Robotik 1 - Robot Design Lab

Actuators

DFKI Bremen & Universität Bremen
Robotics research group

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Overview

- Motor & actuator types:
  - DC motors
    - Brush motor / brushless Motor
    - Inner runner / outer runner
  - Stepmotors
  - Servomotors
  - Quickshaft actuators
  - Electric Series Elastic Actuators
  - Hydraulics
  - Pneumatics
  - Artificial muscles (McKibben)
  - Fluidic microactors
  - Piezo actuators
    - Linear actuators
    - Stepmotors & travenling wave motors
  - Squiggle-motors
  - Smart materials
    - Elektroactive Polymers
    - Shape Memory Alloys
    - Muscle wires

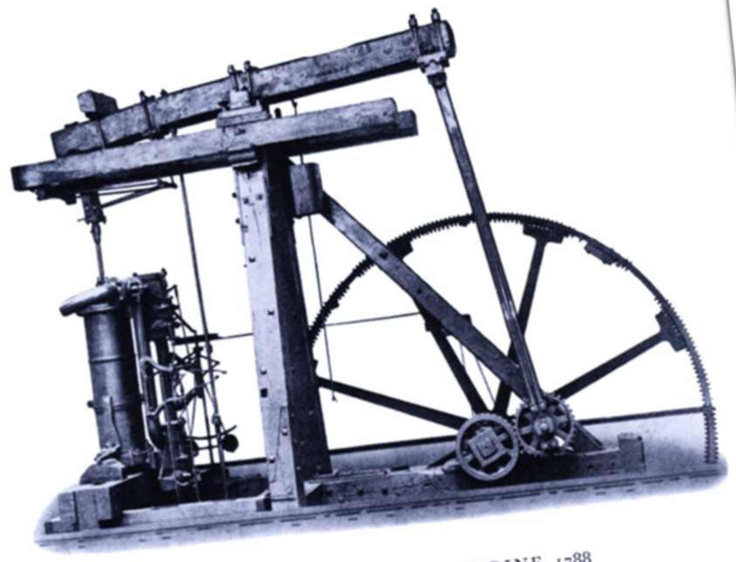


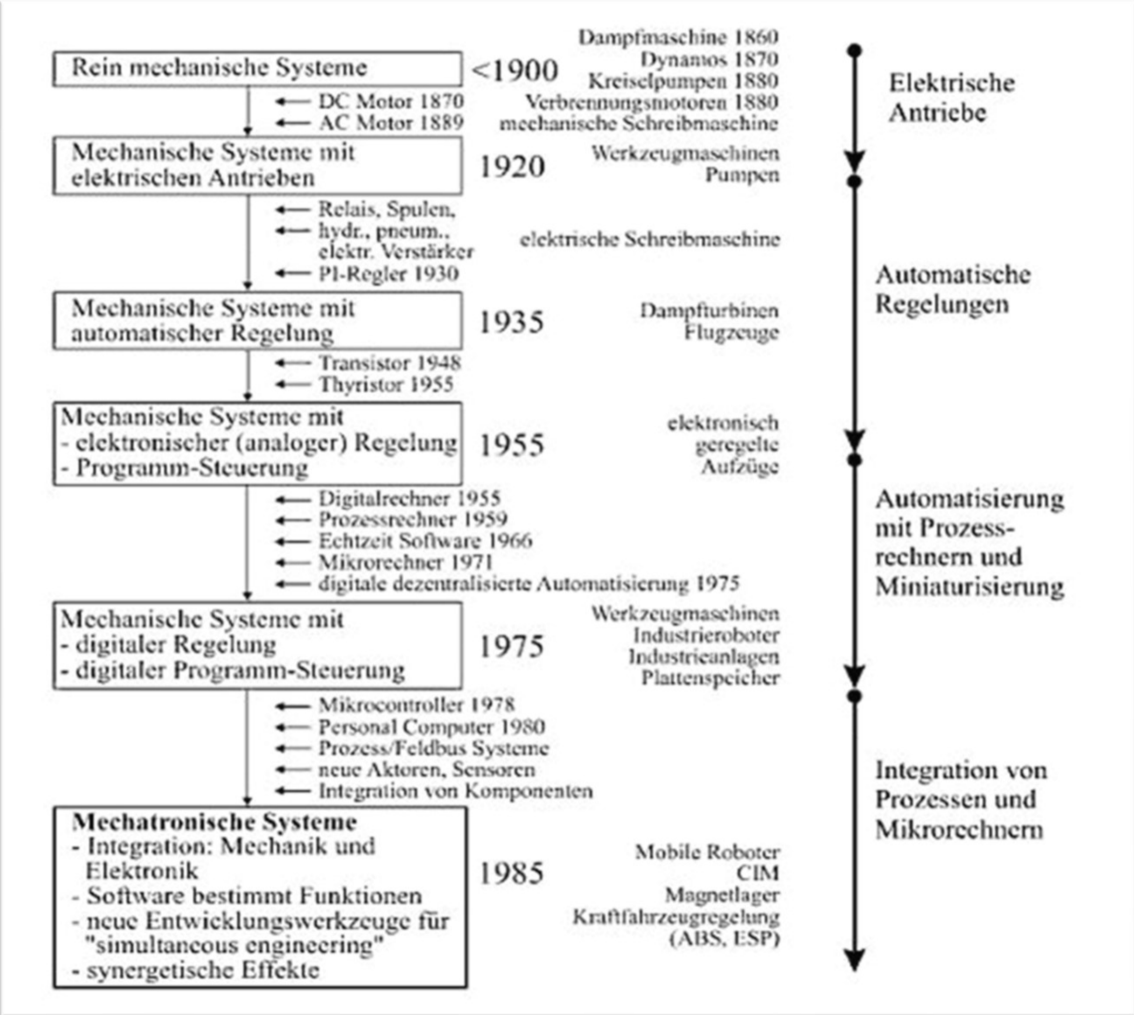
PLATE XII. THE "LAP" ENGINE, 1788
Courtesy of the Science Museum

