ShanghAI Lectures 2013

Pisa, November 21, 2013

Soft robotics and Bioinspiration II

Soft actuators design method

Matteo Cianchetti

The BioRobotics Institute - Scuola Superiore Sant'Anna, Pisa, Italy

How to turn octopus in OCTOPUS

The challange

Octopus vulgaris

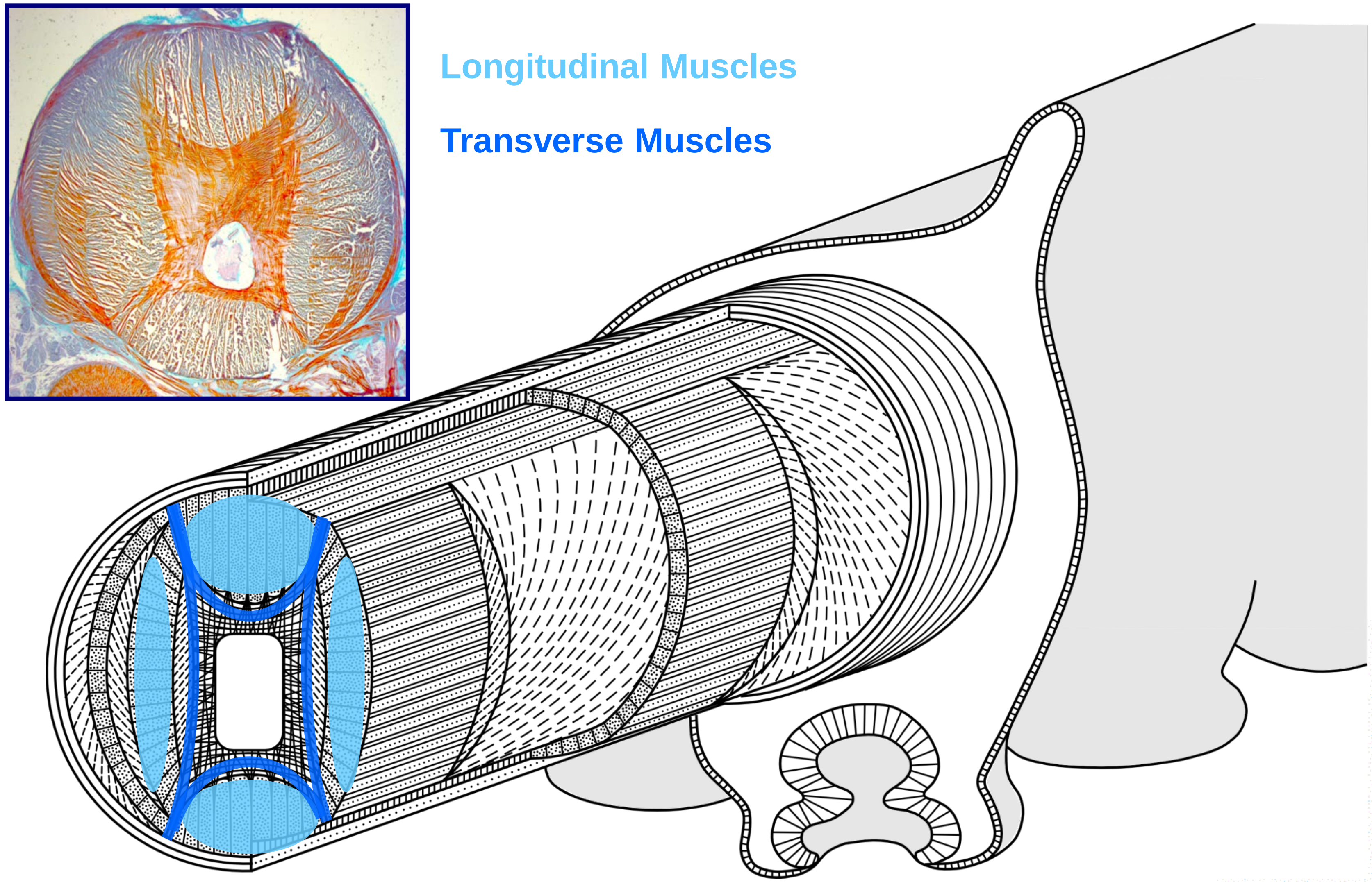
(phylum *Mollusca*, class *Cephalopoda*)

- No rigid structures:
  - virtually infinite number of DOF
  - all-direction bending
  - capability to squeeze into small apertures
    (same size of their brain capsule – Ex: 1-inch hole)
- Variable and controllable stiffness
- Manipulation and locomotion capabilities

From biology to bioinspired robot

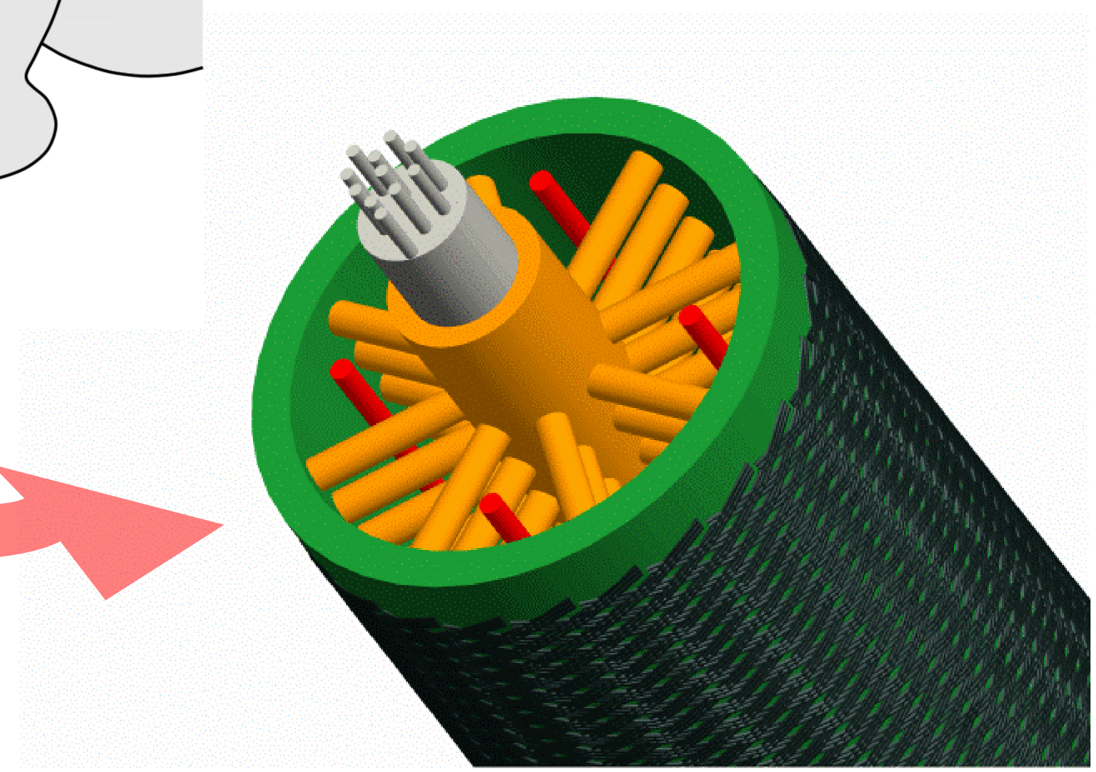
Longitudinal Muscles

Transverse Muscles



Muscular Hydrostat:
Constant volume during contractions

The muscular system serves as a modifiable skeleton and allows the transformation of force into motion



What kind of technology?

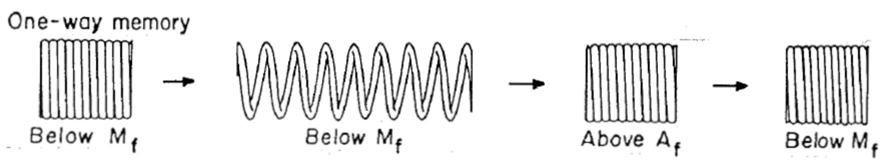
Soft robotics actuation technologies

Actuation technology			*Physical phenomenon*	*Scaling of dimensions*	*Strain*	*Stress*	*Power density*	*Response velocity*	*Remotability*
Motor-driven cables	electromagnetism		electrmagnetic motors pulling cables fixed at distal points along the structure	low mainly because of the motors	high	medium / low	medium	high	partially
SMA	temperature change		thermal driven change of crystalline structure leading to a shape change	high	wires: very low springs: high	wires: high springs: medium / low	high	medium / low	yes
SMP	light, electric current, magnetic field, chemical stimuli		light, electric current, magnetic field or chemical stimuli can change polymer chain structure leading to a shape change	high	medium	medium	medium / low	low	yes
EAP	electric field	electrons	the application of a potential difference leads to electro-static interactions generating internal stresses and deformations	medium / high	medium / high	medium	medium / low	high	yes
		ions	the application of a potential difference leads to ions migration causing deformations	medium / high	axial: low bending: medium / high	medium / low	medium / low	high	partially
Flexible fluidic actuators	pressurized fluids	liquids (hydraulic)	pressurized liquid to change elastomeric chambers volume converted into specific movements	medium / low mainly because of the hydraulic pumps	high	high	medium / high	medium / high	no
		gases (pneumatic)	pressurized gas to change elastomeric chambers volume converted into specific movements	medium mainly because of the pneumatic pumps	high	medium	high	high	no

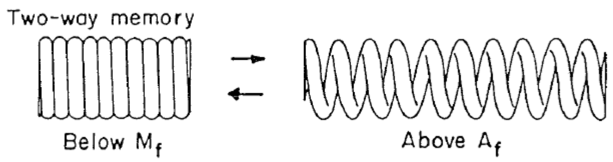
Shape Memory Effect

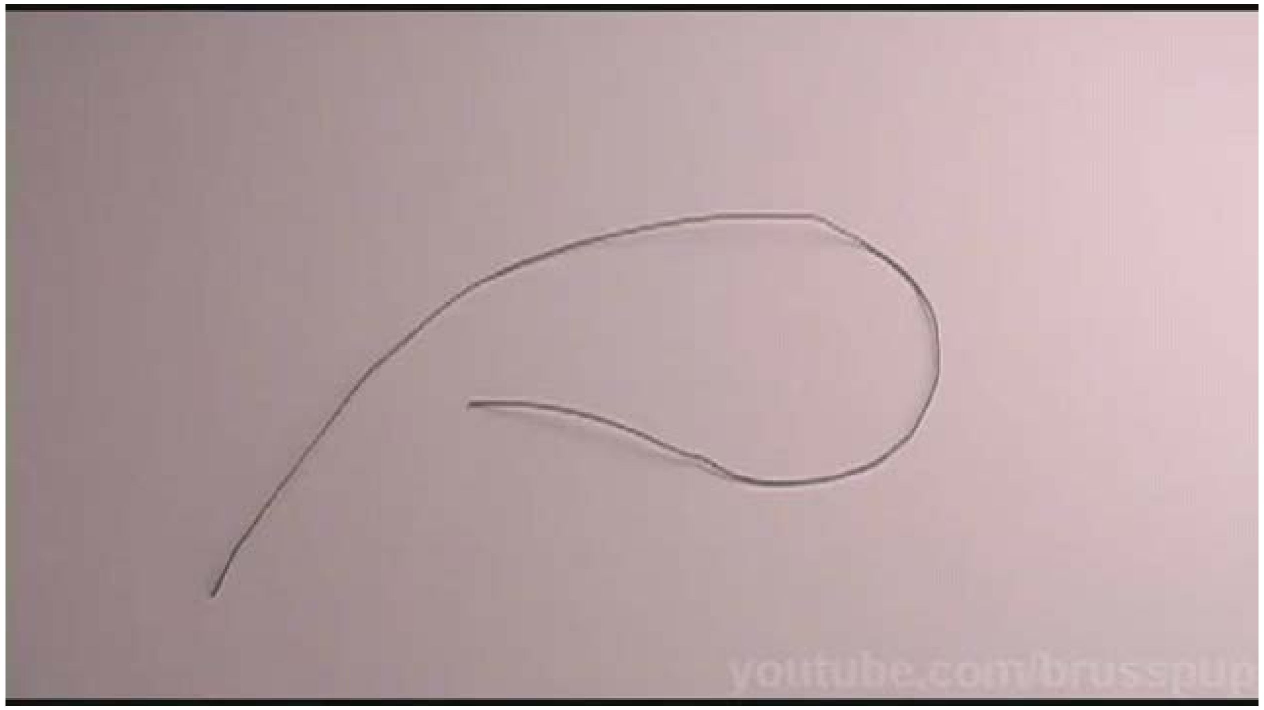
Shape Memory Effect (SME) refers to the recovery of shape (i.e. strain) after apparent “permanent” deformation (induced at relatively cold temperatures) by heating above a characteristic transformation temperature.

