Chapter 5
Introduction

- **Smart systems** consist of sensors and actuators that are either embedded in or attached to the system containing central control and command unit to form an integral part of it.

- **Smart or intelligent materials** are materials that have the intrinsic and extrinsic capabilities, first, to respond to stimuli and environmental changes and, second, to activate their functions according to these changes.
  - Stimulus —stress, strain, light, electric field, temperature and pressure, etc.
  - Response —motion or change in optical properties, modulus, surface tension, piezoelectricity etc.
Classification of Smart Materials

- **Actively Smart**
  - They possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic fields, thereby acquiring an inherent capacity to transduce energy.
    - Piezoelectric
    - Magnetostrictive
    - Shape memory alloys
    - Electro-Rheological fluid, etc.

*They can be used as force transducers and actuators*
• Passively Smart

• Those smart materials that are not active are called passively smart materials. Although smart, they lack the inherent capability to transduce energy.
  • Optic fibers

*These materials can act as sensors but not as actuators or transducers.*
Common smart materials and associated stimulus response
Smart Technologies Prospects*

- New sensing materials and devices.
- New actuation materials and devices.
- New control devices and techniques.
- Self-detection, self-diagnostic, self-corrective and
- Self-controlled functions of smart materials/systems.

*by Georges Akhras, SMART MATERIALS AND SMART SYSTEMS FOR THE FUTURE
Smart Structure

- A **smart structure** is a system that incorporates particular functions of sensing and actuation to perform smart actions in an ingenious way.

- The basic five components of a smart structure are
  - **Data Acquisition**: the aim of this component is to collect the required raw data needed for an appropriate sensing and monitoring of the structure.
  - **Data Transmission** (sensory nerves): the purpose of this part is to forward the raw data to the local and/or central command and control units.
  - **Command and Control Unit (brain)**: the role of this unit is to manage and control the whole system by analyzing the data, reaching the appropriate conclusion, and determining the actions required.
  - **Data Instructions (motor nerves)**: the function of this part is to transmit the decisions and the associated instructions back to the members of the structure.
  - **Action Devices (muscles)**: the purpose of this part is to take action by triggering the controlling devices/units.
Smart Structure
Smart Structure (Examples)

Smart Bridges

Akhras, 1997

Akhras, G. 1998, "How smart a bridge can be?" Proc., Canada-Taiwan Workshop on Medium and Long-Span Bridges, Taipei.

Smart Materials for Unmanned Aircraft Systems

The physical properties of smart materials can be manipulated for the purposes of unmanned aircraft system (UAS) control. Piezoelectric materials, for example, are smart materials which can stretch or bend in response to an applied electrical voltage. By replacing the servomotors that typically actuate or move the control surfaces of the aircraft with smart materials, many potential advantages may be achieved.
General Overview

- **Smart materials** are materials that have one or more properties that can be significantly altered in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.

- **Examples:**
  - Piezoelectric materials
  - Shape memory alloys
  - Magnetic shape memory alloys
  - Shape memory Polymers
  - PH sensitive polymers
• **Piezoelectric materials** are materials that produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied.

• **Shape memory alloys** and shape memory polymers are thermoresponsive materials where deformation can be induced and recovered through temperature changes, an example is NiTinol™ (Nickel Titanium).
• Magnetic Shape Memory alloys are materials that change their shape in response to a significant change in the magnetic field.

• Shape-memory polymers (SMPs) are polymeric smart materials that have the ability to return from a deformed state to their original shape induced by an external stimulus (trigger), such as temperature change.