- Actuators
  - Drive element / (energy-)converter
  - converts signals (energy) into mechanical movement
  - e.g.: DC-motor, hydraulics, piezo-actuators, combustion engines etc.

Terminology

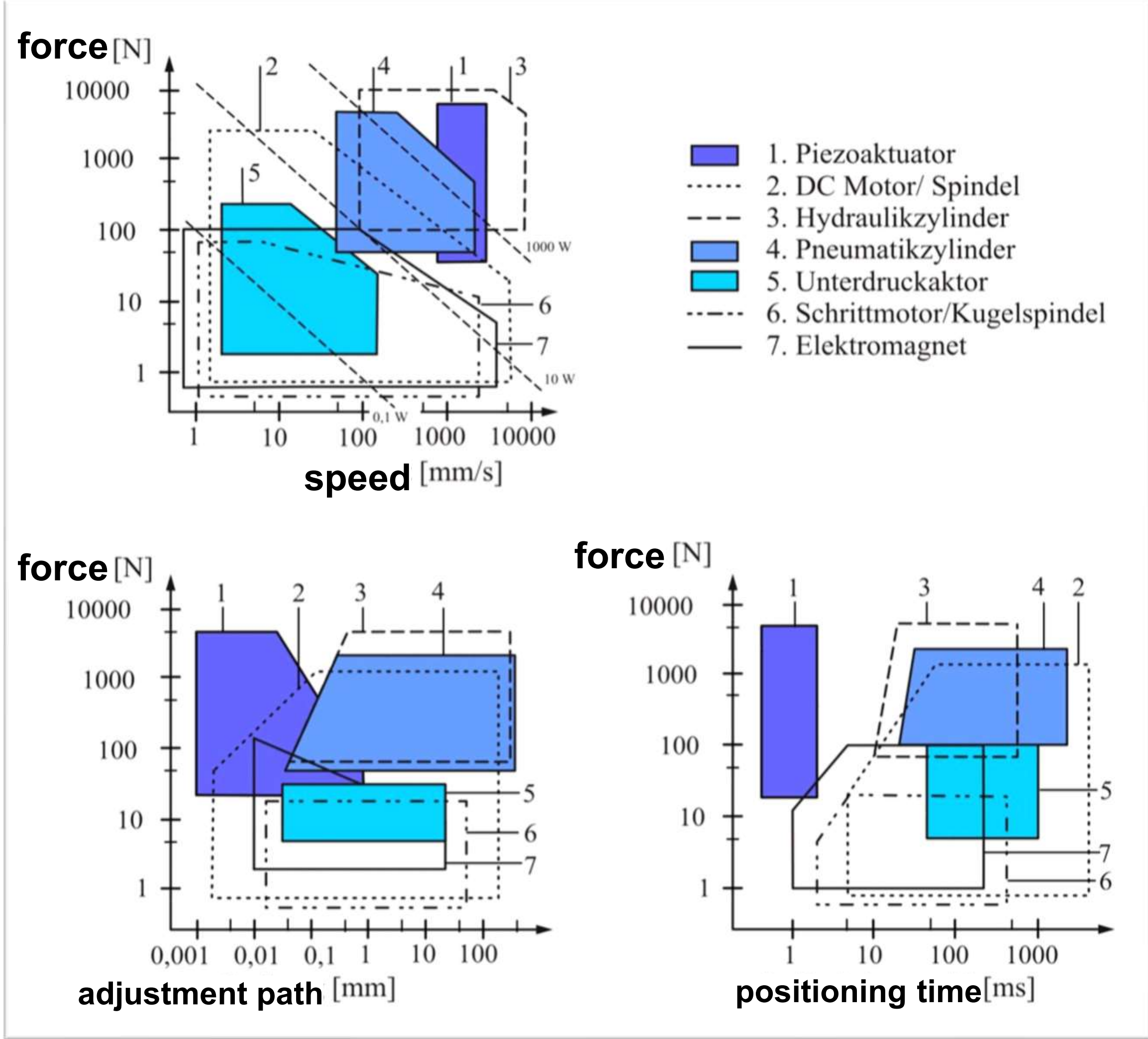
- Bus System – Communication System between a controller and several attached devices e.g. CAN
- Load – a load connected to the actual actuator [Watt]
- Piston – an pneumatic or hydraulic actuator for linear movements
- Position control – moving an actuator by position informations
- Rotor – moving part of an electric motor (anchor)
- Rpm – revolutions per minute
- Speed control – moving an actuator by actual speed values
- Stator – Static part of an electric motor (coil)
- Shaft – connection of a rotating or a linear actuator to their environment
- Torque – M = r * F / torque = position vector x force vector [kg m^2 s^-2]