One way (OWME)



Two ways (TWME)





Note: this is an acquired property!

Training needed (thermo-mechanical treatments)

Brief history of Shape Memory Alloys

1932. Swedish physicist Arne Olander discovered the shape memory effect on an Au–Cd alloy

1958. Researchers Chang and Read demonstrated the shape memory effect at the Brussels World's Fair and used it to perform mechanical work by cyclically lifting a weight

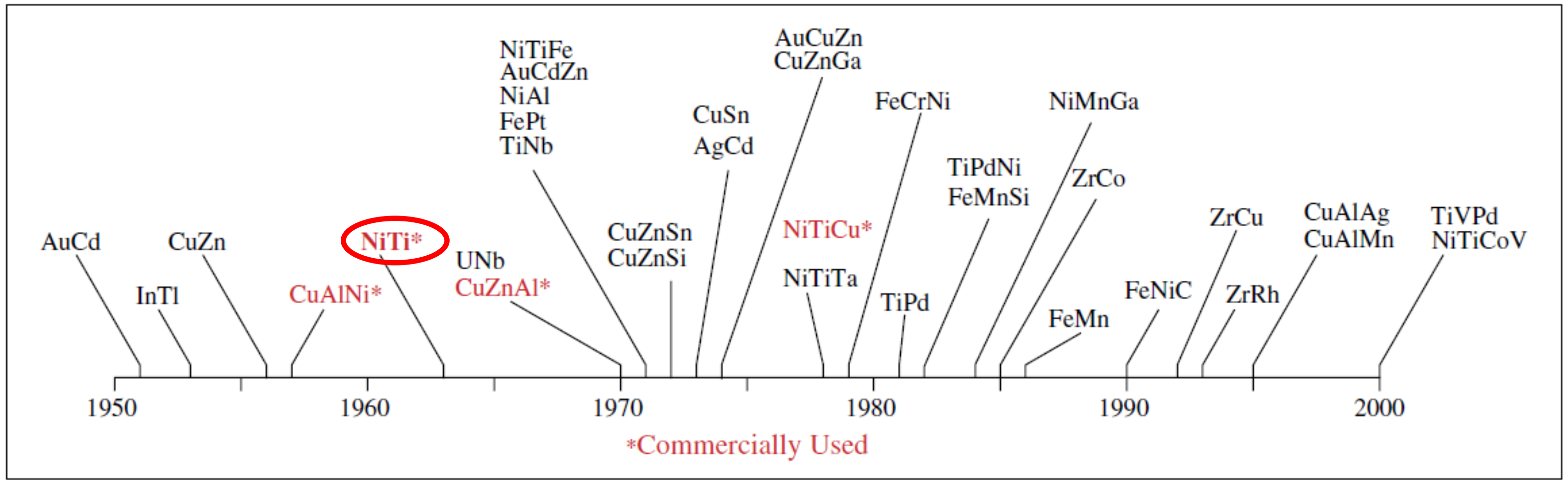
1961. A group of U.S. Naval Ordnance Laboratory researchers led by William Beuhler discovered that an alloy of nickel and titanium exhibited the SME too. (Ni-Ti-NOL)

1970. First Commercial Use of NiTiNOL in F14 Tomcat

Shape Memory Alloys

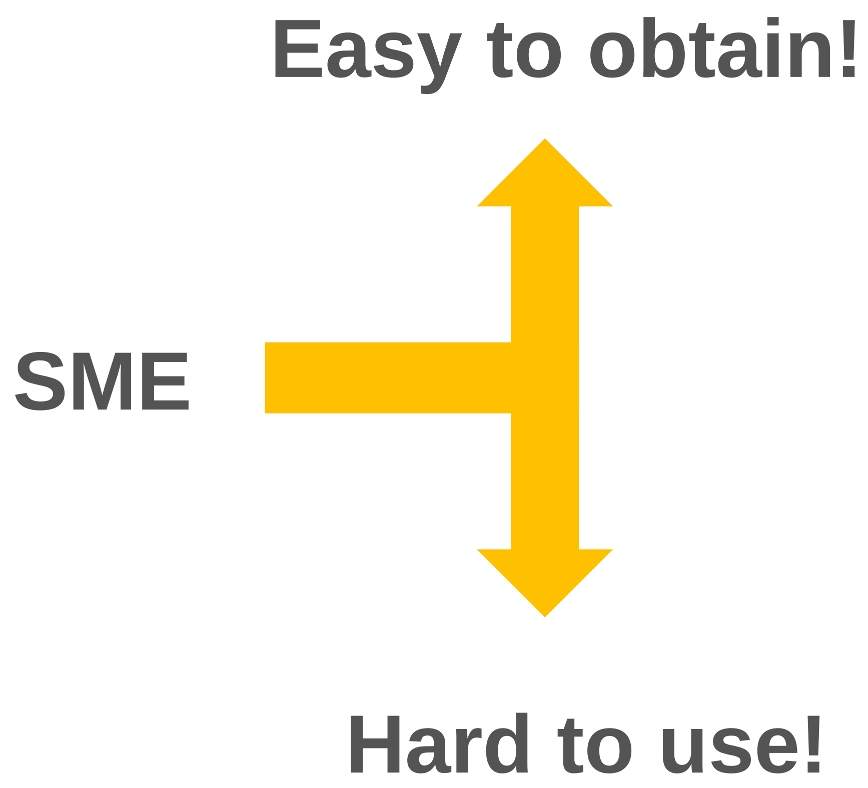
Several alloys

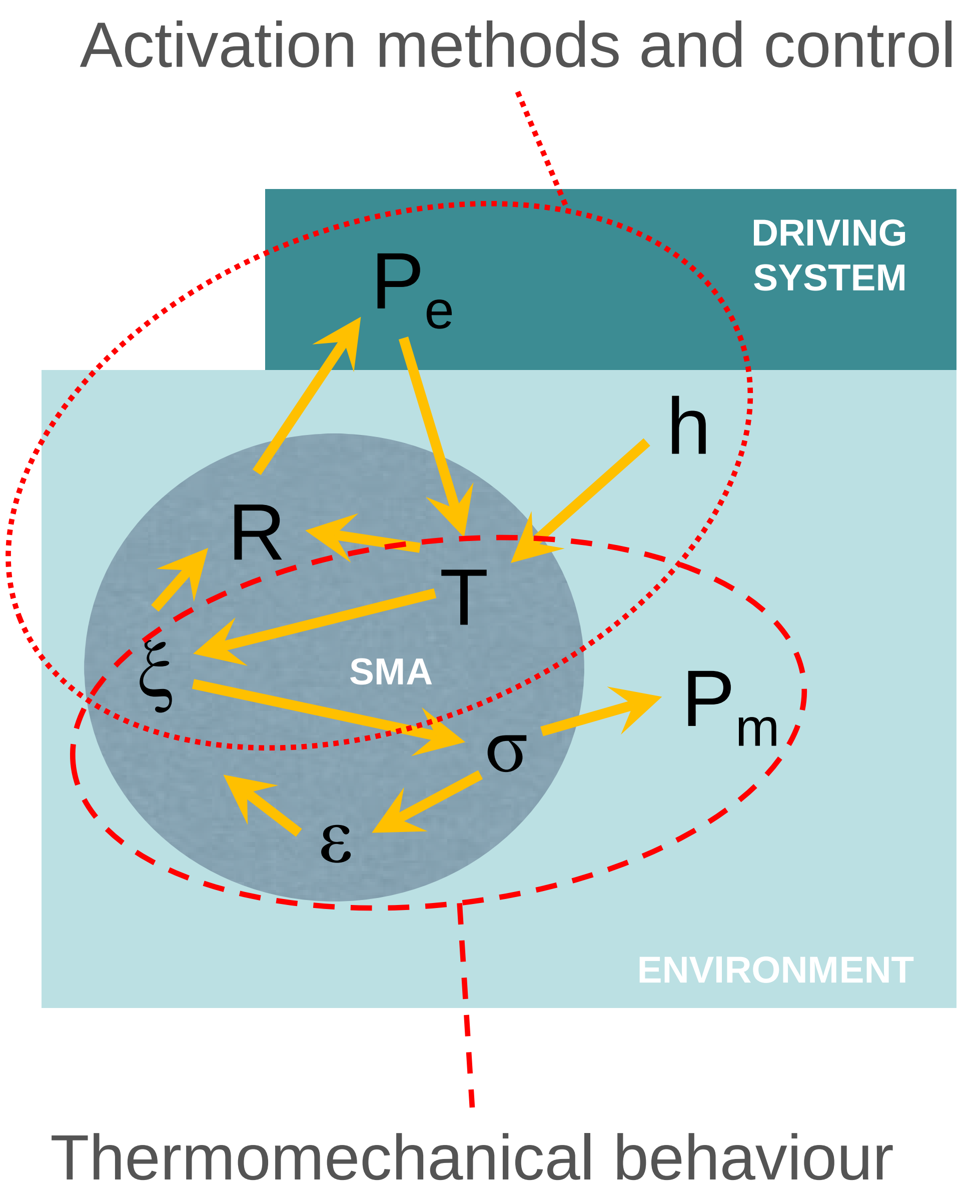
The field remains an active area, but advances in materials processing have resulted in production on Ni-Ti based materials with good quality control, with reproducible properties and in relatively large quantities



Shape Memory Alloys actuators design

SME dependent variables flow chart





Cianchetti M (2013) Fundamentals on the Use of Shape Memory Alloys in Soft Robotics, in Interdisciplinary Mechatronics: Engineering Science and Research Development, edited by M. K. Habib and J. Paulo Davim, pp. 227-254, Wiley-ISTE.