• PH-sensitive polymers are materials which swell/collapse when the pH of the surrounding media changes.
General Overview (Smart Structure Applications)

- **Aerospace**
  - Damage detection
  - Vibration control
  - Shape control
  - Adaptive structures

- **Defense**
  - Firing accuracy of weapons
  - Vibration and noise reduction in submarines
  - Smart missiles use smart fins which can warp to appropriate shapes
• **Automotive**
  • Passenger comfort (noise control in cabin)
  • Vibration control (active engine mounts)
  • Health monitoring (smart sensors)

• **Industrial**
  • Manufacturing (machine tool chatter control)
  • Air conditioning and ventilation (noise control)
  • Mining machinery (vibration control)

• **Medical**
  • Smart sensors
  • Micro robotics
  • Surgical tools

• **Civil**
  • Bridges
  • Earthquake protection
Smart materials (3 of 5): shape shifting material, drug delivering nano particles

https://youtu.be/i6n8cpLKzHE
Shape Memory Alloys

Cu-based Alloys
- Cu-Al-Ni with 14/14.5 wt.% Al and 3/4.5 wt.% Ni
- Cu-Sn approx. 15 at.% Sn
- Cu-Zn 38.5/41.5 wt.% Zn
- Cu-Zn-X (X = Si, Al, Sn)

Other shape memory alloys include:
- Ni-Ti (~55% Ni)
- Ag-Cd 44/49 at.% Cd
- Au-Cd 46.5/50 at.% Cd
- Fe-Pt approx. 25 at.% Pt
- Mn-Cu 5/35 at.% Cu
- Fe-Mn-Si
- Pt alloys
- Co-Ni-Al
- Co-Ni-Ga
- Ni-Fe-Ga

“Red” denotes major shape memory alloys
What are Shape Memory Alloys?

- Shape memory alloys (SMA's) are metals, which exhibit pseudo-elasticity and the shape memory effect.
- The most effective and widely used alloys include CuAlNi, CuZnAl, and NiTi
- The shape change involves a solid state phase change involving a molecular rearrangement between Martensite and Austenite.
- A temperature change of only about 10 °C is necessary to initiate this phase change
Shape Memory Alloys

The Shape alloys are currently being used in:

- The space shuttle
- Thermostats
- Vascular Stents
- Hydraulic Fittings (for Airplanes)
- Coffee pots
Shape memory effect

- The Shape memory effect is controlled by a structural rearrangement on the atomic scale. At room temperature the atoms from the structure shown below:
The special property that allows shape-memory alloys to revert to their original shape after heating is that their crystal transformation is fully reversible.

This phenomenon results from a crystalline phase change known as "thermoelastic martensitic transformation".

At temperatures below the transformation temperature, shape memory alloys are martensitic. In this condition, their microstructure is characterized by "self-accommodating twins". The martensite* is soft and can be deformed quite easily by de-twinning. Heating above the transformation temperature recovers the original shape and converts the material to its high strength austenitic condition.

* Martensite, named after the German metallurgist Adolf Martens (1850–1914)
Superelasticity and the Shape Memory Effect

A thermal reaction with no diffusion.
cool
Abkühlen

Verformen
deform

Erwärmen
warm

Martensit B19’ (verzwilligt)

Austenit B2

Martensit B19’ (entwillingt)
In this figure, $\xi(T)$ represents the martensite fraction. The difference between the heating transition and the cooling transition gives rise to hysteresis where some of the mechanical energy is lost in the process. The shape of the curve depends on the material properties of the shape-memory alloy.

The transformation is reversible over temperature ranges determined during the formation of the material. NiTi alloys change from austenite to martensite upon cooling; $M_f$ is the temperature at which the transition to martensite completes upon cooling. Accordingly, during heating $A_s$ and $A_f$ are the temperatures at which the transformation from martensite to austenite starts and finishes.
Martensite - Austenite Transformation

Let’s define the fraction of the martensite phase in the SMA as follows:

$$\xi = 0.5 \left( \cos \left( \frac{\pi (T - M_f)}{M_s - M_f} \right) + 1 \right)$$

For the range of

$$M_f \leq T \leq M_s$$
Similarly, we may write an expression for the transformation

$$\xi = 0.5 \left( \cos \left( \frac{\pi (T - A_s)}{A_f - A_s} \right) + 1 \right)$$

$$A_s \leq T \leq A_f$$
Figure 1. The elastic strain range for superelastic Nitinol compared to 316 stainless steel.
Applications for Shape Memory alloys

- Aeronautic coupling & Solid-state actuator
- Orthodontic archwire
- Endodontic SMA tool
- Self-expanding stent
- SMA bone staple
- Robotic application
- SMA damper
- Eyeglass frame
- SMA thin film & MEMS
- SMA art application
A detector for fire alarm sprinkler system.