Historical development



(Source: Isermann, 1999)

Comparison of actuators



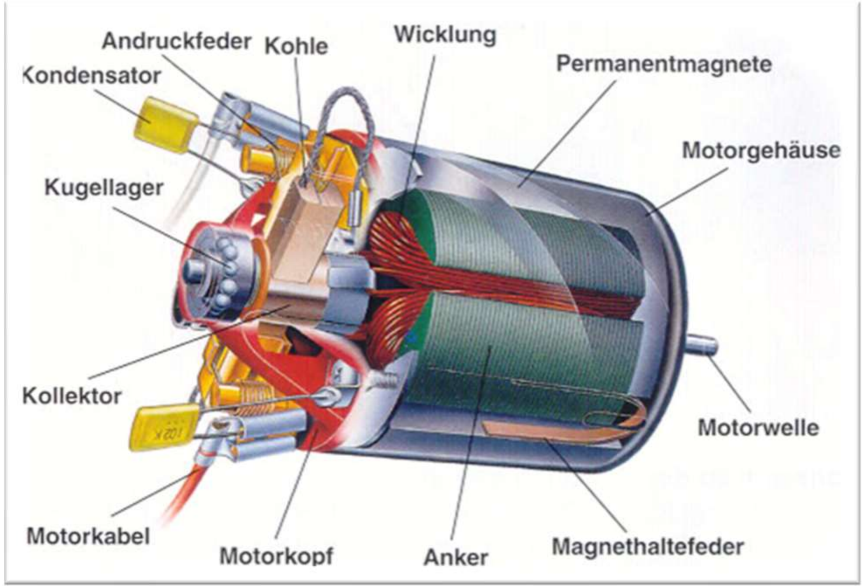
(Source: modified after Isermann, 1999)

DC - motors

- Direct current motors
  - Up to 98% efficiency
  - Power cord or battery

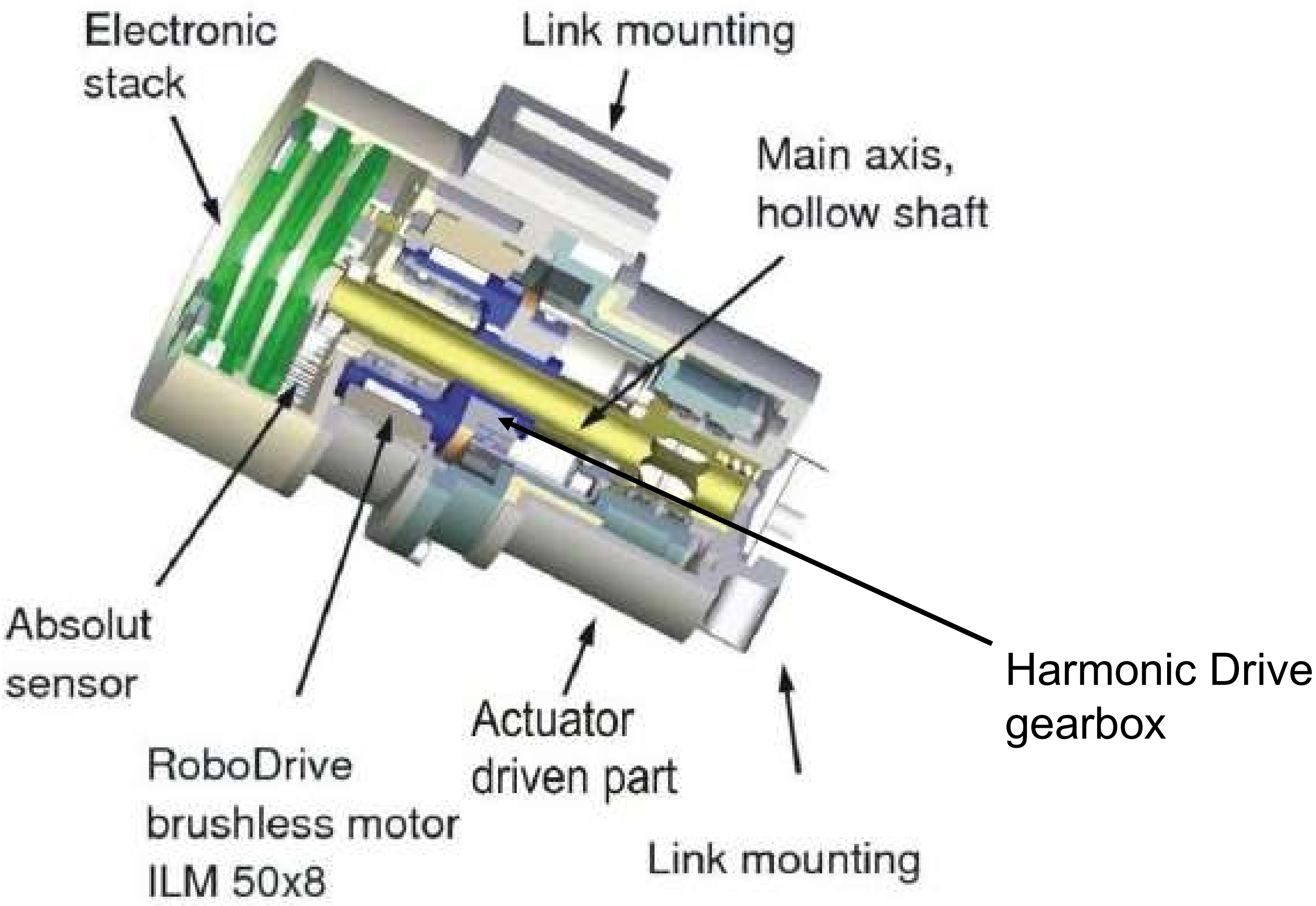
  - Brush motor:
    - cheap
    - Mature technology
    - Sparking / high-frequency interferences
    - Life limit – carbon brushes