Shape Memory Alloys actuators design

Workflow

1. Derive your actuator specifications
2. Design the actuator (and the counter-actuator)
3. Know your alloy

MODELLING THE MECHANICAL PERFORMANCES OF THE ACTUATOR

4. Describe the environment
5. Decide the activation and the cooling method

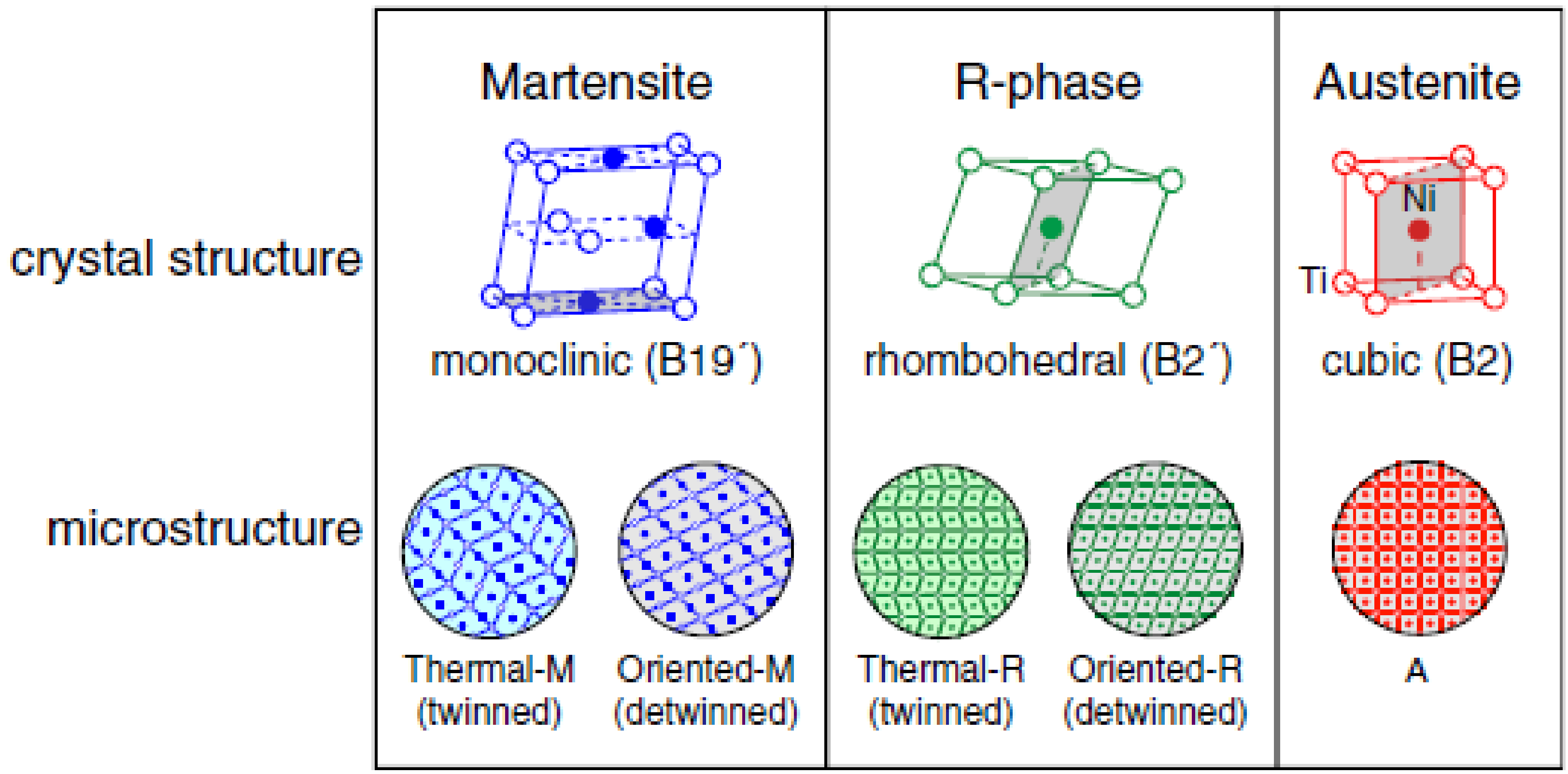
MODELLING THE THERMODYNAMIC CYCLES DURING HEATING AND COOLING

6. Design the driving system

DIMENSIONING THE CONTROL CURRENT

Shape Memory Alloys structure

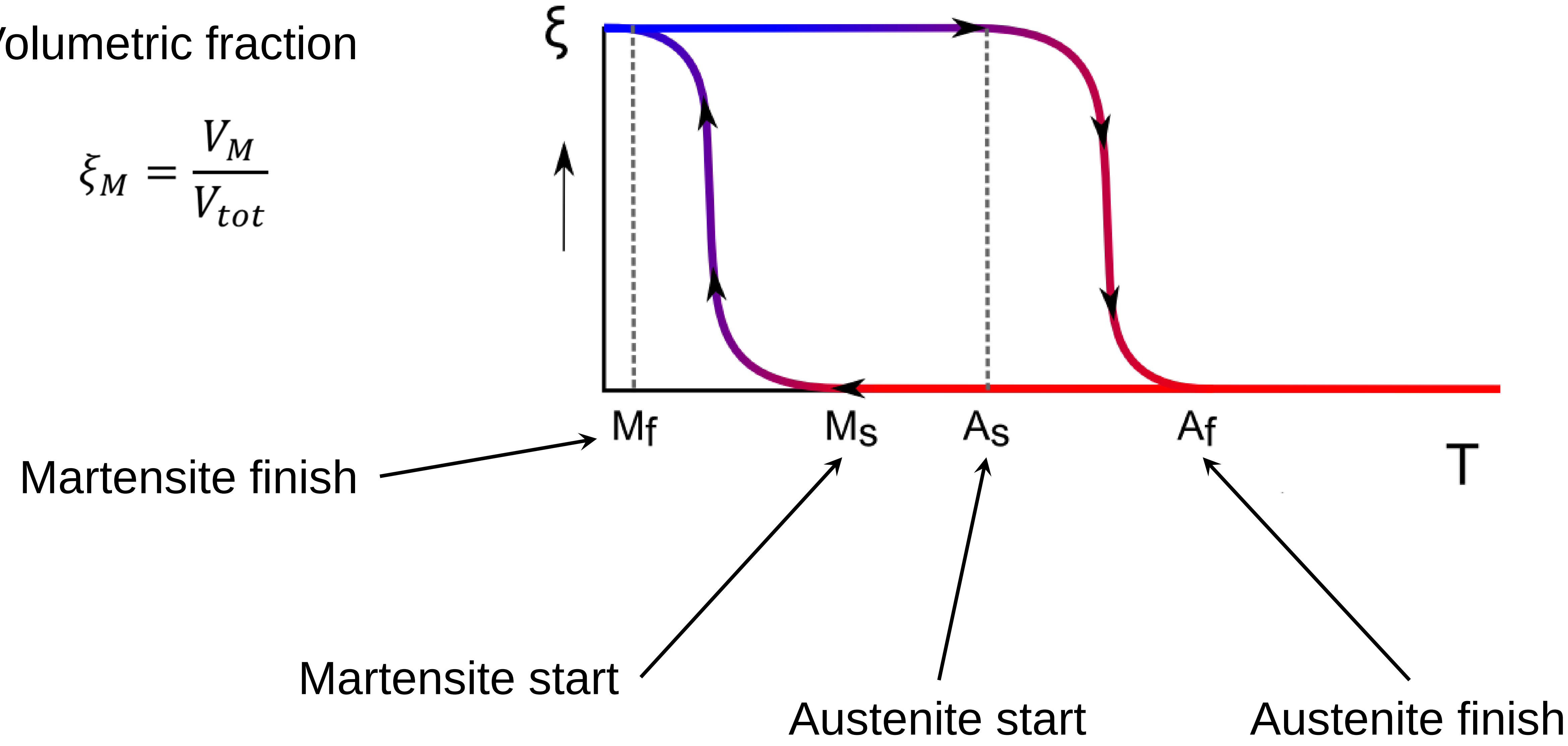
The structure change can occur by small, coordinated shifts of the atomic positions without diffusion or plasticity



Transition temperatures

Volumetric fraction

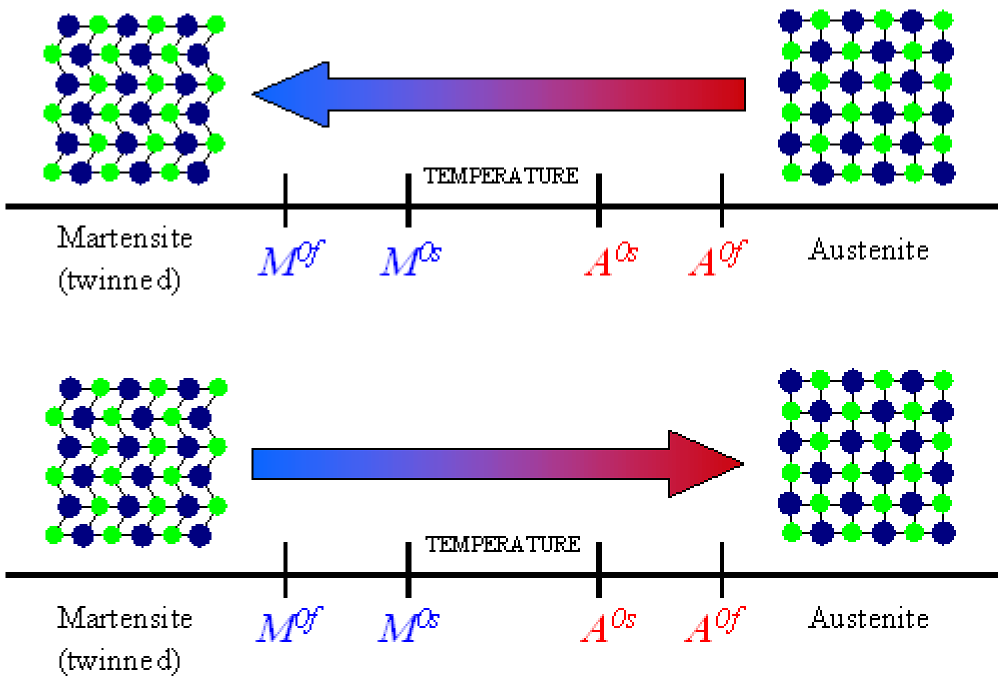
$$\xi_M = \frac{V_M}{V_{tot}}$$



N.B. Several ranges and combinations available

Thermomechanical behaviour

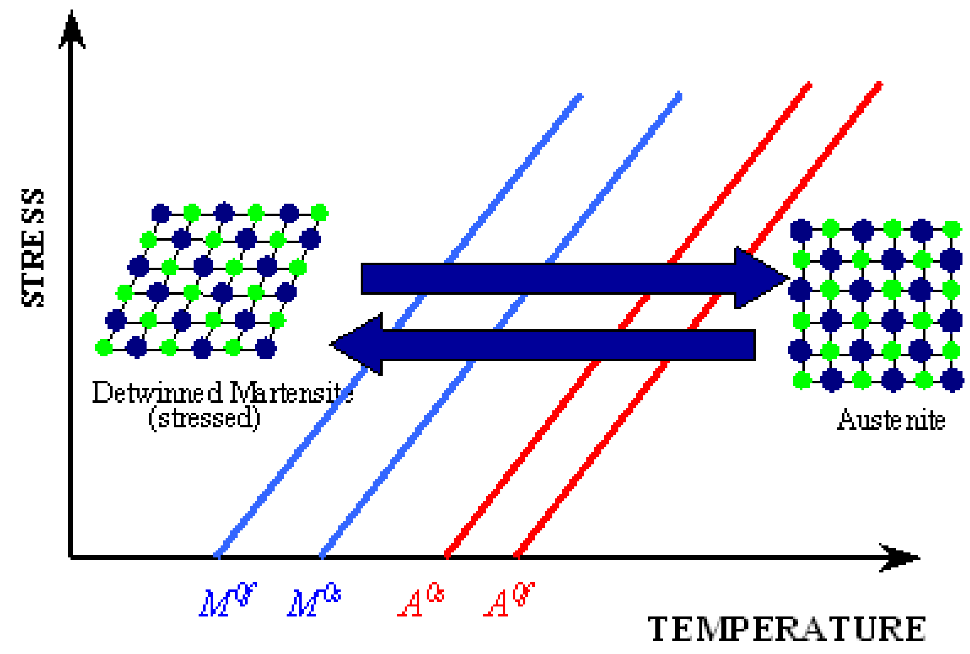
Shape Memory Effect – without mechanical loading



Temperature-induced phase transformation of an SMA without mechanical loading.

