Artificial Muscles: how much bionics is there in modern solid state actuators?
Overview

- **Introduction**
- Actuators
- Energy Domains and energy storage
- Muscle: An outstanding chemo-mechanical actuators
- Examples of ‘Artificial Muscles’: What we can do
- Conclusions
Bionics

- Definitions of BIONICS:
  - A science concerned with the application of data about the functioning of biological systems to the solution of engineering problems. *(Merriam-Webster Dictionary)*
  
  - The study of mechanical systems that function like living organisms or parts of living organisms. *(Oxford Dictionaries)*
Some Examples of Bionic Structural and Functional Design

Source: http://ballistics.grc.nasa.gov/Photographic%20Data/Images/glare_honeycomb.jpg

What is an actuator

- For our purposes we shall define an actuator as a device that provides mechanical power in a controlled way:
Geometry based actuators
Solid State Actuators (‘Smart Materials’)
# Geometry and Materials Based Actuators

<table>
<thead>
<tr>
<th></th>
<th>Materials Based Actuators</th>
<th>Geometry Based Actuators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power conversion</td>
<td>Rely on phenomena at the material level to exploit laws of physics for power conversion</td>
<td>Rely on the geometry of a device to exploit laws of physics for power conversion</td>
</tr>
<tr>
<td>System optimization</td>
<td>Primarily by selection of appropriate composition, (thermal) treatment and process parameters</td>
<td>Primarily by selection of materials and geometry</td>
</tr>
<tr>
<td>Geometry</td>
<td>Mostly simple</td>
<td>Mostly complex</td>
</tr>
<tr>
<td>Maturity</td>
<td>Mostly in research</td>
<td>Highly level of maturity</td>
</tr>
<tr>
<td>Rotational motion</td>
<td>Only if the materials based actuator is part of a more complex system</td>
<td>Possible</td>
</tr>
<tr>
<td>possible</td>
<td></td>
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</tr>
<tr>
<td>Integrability in</td>
<td>Good</td>
<td>More challenging</td>
</tr>
<tr>
<td>structures</td>
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Actuators exploit the laws of physics through a suitable geometric set-up or atomic-level processes to convert power from one energy domain into the mechanical domain.
Comparison of Energy Density for Different Storage Methods

- Mass density [MJ/kg]
- Volume density [MJ/l]
Chemical energy storage offers:

- A wide selection of energy carriers (molecules)
- A spectrum of reactions to set energy free or bind it into molecules
- High density per volume and/or mass
- Very long shelf life, thanks to the stability induced by activation energy barriers that keep reaction from happening without ‘some help’
Muscle, a Class of Outstanding Chemo-Mechanical Actuators
The ‘Actuators’ of Our Body

- The actuators of our body can be roughly identified with the skeletal muscles.
- **Skeletal muscle** is striated muscle that is usually attached to the skeleton and is typically under voluntary control (Merriam Webster Medical Dictionary online).
- Other types of muscle are:
  - **Smooth muscle**: muscle found especially in vertebrate hollow organs and structures (as the small intestine and bladder) and blood vessels as thin sheets performing functions not subject to direct voluntary control and in all or most of the musculature of invertebrates other than arthropods (ibid).
  - **Cardiac muscle** (also striated, but obviously not skeletal): the muscle that makes up the heart. There are many differences between skeletal and cardiac muscle that will not be treated here.
Muscle Architecture

One criterion to categorize them is based on their architecture (direction of the fibers relative to the muscle axis):

A. Fusiform
B. Unipennate
C. Bipennate
D. (not shown) Multipennate

Muscle architecture has an influence on two important actuator properties:

• Blocking force
• Stroke
Two muscles: same volume, different architecture and different properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Strap muscle</th>
<th>Pennate muscle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [mm$^3$]</td>
<td>V</td>
<td>300'000</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>L</td>
<td>300</td>
</tr>
<tr>
<td>Pennation angle</td>
<td>$\alpha$</td>
<td>0°</td>
</tr>
<tr>
<td>Anatomical cross-sectional area [mm$^2$]</td>
<td>ACSA</td>
<td>1'000</td>
</tr>
<tr>
<td>Fiber length [mm]</td>
<td>L</td>
<td>300</td>
</tr>
<tr>
<td>Physiological cross-sectional area [mm$^2$]</td>
<td>PCSA</td>
<td>1'000</td>
</tr>
<tr>
<td>Fiber blocking stress [MPa]</td>
<td>$\sigma_f$</td>
<td>0.2</td>
</tr>
<tr>
<td>Fiber strain</td>
<td>$\varepsilon$</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Muscle fibers

- Muscle fibers are cells with multiple nuclei.
- The fibers are wrapped by a membrane called endomysium. In these membranes capillary vessels are embedded.
- They are specialized in the generation of mechanical power.
- They have special devices that serve this purpose: In particular a number of vessels that surround the myofibrils.
- The myofibrils are the ‘actuators’ responsible for power generation.
The Sarcomere: the Fundamental Unit of Muscle Contraction

~10^{-6} \text{ m}

Myofilaments: The Components of the Sarcomere

- **Myosin Filament**
  - Myosin dimers
  - Spontaneous assembly
  - ~43 nm

- **Actin Filament**
  - Actin filament (blue)
  - Tropomyosin filament (green)
  - Troponin (yellow)
  - ~37.5 nm

- **Light fraction**
- **Heavy fraction**

~10^{-9} \text{ m}
The Lymn-Taylor Cycle: Myosin Moves Along The Actin Filament ➔ Cross Bridge Cycle,
Control of the Sliding Filament Motion via Ca$^{2+}$ Ion Concentration

- When the Ca$^{2+}$ concentration is low, the myosin head cannot dock onto the actin filaments, as the myosin binding sites are covered by the tropomyosin filament (green).

- An increase of Ca$^{2+}$ concentration causes a change in conformation of the troponin units (yellow) that push the tropomyosin filament away from the binding sites (dark dots now visible in the bottom illustration).

- By gaining access to the binding sites, the myosin heads are now able to move relative to the actin filaments.
The hierarchical organization of muscles has advantages:

- Efficient transport of matter (e.g. ‘fuel’) to the muscle fibers. The blood vessels are highly branched. The blood can flow close to all muscle fibers before molecules are exchanged by other, slower methods (e.g. diffusion).
- Efficient load transfer from the actuator units (muscle fibers) to the structure.
Three Remarkable Things about Muscle

- Muscles convert chemical energy into mechanical energy without a ‘detour’ through thermal energy. High performance of the system is also due to the high energy density of the storage medium.
- Through their hierarchical design and sophisticated power controller mechanisms, muscles can overcome the limitation that mass transport would impose on bandwidth.
- While most muscles are essentially made of the same actuator material, they realize a wide spectrum of force-stroke combinations by exploiting refined actuator architectures.
When a new type of actuator is developed, it is tempting to call it ‘artificial muscle’.

Today we will briefly discuss three examples of ‘artificial muscles’:

- Chemo-mechanical coupling (with a detour through the thermal domain)
- Electro-mechanical coupling
- A mechanical-mechanical converter

… and we will ask ourselves what there is bionic in them
Macroscopic Behavior of Shape Memory Alloys

- One-way and Two-way Shape Memory Effect

![Graph showing the macroscopic behavior of shape memory alloys with different states and temperature changes.](image_url)
Pt-Coated Shape Memory Alloys

Activation Energy $\Delta E$

Pt-particle catalytic action

SMA wire

$H_2O ( + CO_2)$

$H_2$ or $C_{x}H_{y}O_{z}$

$O_2$

$N_2$
Robotic Jellyfish

Actuation by the SMA wires (yellow) over pulleys. Restoring force comes from leaf springs.

Actuation takes place when the hydrogen and oxygen are injected into the system. Recovery phase is initiated by flushing the system with purge gas (nitrogen or argon).