  - Brushless motor:
    - More efficient / less heat
    - Less wear
    - Mor power per weight
    - Requires a controller



(Sources: oben: rc-forum.de, 2010; unten: tq.group.com 2015)

DFKI SpaceClimber joint



DC – motors

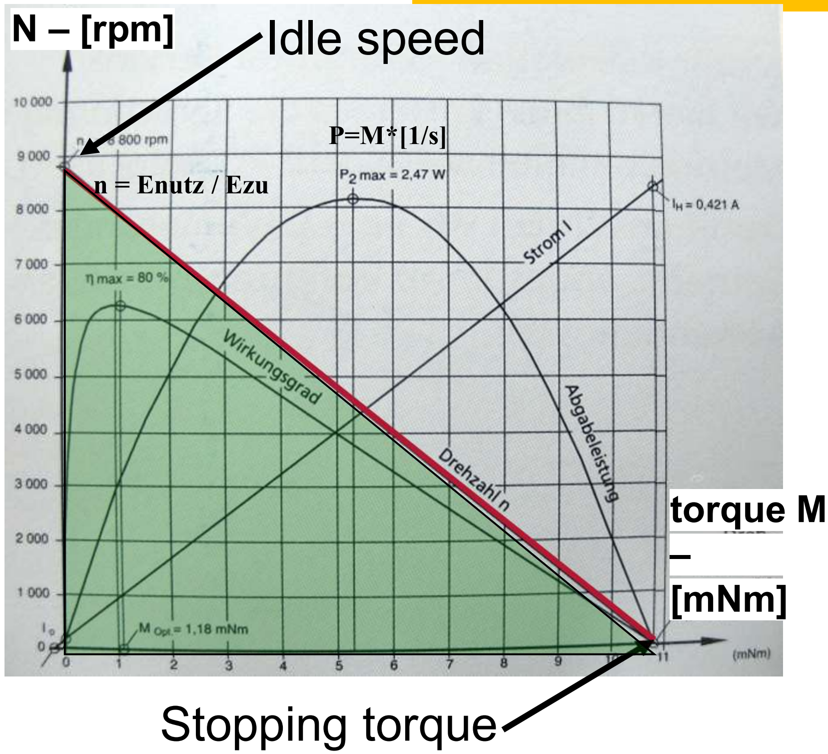
- Inner rotor motor / external rotor motor
  - This refers to the arrangemant of the rotor, stator and the shaft
  - Inner rotor: low mass on the shaft
    - Permanent magnets inside – coils outside
    - High speeds / high performance level
  - Outer rotor: higher weight on the shaft
    - Permanent magnets outside – coils inside
    - Constant running behaviour /
      high torque and overload potential at low speeds

(Source: powercroco.de, 2010)