Thermomechanical behaviour

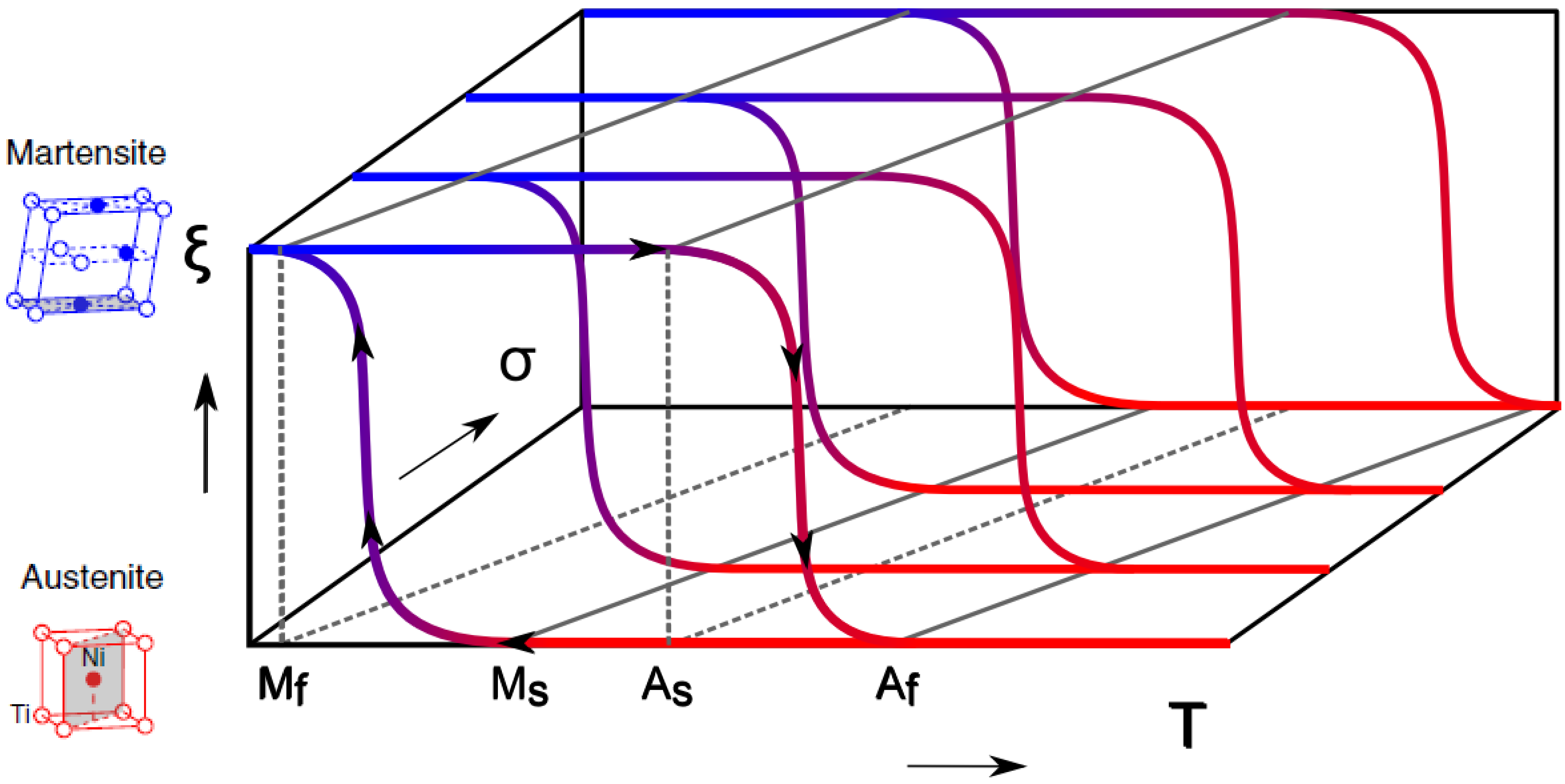
Shape Memory Effect – with mechanical loading (I)



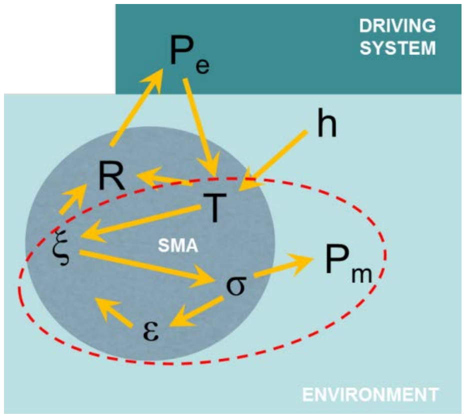
Dependence of the transformation temperature on the applied load

Thermomechanical behaviour

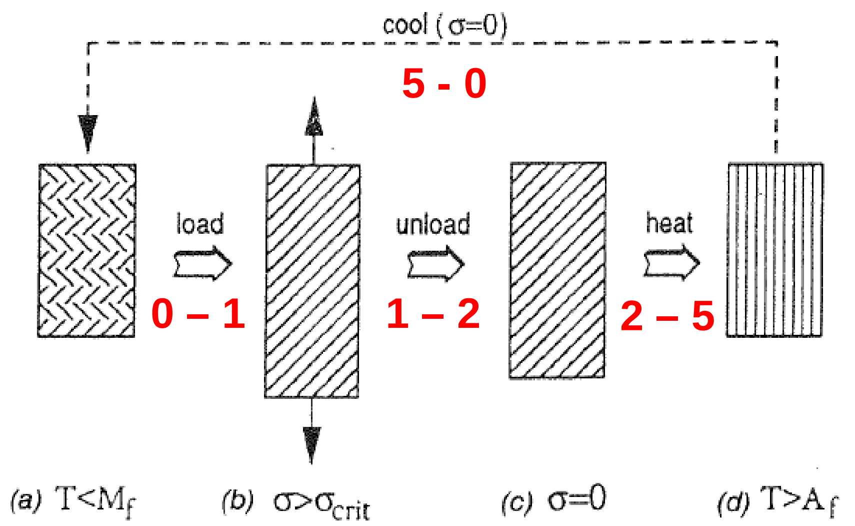
Martensitic transformation cycles and “stress gradient”

