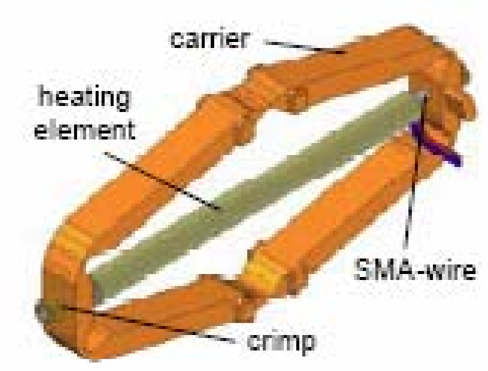
actuators developed::1

- natural length of SMA spring 60mm
- bias spring length 45 mm
- displacement achieved 12mm

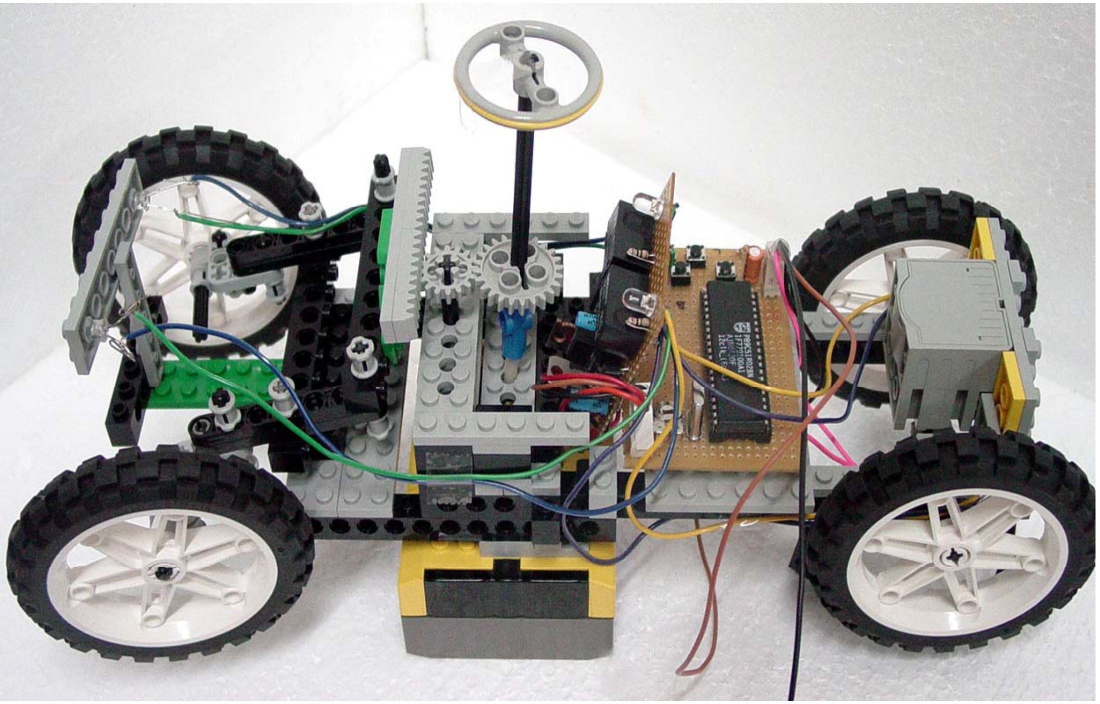