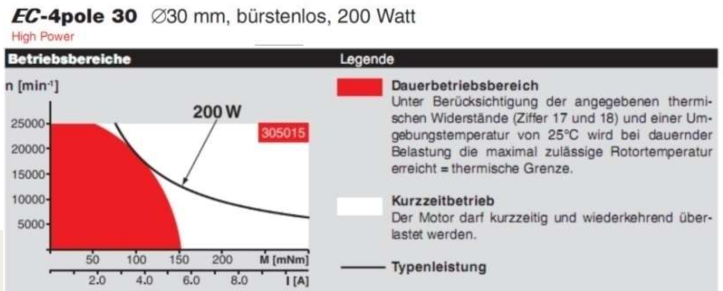
DC motor parameters

- Example: Faulhaber 3257 motor
- 169 : 1 reduction gear
- Speed-dependent maximum torque

Motor characteristics



Rotary encoder



Source: Faulhaber u. Maxon Katalog

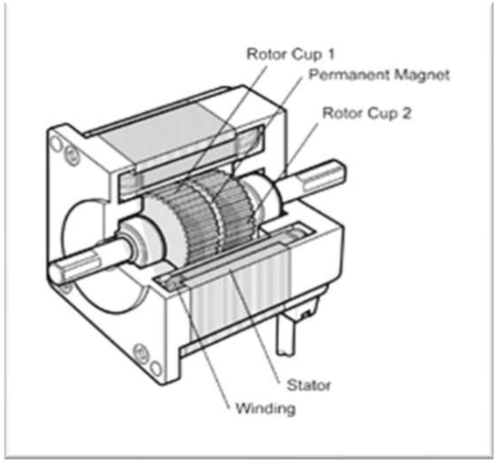
Universität Bremen

Stepper motors

- **Revolutions will be made in an amount of steps (degree), not as a constant movement, exact positions can be achieved**

- **Bipolar:** 2 coils 4 connections (more power per motor-volume)
- **Unipolar:** at least 5 connections, simpler control

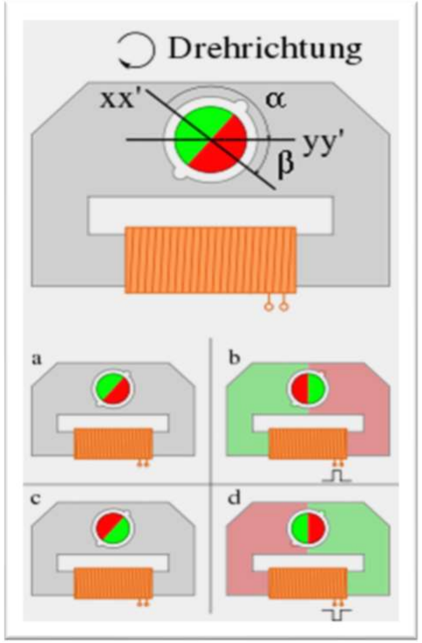
- Reluctance motor
  - toothed soft iron structured rotor
  - No permanent magnets
  - Free magnetic flow,
    no magnetic field after switched off
- Permanentmagnet motor
  - Permanentmagnet on the shaft / Stator made of soft iron
  - Moment of rest
  - Lower resolution in comparison to ther reluktance motor
- Hybridmotor
  - Permanentmagnet and
    toothed soft iron core on the shaft



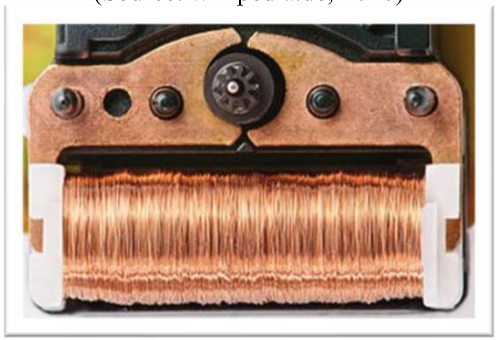
(Source: orientalmotor.com, 2010)

Stepper motors

- Lavet-Stepper motor
  - Single phased stepper motor
  - Only one direction of rotation
  - Rotor is equiped with permanent magnet
  - Moments of rest of the motor are important for its function principle (Pic. r/o a & c)
  - Miniaturisized version of the Lavet-stepper motor → turns the clock hands (seconds)



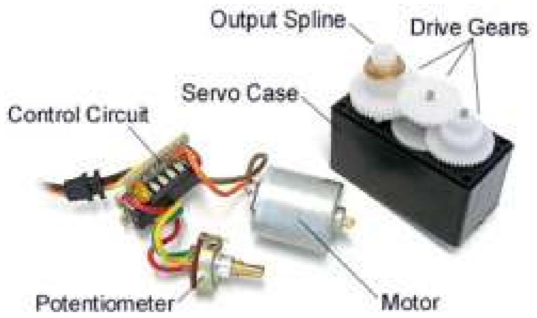
(Source: wikipedia.de, 2016)