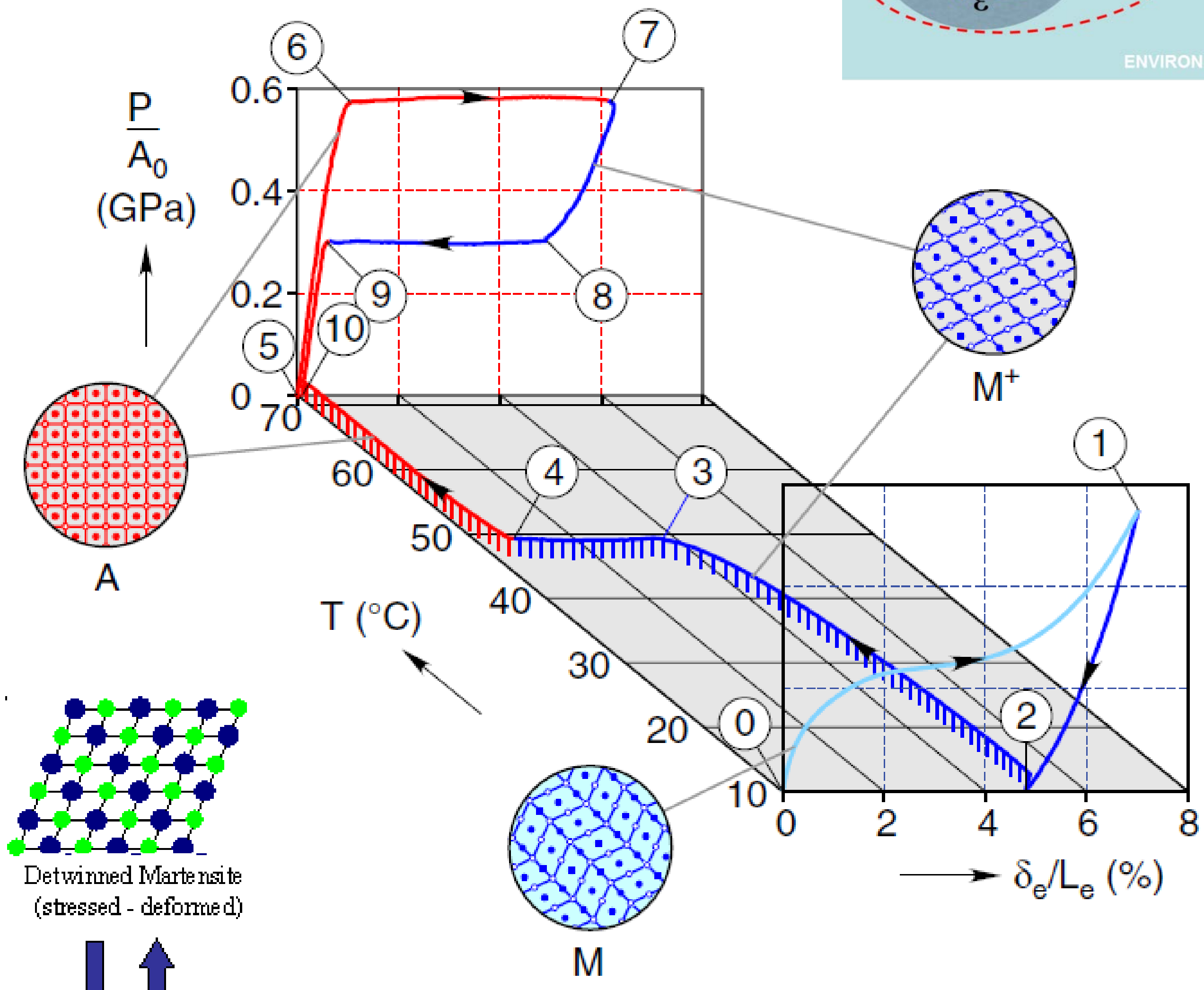


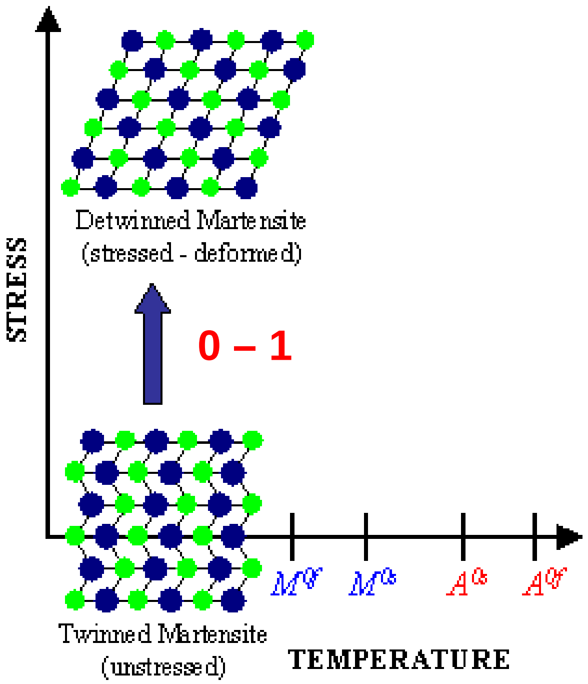
Thermomechanical behaviour

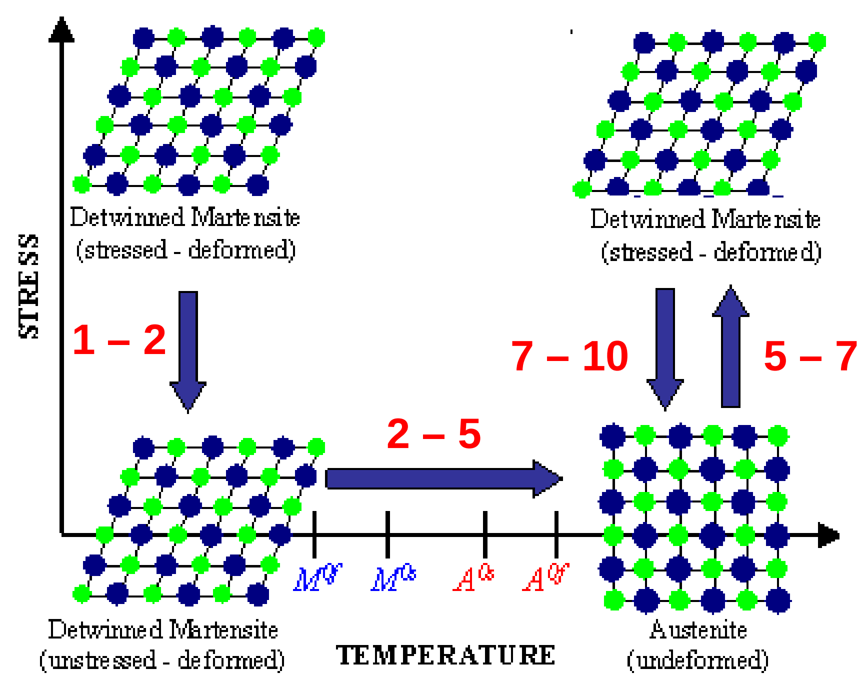


Shape Memory Effect – with mechanical loading (II)









Shaw JA, Churchill CB, Iadicola MA (2008) "Tips and tricks for characterizing shape memory alloy wire: part 1 – Differential scanning calorimetry and basic phenomena" *Experimental techniques*, 32 (5), pp. 55-62

Modelling the SME

- The SMA exhibits a **nonlinear** and **pseudo-elastic response** that varies depending on the temperature and loading conditions.

- An **accurate model** of this behavior is a necessary prerequisite for the use of the SMA as actuator.

- Models representing the thermo-mechanical behaviour and have mathematical expression in a form that is **amenable to incorporation into other engineering tools** (finite element procedures or control analysis programs).

- Due to the complex interactions of the different parameters controlling the SMA behavior, these materials have been the subjects of **numerous constitutive models**.

Modelling the SME

Classification

1. Microscopic (molecular level) or mesoscopic (lattice particles) phenomena

These approaches have been studied by several authors including Warlimont et al. [1974], Perkins [1975], Nishiyama [1978], Achenbach, and Muller [1982], Sun and Hwang [1993], Fischer and Tanaka [1992], Comstock et al. [1996], Lu and Weng [1998], Levitas et al. [1998], Gall et al. [1999], Sittner and Novak [2000], Kloucek et al. [2004], Muller and Seelecke [2001]

2. Macroscopic approach (phenomenological features) – THE SIMPLEST

Falk [1983], Falk and Konopka [1990] and The Landau-Devonshire theory

3. Models with assumed phase transformation kinetics (preestablished simple mathematical functions to describe the phase transformation kinetics) – THE MOST POPULAR

Tanaka and Nagaki [1982] that motivated other researchers who present modified transformation kinetics laws as Liang and Rogers [2000], Brinson [1993], Ivshin and Pence [1994], Boyd and Lagoudas [1996]

4. Models based on elastoplasticity theory

Simo and Taylor [1986]

5. Models based on plasticity concepts

Silva [1995], Souza et al. [1998], Auricchio et al. [1997], Govindjee and Kasper [1997] and Leclercq et al. [1995]

Paiva A, Savi MA (2006) “An overview of constitutive models for shape memory alloys” Mathematical Problems in Engineering, pp 1–30

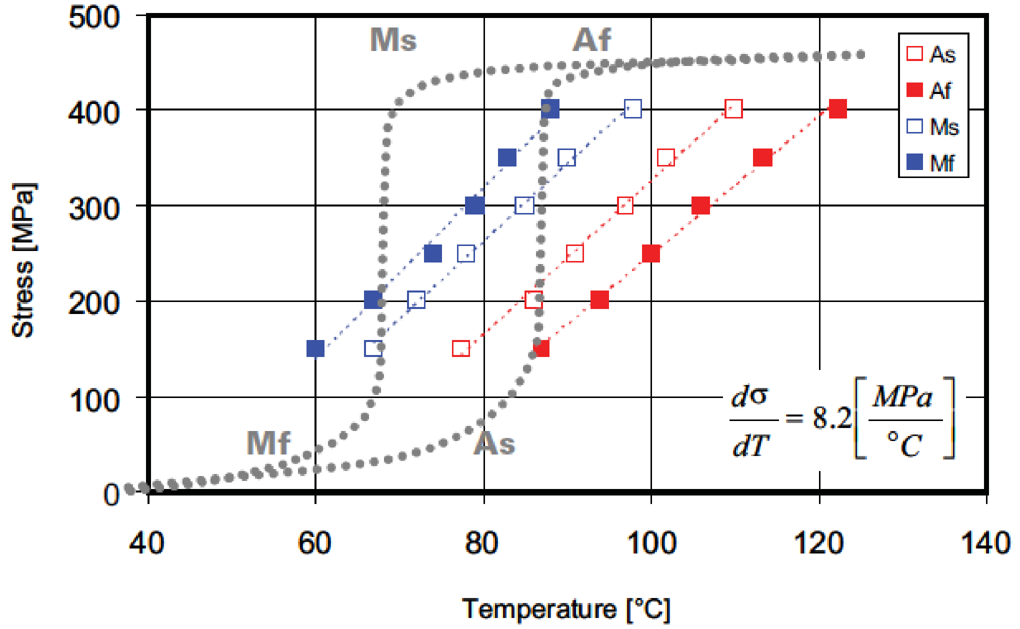
Modelling the SME

FROM THE PERSPECTIVE OF A CONTROLS ENGINEER, ANY MODEL THAT CAN CAPTURE THE SMA RESPONSE ADEQUATELY AND EFFICIENTLY (POSSIBLY IN REAL TIME) IS A "GOOD" MODEL, IRRESPECTIVE OF WHETHER THAT MODEL HAS BEEN BUILT ON PHYSICAL PRINCIPLES OR PURELY EMPIRICALLY.

Modelling the SME

Useful data

1. Characteristic transformation temperatures
2. Young modulus of both phases (Martensite and Austenite)
3. Stress dependency of the transformation temperatures



The testing of SMAs is **not yet standardized** and unlike conventional alloys, material property tables either are not available or provide **incomplete**, or even **incorrect**, information for the user.

Since each SMA is different, user is often faced with **testing SMAs in their own laboratory** to obtain a satisfactory characterization of the material at hand.

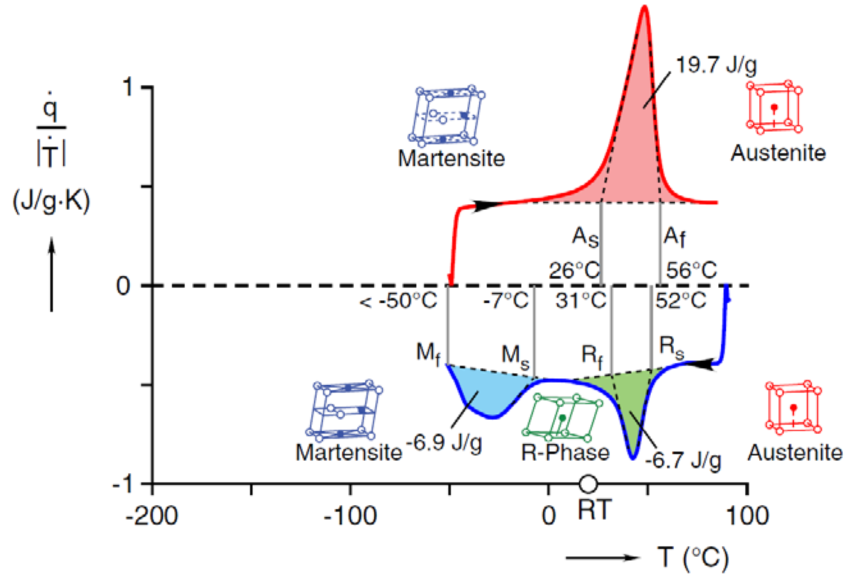
Transition T	-200 ÷ 100°C
Transformation strain	8% (1 cycle), 6% (10^2 cycles), 4% (10^5 cycles)
Thermal hysteresis	15 - 30°C
Bulk density	6,45 g/cm^3
Electrical resistivity	80 μΩcm (M) ; 100 μΩcm (A)
Corrosion resistance	Excellent
Melting point	1310°C
Elastic modulus	28 ÷ 41 GPa (Martensite), 83 GPa (Austenite)
Breaking load	1500 (cold worked) MPa