Actuator in action

Amplified SMA Actuator

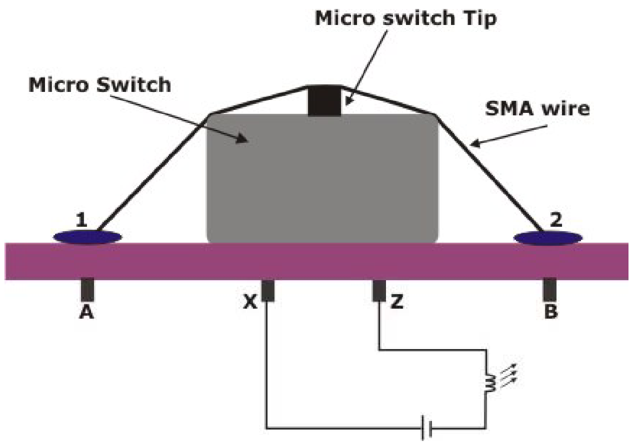


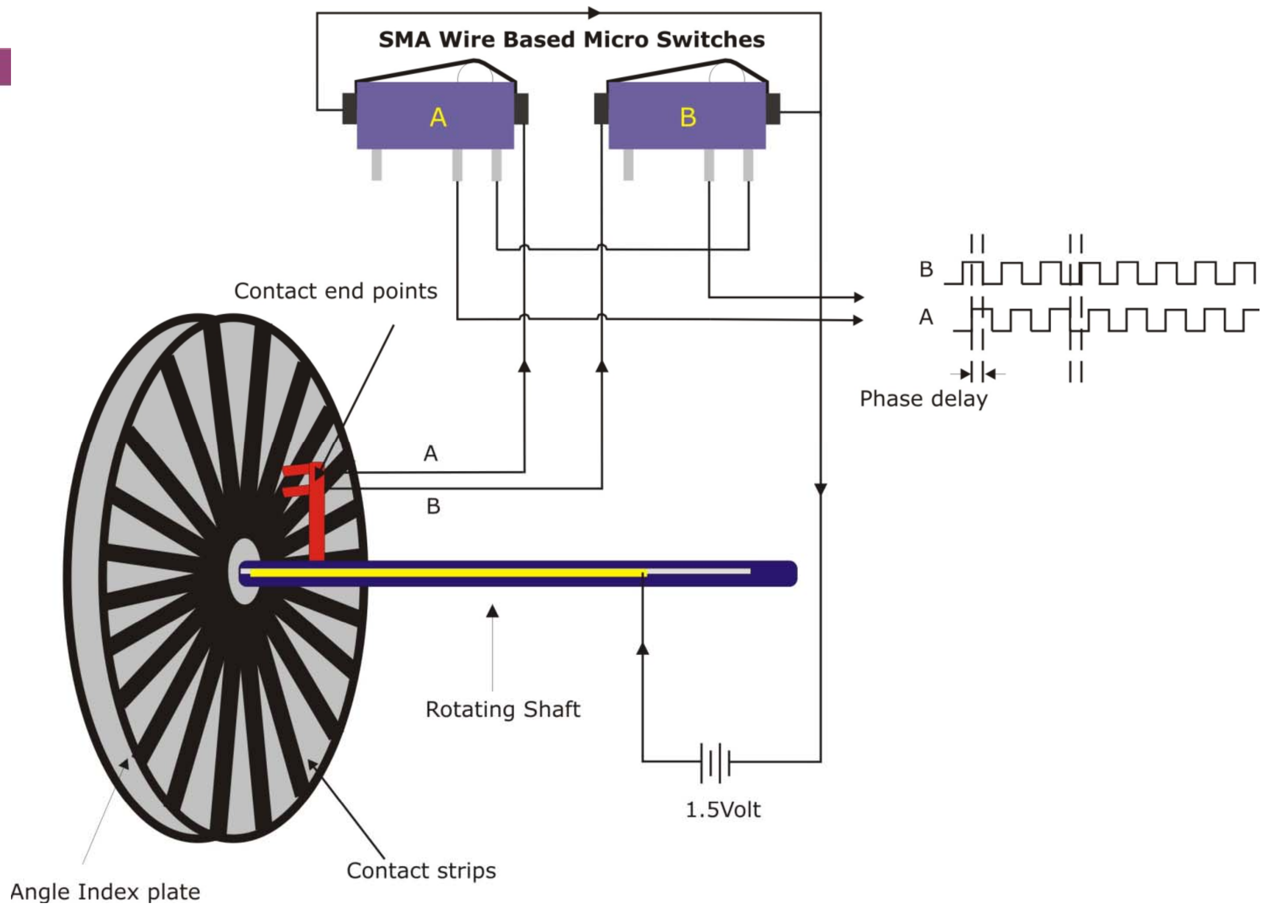
mechamatronics model developed:



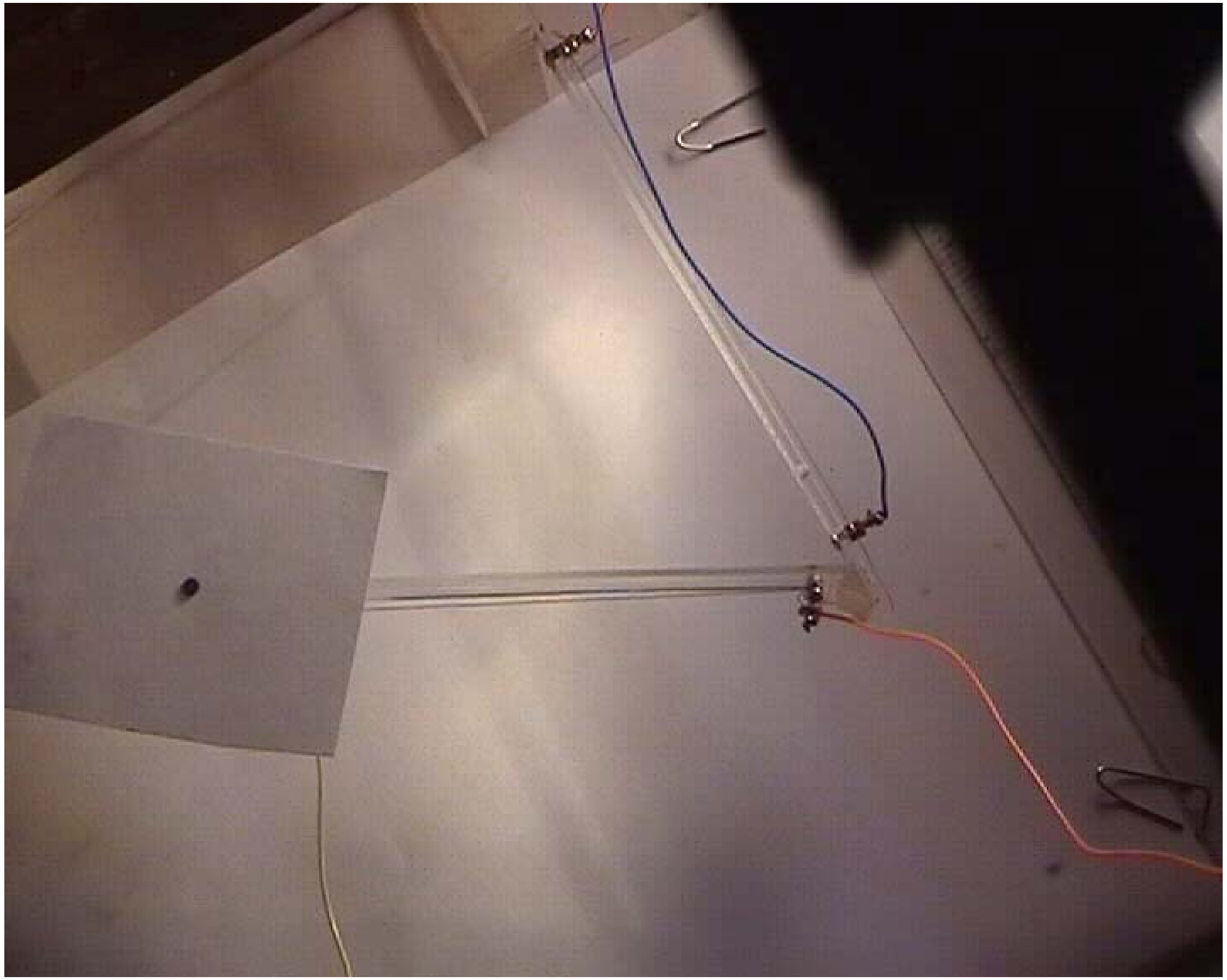
Ready to take a SMArt turn

An SMA based Rotational Sensor





An SMA based Trajectory Tracking System



References

- A. Banerjee, J. Badothiya, B. Bhattacharya and A. K. Mallik, "Optimum discrete location of Shape memory alloy wire for enhanced actuation of slender fixed-free beam", ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 2008.

END OF LECTURE 7