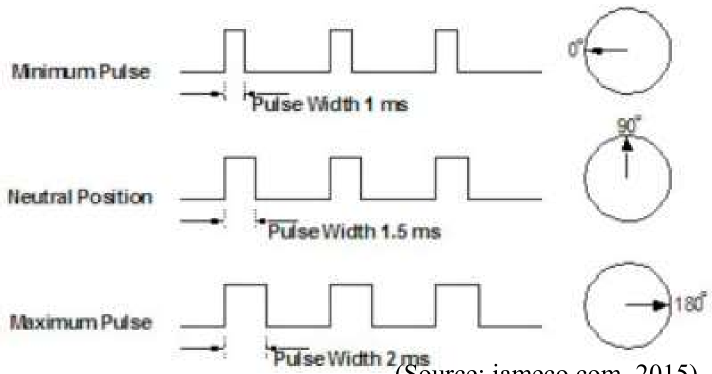


(Source: wikipedia.de, 2016)

Servo motores

- Analog servos
  - Low power consumption
  - Low price
- Digital servos
  - Faster positioning time
  - Higher resolution
  - Partly programmable
- PWM-control
  - Common for hobby servos
  - Servo elektronics regulate the actor (potentiometer) against the motor position
  - The pulse width of the control signal regulates the target position
  - Various variations on pulse widths and travel ranges





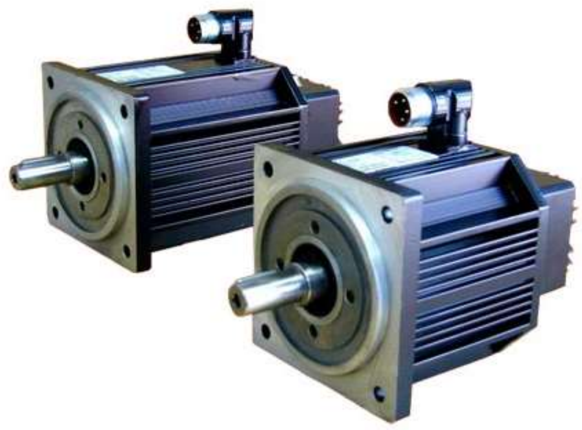
(Source: jameco.com, 2015)

(Source: wikimedia.org, 2015)

Servo motors

- Industrial Servo motors
  - Higher performances
  - Higher precision

  - Avaible bus-systems:
    - RS232 / RS 485
    - CAN
    - Profibus DP
    - INTERBUS
    - SERCOS
    - EtherCAT
    - FIREWIRE IEEE1394
    - And more…



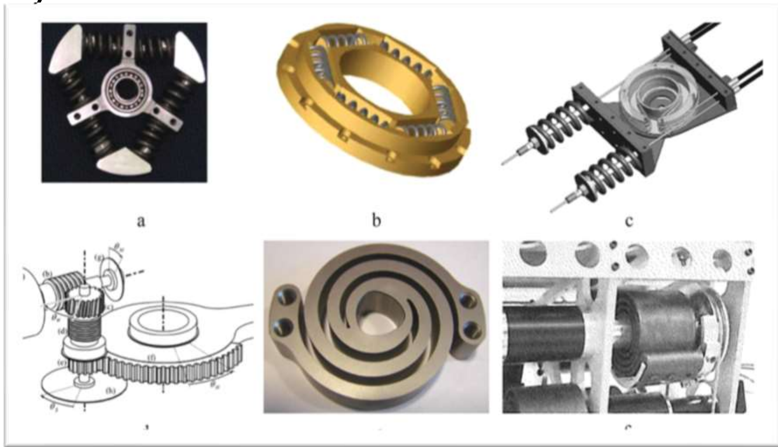
(Source: jameco.com, 2015)

Series Elastic Actuator

- Combination of:
  - Static drive
  - Elastic element (e.g. spring, polymer etc.)

  - properties:
    - Good force regulation in unstatic environments
    - High force accuracy
    - Low impedance (vibration resistance)
    - Low frictional forces
    - Large range of force regulation

(Source: ihmc.us/groups/sea/, 2015)

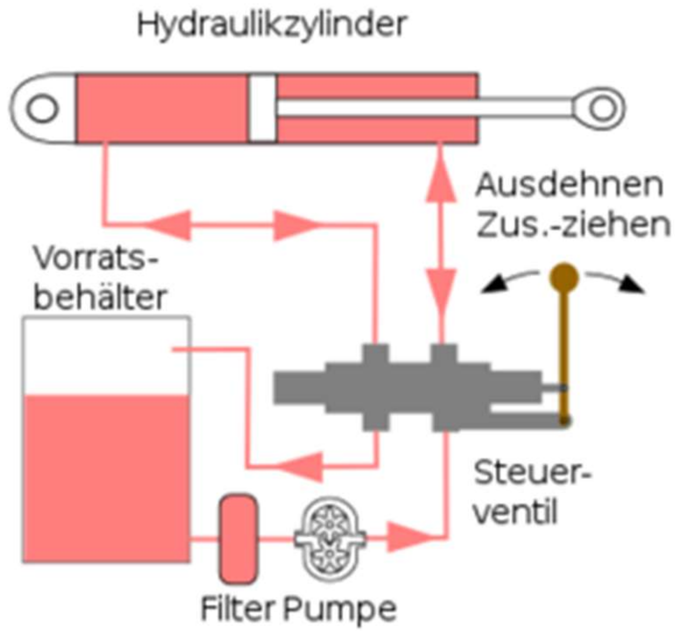


(Source: asme.org, 2016)