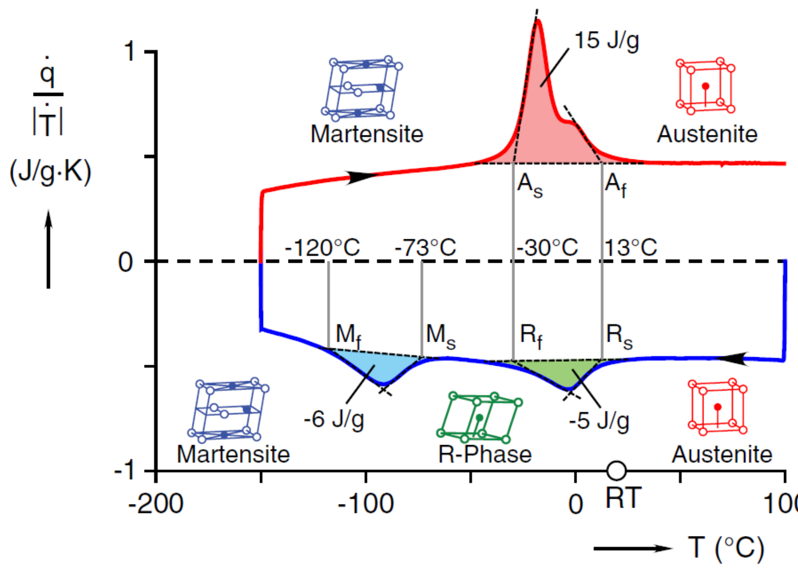
Thermomechanical testing

Characteristic transformation temperatures

DSC (Differential Scanning Calorimetry) thermograms

Complete description, DSC machine needed





Electrical resistivity scanning

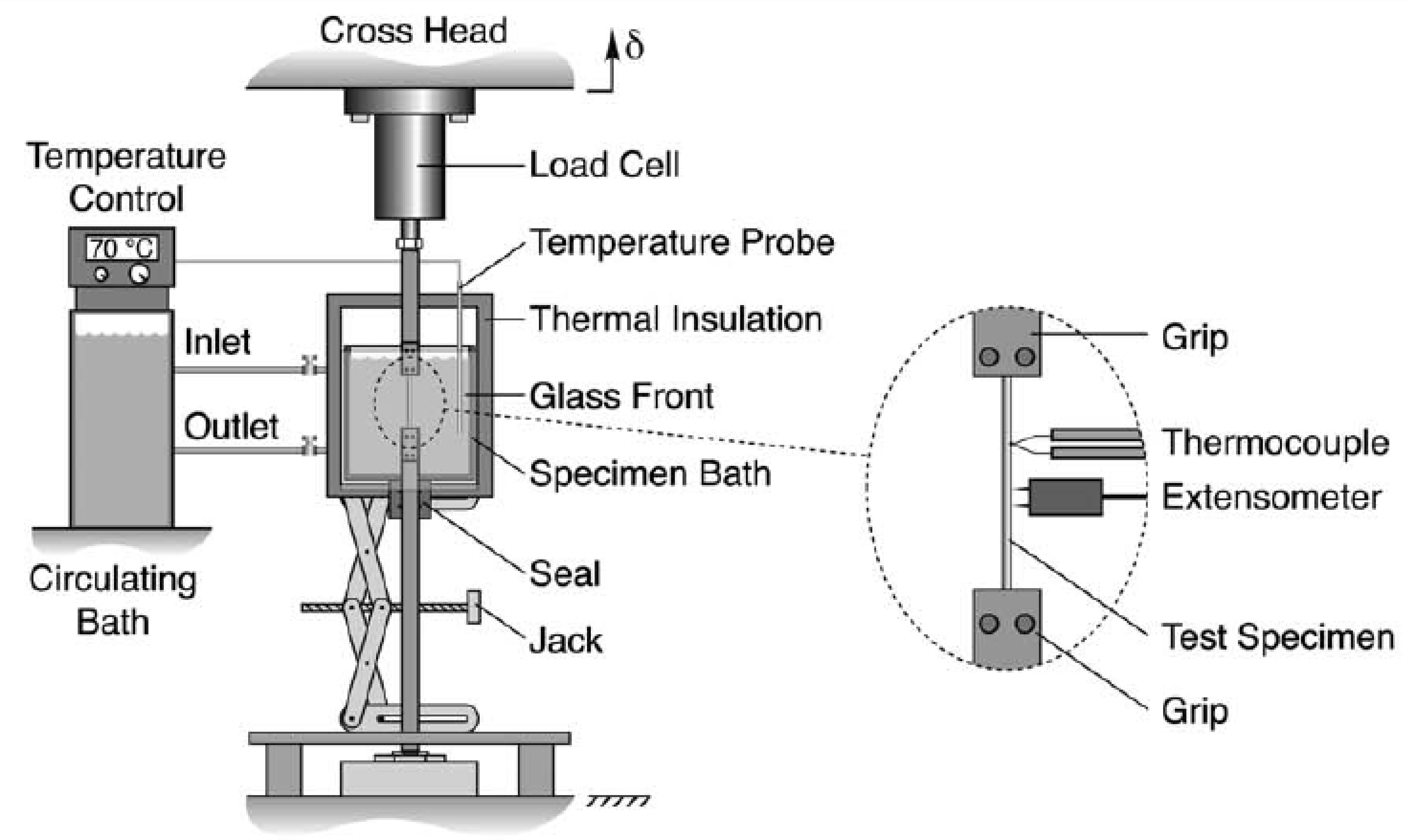
Easy to perform, difficult to interpret, no information on latent or specific heats

Tips:

- probe dimensions do matter!
- use thermally conductive paste

Thermomechanical testing

Shape Memory Effect set-up



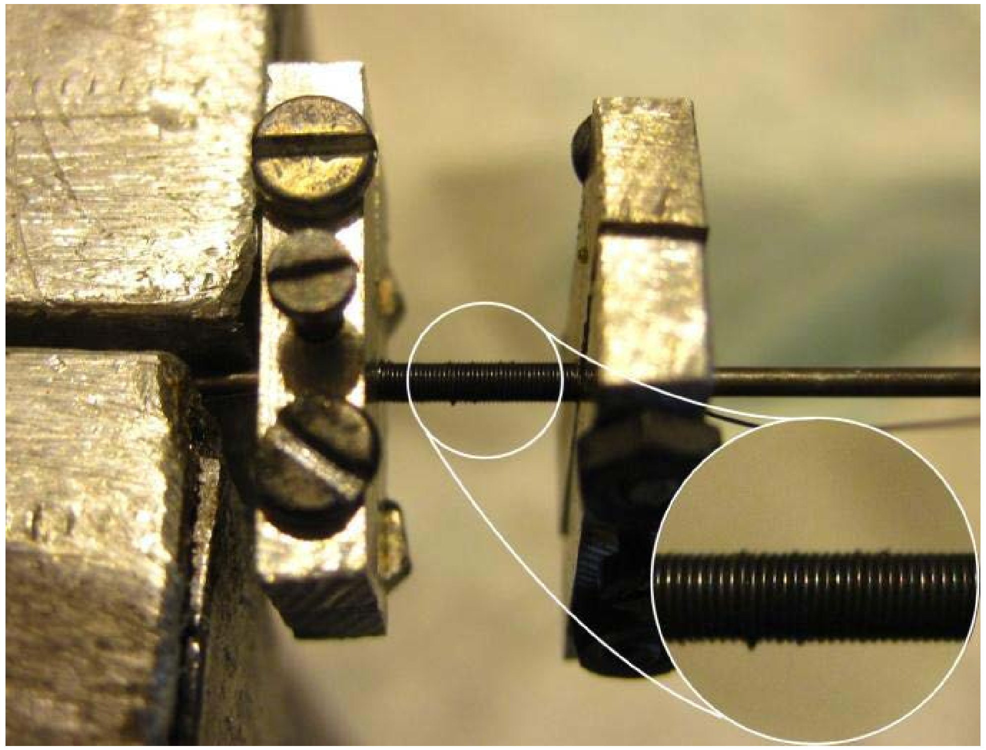
Practical use of SMAs

Forming (memorization)

1. Nitinol components are normally fabricated by holding the part in a fixture during heat treatment.

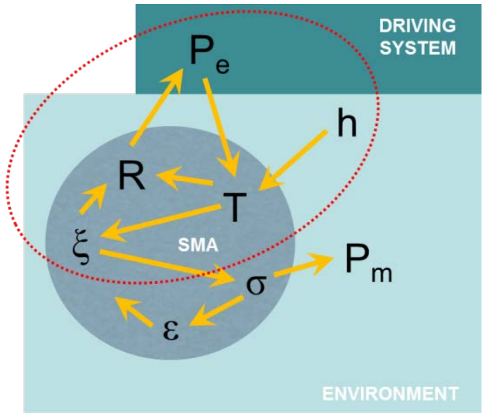
2. To memorize the desired shape, the spring has to be maintained at **450° C** for **20 minutes** under flowing **nitrogen** or other inert gases (to prevent oxidation).

3. After this time has elapsed, the spring has to be **water quenched**.



A good fabrication method is necessary to obtain repeatability among different actuator prototypes, since **small differences and imprecision can deeply affect the mechanical performances of the actuators**.

Control methods



Heavily dependent on the application

- on-off / modulated activation
- open / closed loop
- simple / complex geometry
- well known / unknown environment

Control methods

$$\rho c V \frac{dT}{dt} = Ri^2(t) - hA(T - T_a)$$

ρ - mass density
c - specific heat
V - volume
i - electric current
R - electric resistance

h - Convection heat transfer coefficient
A - heat exchanging surface area
T_a - ambient temperature

- on-off/modulated activation
- open/closed loop
- simple/complex geometry
- well known/unknown environment

Convective heat transfer correlations

Natural convection, External flow

Vertical plate
$$h = \frac{k}{L}\left(0.68 + \frac{0.67 Ra_L^{1/4}}{(1+(0.49/\mathrm{Pr})^{9/16})^{8/27}}\right)^2$$

Vertical cylinder The same if $\frac{D}{L} \geq \frac{35}{Gr_L^{1/4}}$

Horizontal plate
$$h = \frac{k0.54 Ra_L^{1/4}}{L} \qquad 10^5 \leq Ra_L \leq 2\times10^7$$
$$h = \frac{k0.14 Ra_L^{1/3}}{L} \qquad 2\times10^7 \leq Ra_L \leq 3\times10^{10}$$
$$h = \frac{k0.27 Ra_L^{1/3}}{L} \qquad 3\times10^5 \leq Ra_L \leq 10^{10}$$

Horizontal cylinder
$$h = \frac{k}{D}\left(0.6 + \frac{0.38 Ra_D^{1/6}}{(1+(0.559/\mathrm{Pr})^{9/16})^{8/27}}\right)^2$$

Forced convection, Internal flow

Laminar flow
$$N_{uD} = 1.86(\mathrm{Re}\,\mathrm{Pr})^{1/3}\left(\frac{D}{L}\right)^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

Turbulent flow
$$h = \frac{k_w}{D_H} N_u$$

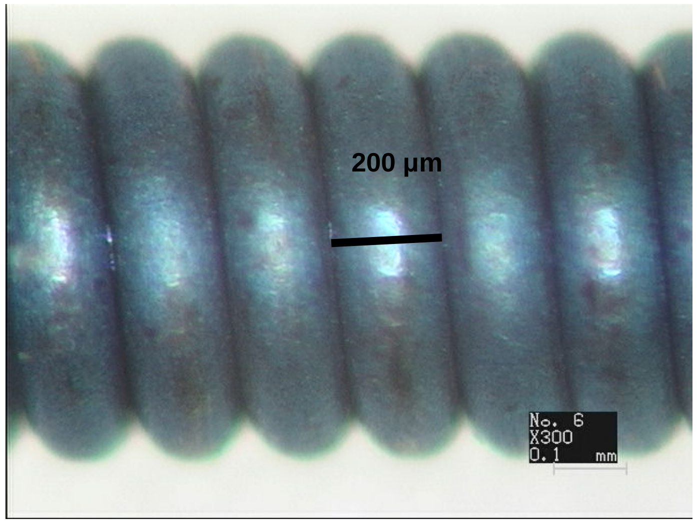
Control methods

$$\rho c V \frac{dT}{dt} = R i^2(t) - hA(T - T_a)$$

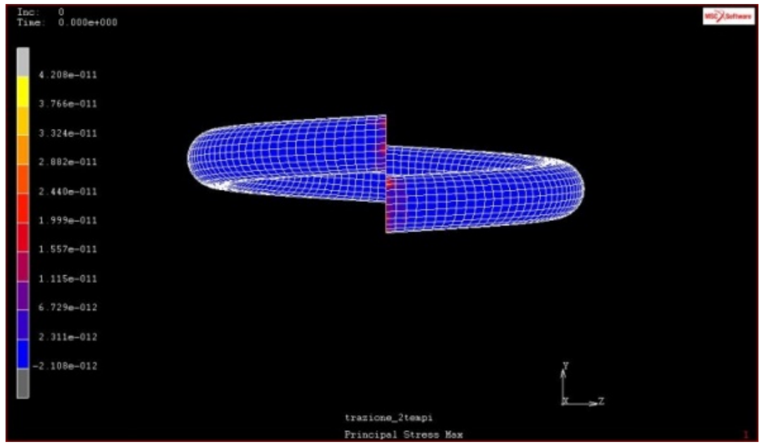
ρ - mass density
c - specific heat
V - volume
i - electric current
R - electric resistance