Dielectric Elastomer Actuators (DEA): Electromechanical coupling

- DEAs exploit electrostatic forces in dielectrics to convert electrical power into mechanical:

\[ \sigma = \varepsilon \varepsilon_0 \frac{U^2}{z^2} \]

\[ \lambda = f(\sigma, E(...), t, ...) \]

Compliant Electrodes

- Compliant (elastomer)
- ~ Incompressible
- Large deformation (l=3...5)
Bionic design and function

Connection in series of actuator units, similar to the sarcomeres in a myofibril

Fish-like propulsion through deformation of the complete ‘body’ by integrated actuators in ‘agonist-antagonist’ configuration

Videos: courtesy Empa
# Pneumatic Muscle: mechanical-mechanical power converter

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Angular Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kPa (0 psi)</td>
<td>$\theta_a = 67.36^\circ$</td>
</tr>
<tr>
<td>621 kPa (90 psi)</td>
<td>$\theta_a = 40.09^\circ$</td>
</tr>
</tbody>
</table>

Source: Michael F. Gentry Norman M. Wereley, EFFECTS OF BRAID ANGLE ON PNEUMATIC ARTIFICIAL MUSCLE ACTUATOR PERFORMANCE, Proceedings of SMASIS08
How Much Bionics is There in SMA Artificial Muscles?

✓ **Almost** direct conversion of chemical energy into mechanical energy
   → great advantage in terms of energy storage
✓ **Fiber-like** actuator base unit
   → possibility to tailor power output (force x velocity) by modifying the actuator architecture (pennation)

✗ Power controller function is realized by mass flow control.
✗ Chemical energy carrier not available ‘on site’
→ Limitations in actuation bandwidth
How Much Bionics is There in DEA Artificial Muscles?

✓ Stacked actuators offer the possibility to exploit architecture tailoring to modulate $F \cdot x$ output
  → flexibility in the mechanical output of the actuator
✓ Integration of actuators allows for agonist/antagonist actuation
  → Bionic propulsion has been demonstrated

✗ Source energy domain electrical.
  → Limited Energy density for storage
How Much Bionics is There in Pneumatic Artificial Muscles?

✓ Some possibility to tailor the actuation action of the muscle by means of the architecture (braid angle of the fibers)
→ flexibility in the mechanical output of the actuator
✓ Integration (origin/insertion) of PAM nearly identical as in
→ possibility to tailor power output (force x velocity) by modifying the actuator architecture (pennation)
✗ Actuated by mass transport
✗ Conversion within the mechanical domain
→ Limited bandwidth, additional conversion from other domain (e.g. electrical) necessary
Fascicles: Sub-units of The Muscle

- Fascicles are bundles muscle fibers. A bundle is comprised of tens to hundreds of fibers. According to Gray, they are prismatic in shape.
- The diameter of fascicles is in the millimeter scale.
- They are wrapped by a membrane called *perimysium*. This is thinner than the epimysium provides space for blood vessels and nerves.

An Old Piece of ‘Science’
Properties of Actuators (1)

- Properties related to energy output:
  - **Force**: Typically given as blocking force, i.e. force at zero displacement. It scales with the cross-sectional area of the actuator. Peak stress is a material property.
  - **Displacement**: Stroke (e.g. in linear actuator) that the actuator can produce. Maximum stroke can generally not be achieved at maximum force. Stroke scales with the length of the actuator.
  - **Work density**: Amount of work generated by the actuator (in one cycle) normalized with the actuator volume
Properties of Actuators (2)

- Properties related to power output:
  - **Strain rate**: Change in strain per unit time during a stroke. Maximum value is typically reported.
  - **Bandwidth**: The frequency at which strain drops to half of its low frequency amplitude.
  - **Specific power**: Power output per unit mass
Properties of Actuators (2)

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  - **Specific power**: Power output per unit mass

- Other Properties:
  - **Cycle life**: Number of stroke cycles that the system can undergo [before failure, statistically].
  - **Efficiency**: Ratio of generated work to input energy.