Developed at:
Florida Institute for Human & Machine Cognition
→ http://www.ihmc.us/groups/sea/

Hydraulics

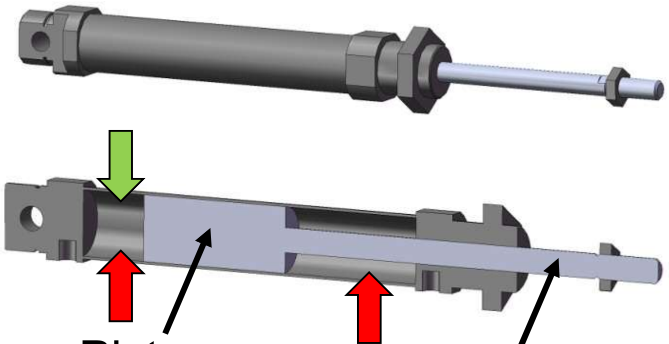
- No actuator but a „gear type“
- → Power, energy, force or torque transfer
- High power
- Slow positioning speed
- Energy density:
  - 210 bar (Industry standard)
  - > 500 bar



(Source: wikimedia.org, 2015)

Cylinders

- Linear actuators
- The range of movement is called the stroke
- Pneumatics – air pressure approx. 10 bar
- Hydraulics – oil pressure approx. 210 bar



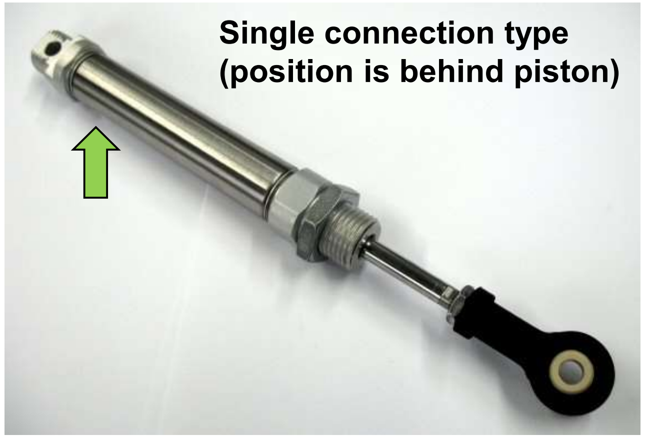
Piston

Piston rod

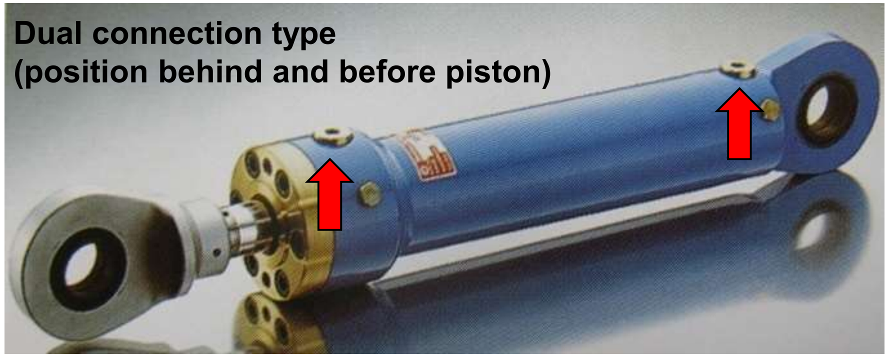
$$F = p \times A$$

force [N] = pressure [N/mm²] x piston surface [mm²]

1 bar = 0,1N/mm²



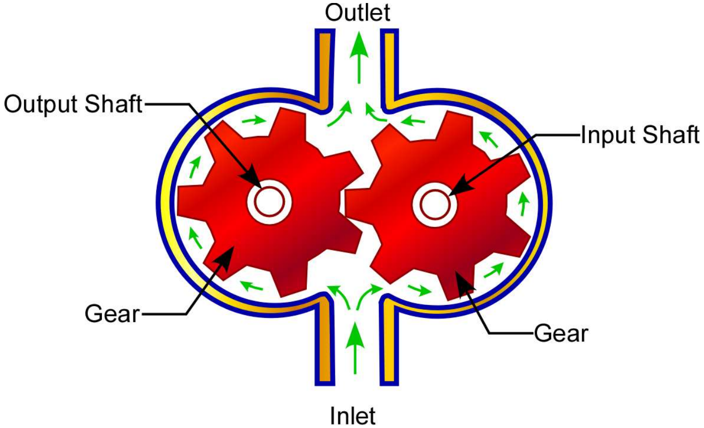
Pneumatic cylinder



Hydraulic cylinder (Source: Hänchen Hydraulik)