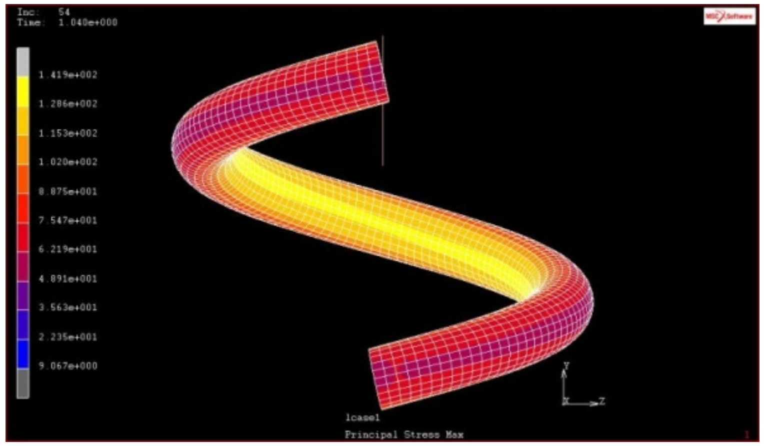
h - Convection heat transfer coefficient
A - heat exchanging surface area
T_a - ambient temperature

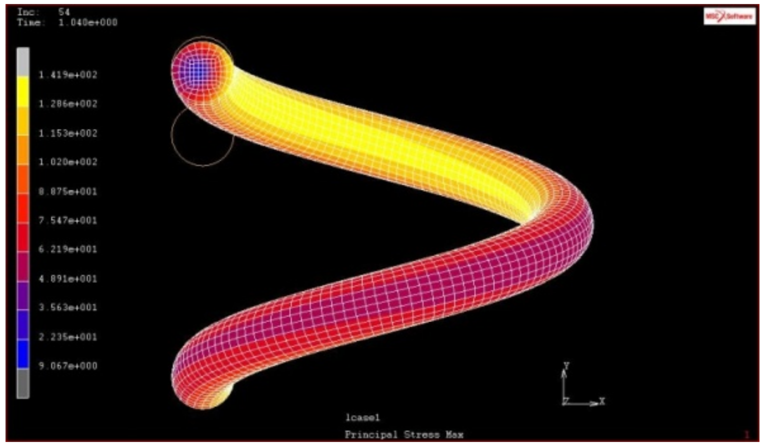
- on-off/modulated activation
- open/closed loop
- simple/complex geometry
- well known/unknown environment



Finite Element Analysis







Control methods

The proportional control of SMAs based on mathematical models have often not sufficient accuracy

- on-off/modulated activation
- open/closed loop
- simple/complex geometry
- well known/unknown environment

Two available methods:

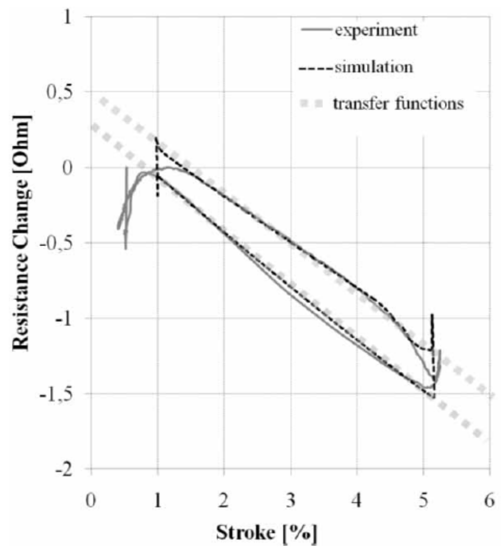
- External variables feedback
  - o displacement
  - o force

likely to cause overheating

- Internal state variable feedback
  - o temperature
  - o electric resistance

difficult to apply in micro-scale application

The detection of inner electrical resistance allows to detect the alloy martensite fraction. The method consists in measuring the electrical resistance of an SMA element, calculating a maximum safe heating current as a function of measured resistance, and ensuring that the actual heating current does not exceed this maximum value.

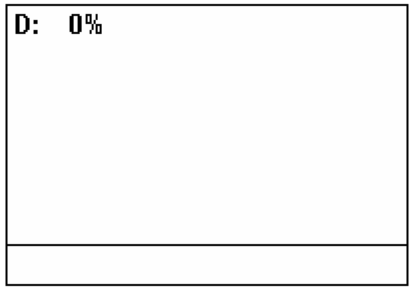


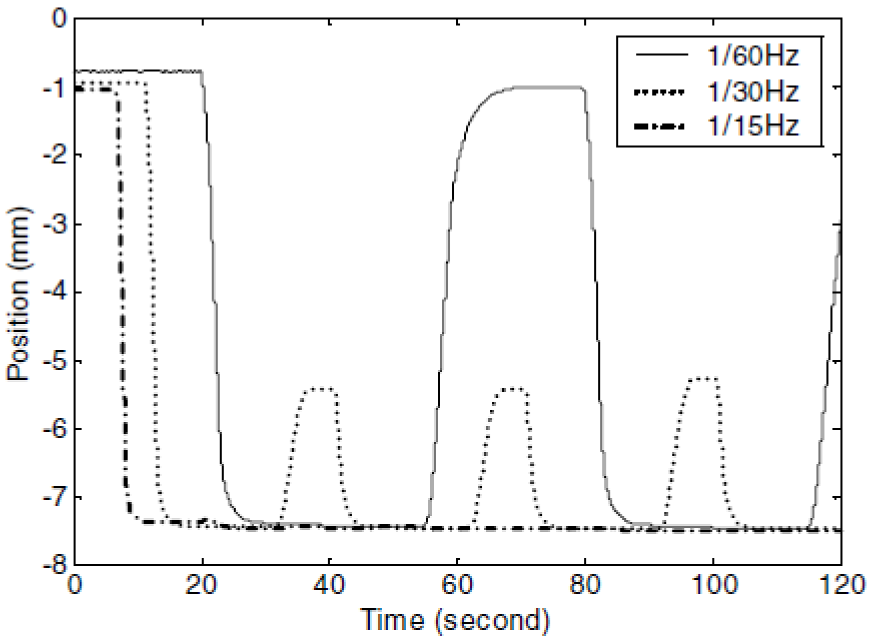
Driving methods

- Continuous PID controller

- PWM PID controller
  - o Duty cycle
  - o Frequency

$$RMS = A_{max}\sqrt{D}$$





$$D = \frac{\tau}{T}$$

- τ - Duration of activation
- T - Period

PWM has the advantages of being **robust to disturbances**, effective in **saving energy** and **easily implemented** using microprocessors

Ma N and Song G (2003) “Control of shape memory alloy actuator using pulse width modulation” *Smart Mater. Struct.* 12, pp. 712–719

Proposed workflow

1. Derive your specifications
   - Force
   - Stroke (linear, angular…)
   - Available space
   - Power limitation
   - One or two ways
2. Design the actuator (and the counter-actuator)
   - Choose your geometry
   - Use a thermo-mechanical model or derive your own
3. Know your alloy
   - Ask for detailed information on the material
   - Test it by yourself if particular and not provided data are needed
4. Describe the environment
   - Take ALWAYS into account the environment conditions the SMA actuators will work
   - Use a model (or derive your own) to predict thermal evolution
5. Decide the activation and the cooling method
   - Heat? Electricity?
   - Water? Air? Forced? Natural?
6. Design the driving system
   - Continuous? PWM?

Case study

OCTOPUS IP (2009-2013)

Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus

1. Derive your specifications
   - Force **DERIVED FROM THE STRUCTURAL MATERIAL TO DEFORM**
   - Stroke (linear, angular…) **20% OF DIAMETER - LINEAR**
   - Available space **FROM 30MM TO 10MM**
   - Power limitation **NO**
   - One or two ways **ONE WAY**
2. Design the actuator (and the counter-actuator)
   - Choose your geometry **SPRING**
   - Use a thermo-mechanical model or derive your own **OUR OWN BASED ON MATERIAL PROPERTIES AND SPRING THEORY**
3. Know your alloy
   - Ask for detailed information on the material **DONE BUT NOT COMPLETE**
   - Test it by yourself if particular and not provided data are needed **DONE**
4. Describe the environment
   - Take ALWAYS into account the environment conditions the SMA actuators will work **WATER**
   - Use a model (or derive your own) to predict thermal evolution **FEM ANALYSIS**
5. Decide the activation and the cooling method
   - Heat? Electricity? **JOULE EFFECT**
   - Water? Air? Forced? Natural? **WATER**
6. Design the driving system
   - Continuous? PWM? **PWM**

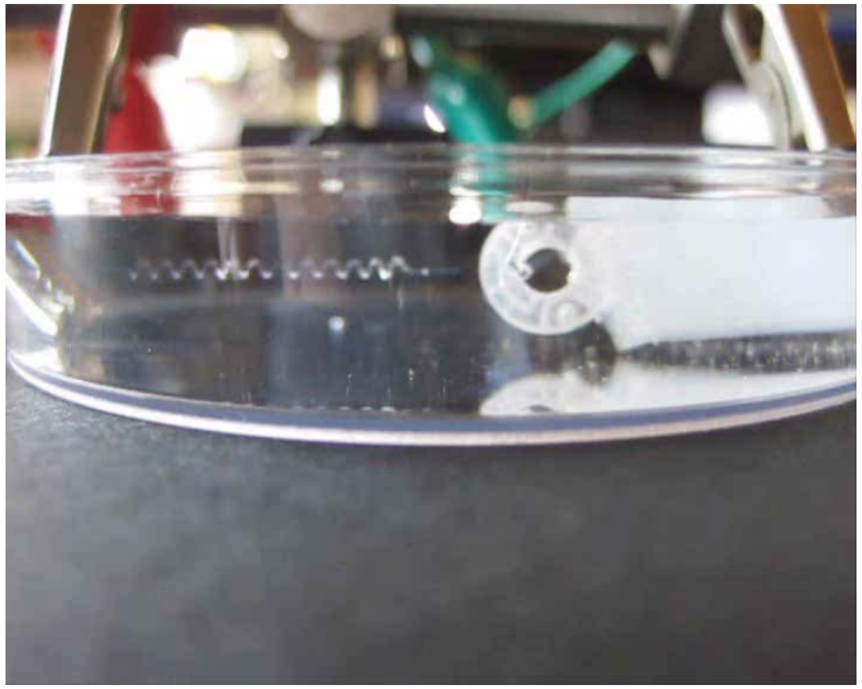
Case study

Single spring

SMA spring with a PTFE sheath **in water** coupled with an elastomeric material that provides a restoring force