When there is a fire the temperature will affect the electrical circuit and trigger the sprinkler.
Magnetic Shape Memory Alloys

- Magnetic shape-memory alloys (MSMAs), or ferromagnetic shape-memory alloys (FSMAs), are ferromagnetic materials which exhibit large strains under the influence of an applied magnetic field due to martensitic phase transformation.
- Prototypical shape-memory alloy: Ni-Mn-Ga (Nickel Manganese Gallium has an $L_{21}$ crystal structure)
- Maximum induced deformation $\sim 10\%$ with an applied field.
## MSMA-Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Authors (Year)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-Mn-X (X= Ga, Al, In, Sn, …)</td>
<td>Ullakko et al., APL, 69, 1966 (1996)</td>
<td>(Ga)</td>
</tr>
<tr>
<td></td>
<td>Fujita et al., APL, 77, 3054 (2000)</td>
<td>(Al)</td>
</tr>
<tr>
<td></td>
<td>Sutou et al., APL, 85, 4358 (2004); Krenke et al., PRB, 72, 014412 (2005); 73, 174413 (2006)</td>
<td></td>
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<tr>
<td>Co-Ni-Al</td>
<td>Oikawa et al., APL, 79, 2472 (2001)</td>
<td></td>
</tr>
<tr>
<td>Ni-Fe-Ga</td>
<td>Morito et al., APL, 81, 5201 (2002); 83, 4993 (2003)</td>
<td></td>
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<tr>
<td>Fe-Pd</td>
<td>James &amp; Wuttig, PMA, 77, 1273 (1998)</td>
<td></td>
</tr>
<tr>
<td>Fe-Pt</td>
<td>Kakeshita et al., APL, 77, 1502, (2000)</td>
<td></td>
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<tr>
<td>Co-Ni</td>
<td>Zhou et al., APL, 82, 760 (2003)</td>
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*Fundamentals of the Magnetic Shape-memory Effect: Material properties and atomistic simulations, Ringberg Castle (Germany), February 14-16, 2007*
Ni-Mn-Ga (Nickel Manganese Gallium)

Ni2MnGa

Heusler, L21

fundamentals of the magnetic shape-memory effect: material properties and atomistic simulations, Ringberg Castle (Germany), February 14-16, 2007
In martensitic materials, the microstructure consists of differently oriented crystals, which are called martensitic variants. When these materials are ferromagnetic, usually a specific crystallographic direction is favorable for the magnetization. The arrows mark the magnetization which lies along this so called easy axis. Magnetically induced reorientation (MIR) can occur when additionally the twin boundaries are easily moveable, so an external magnetic field can move them. **This results in a change of microstructure and external shape.**

http://www.fyslab.hut.fi/epm/heusler/
MSMA linear actuators with reset spring

- **(a)** B = 0 T
  - Initial state
  - Ni-Mn-Ga

- **(b)** B = 0 T
  - Preload of the spring
  - Ni-Mn-Ga

- **(c)** B > 0 T
  - Magnetic contraction
  - Ni-Mn-Ga

- **(d)** B = 0 T
  - Mechanical elongation
  - Ni-Mn-Ga
AdaptaMat

Magnetic shape memory (MSM) Technology

“Materials that make things move”
Magnetic field/strain

The developed strain depends on surface treatment.
MSMA Applications

- Metals that change their shape in a magnetic field have tremendous potential as actuators, sensors and other devices.

Microscanner und optical control systems
High speed record of a microscanner of Ni-Mn-Ga, which is periodically deflecting a laser beam.

https://www.imt.kit.edu/english/1526.php
Interesting Literature selection

- Material Science and Engineering of Niti Shape Memory Alloys, Gunther Eggeler, John Wiley & Sons, Limited, 2014
- First Principles Modelling of Shape Memory Alloys: Molecular Dynamics, Oliver Kastner
- Shape Memory Materials, von K. Otsuka, C. M. Wayman
- Shape Memory Alloys: Modeling and Engineering Applications, Dimitris C. Lagoudas, Springer