OCTOPUS IP (2009-2013)

Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus



- About 1Hz of working frequency
- 1.2A of operating current
- PWM frequency: 100Hz
- PWM duty cycle: 25%
- A_{max}=2.4A

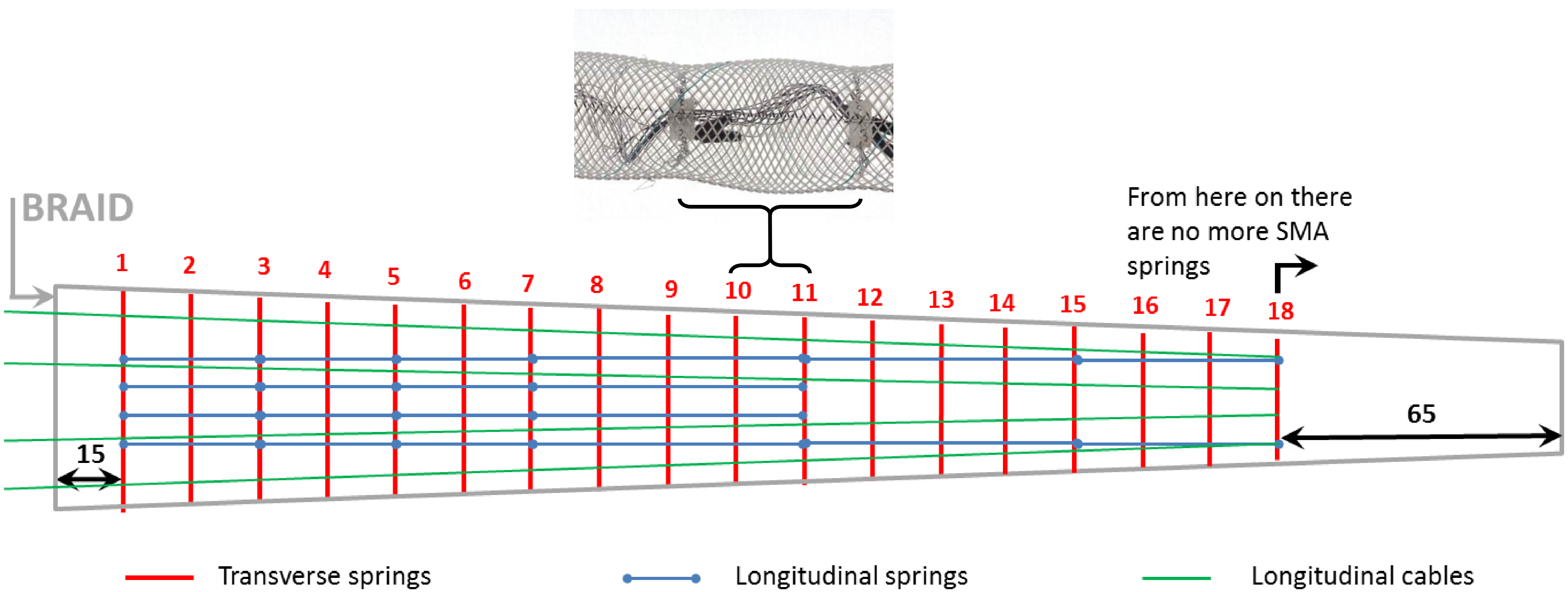
Case study

Entire single arm

OCTOPUS IP (2009-2013)

Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus

- 18 Transverse actuators activated as 12 independent units
- 2 Longitudinal actuators from the base to the tip subdivided in 6 units
- 2 Longitudinal actuators from the base to the 2/3 of actuated part of the arm subdivided in 4 units
- 4 Cable driven by 4 servomotors connected to the tip



Laschi C, Mazzolai B, Cianchetti M, Margheri L, Follador M, Dario P (2012) “A Soft Robot Arm Inspired by the Octopus”, *Advanced Robotics (Special Issue on Soft Robotics), 26 (7), pp. 709-727*

Case study

Entire single arm

Rest length

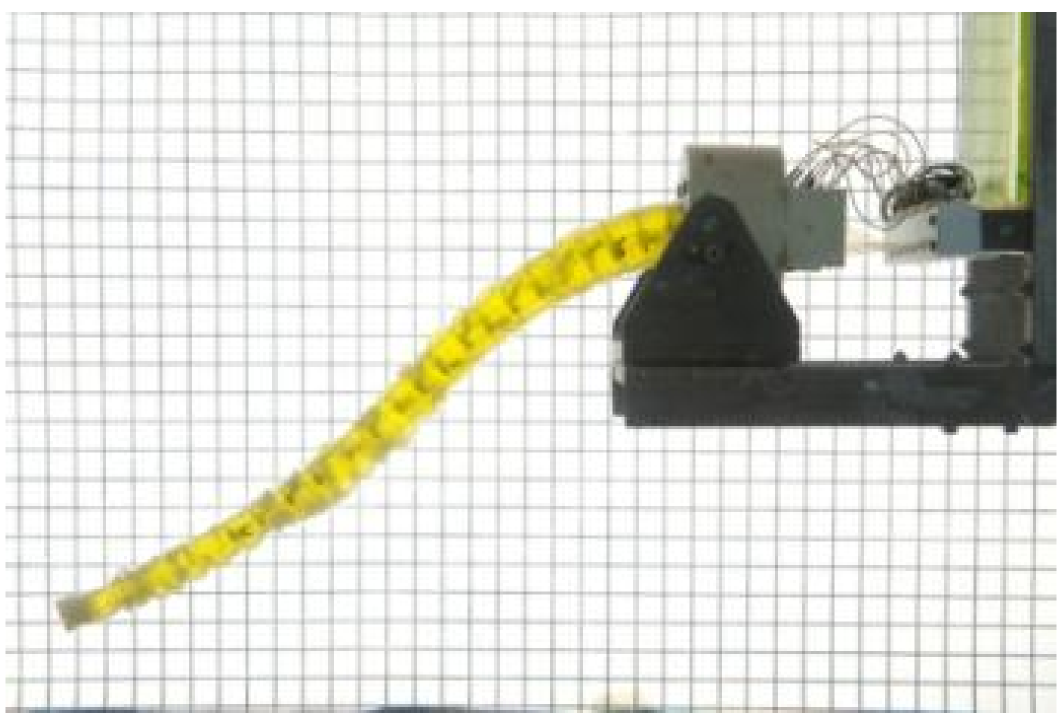
Elongation

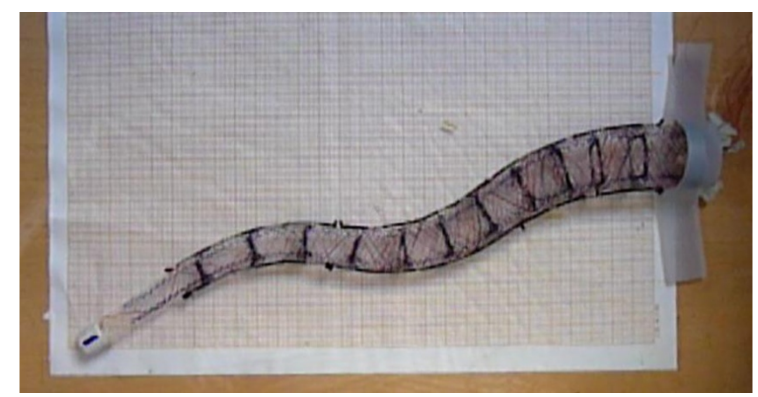
Shortening

Bending

OCTOPUS IP (2009-2013)

Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus





Multi – Bending
performed by local bends

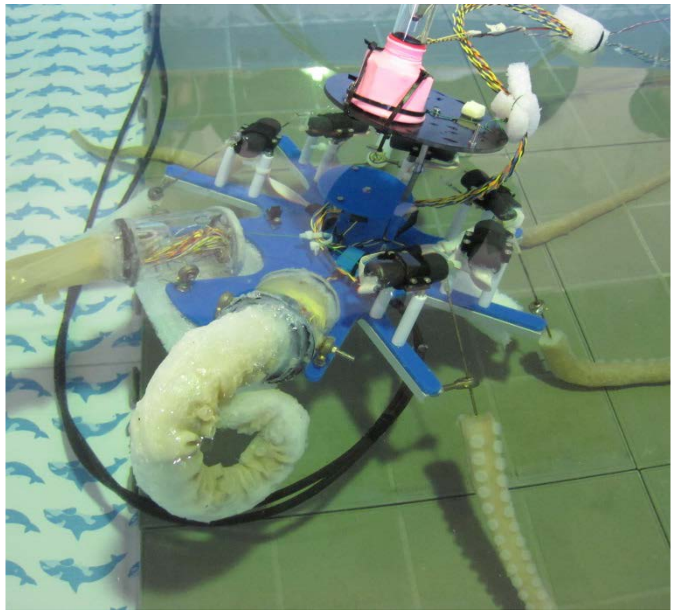
Cianchetti M, Follador M, Mazzolai B, Dario P, Laschi C (2012) “Design and development of a soft robotic octopus arm exploiting embodied intelligence” Conf Proc IEEE on Robotics and Automation – ICRA 2012, 5271-5276

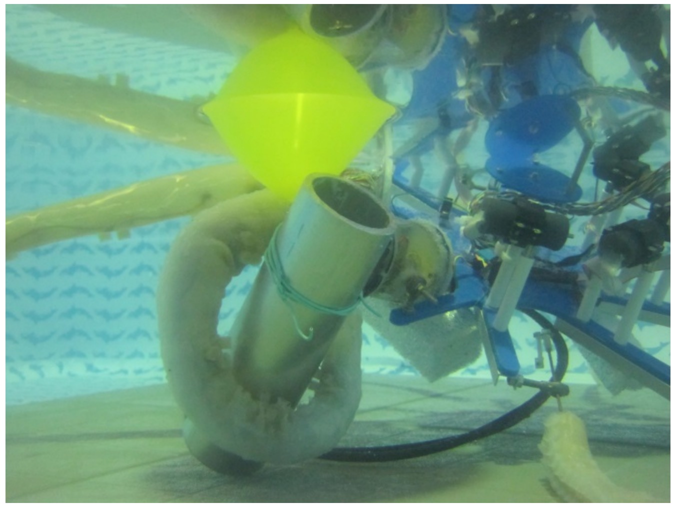
Case study

The OCTOPUS robot

OCTOPUS IP (2009-2013)

Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus





Conclusions and remarks

- An effective example of bioinspired robot
  A deep study of the natural model is fundamental
- Translation of key features into robotic concepts
  Bioinspiration is NOT a copy of the natural counterpart
- Design methodology to develop a soft actuator based on SMA
  Despite all the limitations they represent one of the most promising technologies to substitute natural muscles in bioinspired robots
- Application on the OCTOPUS robot
  The basic capabilities have been reproduced

Thanks

Soft Robotics Team:

- Paolo Dario
- Matteo Cianchetti
- Laura Margheri
- Marcello Calisti
- Francesco Serchi
- Maurizio Follador
- Michele Giorelli
- Federico Renda
- Andrea Arienti
- Ilaria Baldoli
- Alessia Licofonte
- Francesco Rogai
- Serena Tricarico
- Mariangela Manti
- ... our octopuses!

- CFD Octo-Prop, Marie Curie
- PoseiDRONE, Fondazione Livorno
- RoboSoft CA, FET-Open
- Smart-e, Marie Curie ITN

OCTOPUS

www.octopus-project.eu