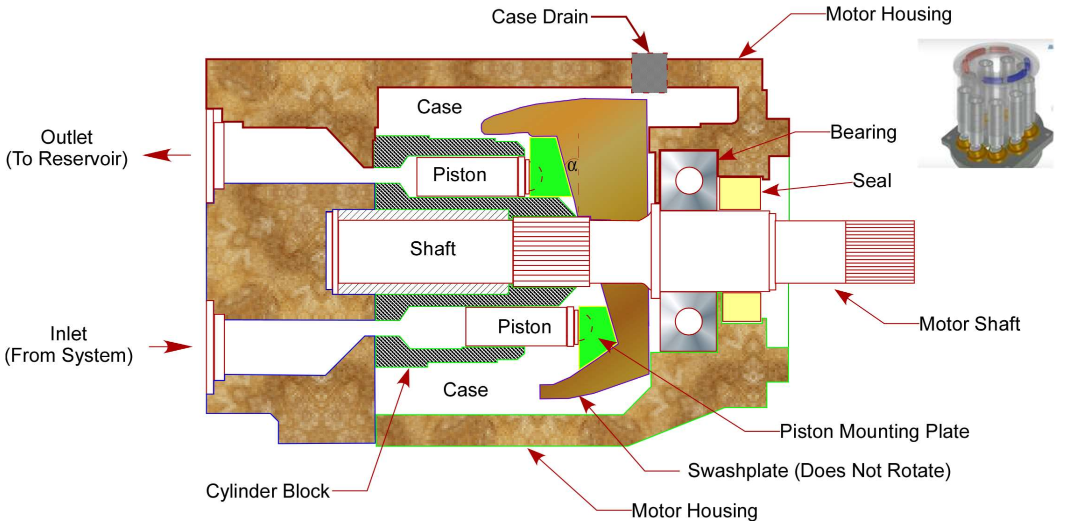
Hydraulic rotary drives

Hydraulic gear motor



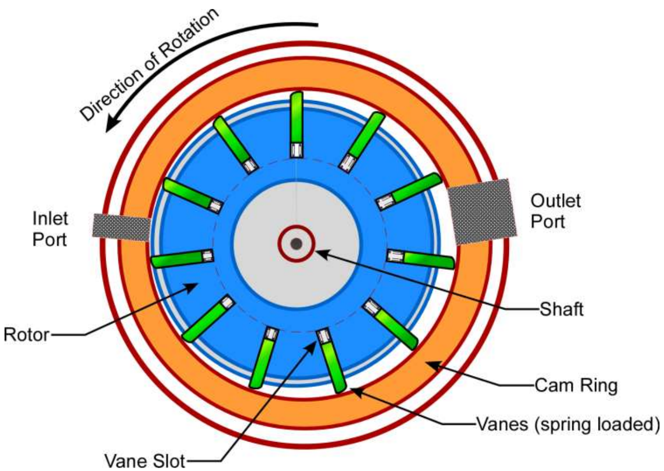
(Quelle: daerospace.com, 2015)

Hydraulic axialpiston motor

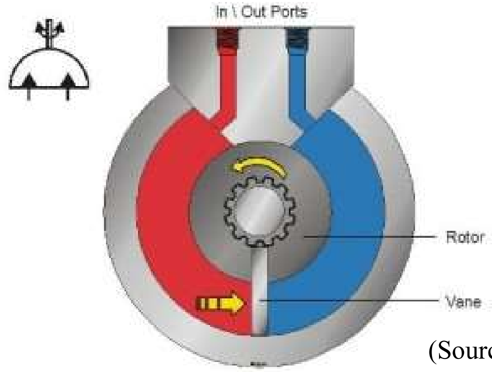


(Source: daerospace.com, 2015)

Hydraulic shovel motor



Hydraulic servo



(Source: hydraulicguide.com, 2015)

Hydraulics

- Advantages
  - High power density
  - Good controllability
  - Good timing behaviour due to low inertia
  - Simple and reliable protection against overload
  - Good energy transmition over medium distances
  - Good lubrication and dissipation of the heat loss through the pressure transmission medium
- Disadvantages
  - High energy consumption
  - High weight of drive and control elements
  - Losses from friction and internal leakage
  - Sensitive to dirt
  - Fire hazard

Pneumatics

- Pneumatic drives have certain similarities to hydraulic drives, but differ enormously from each other in certain areas.
- For a pneumatic system, a compressed air tank or even a compressor is required to bring energy into the system.
- The control processes here also take place via valves, via which the medium is passed on either in cylinders (as a linear drive) or motors (as a rotary drive).

- Expansion tanks ensure even pressure distribution within the system. Nevertheless, precise control of the pneumatic system is not without problems, since air, unlike oil, is compressible.
- However, the higher flow velocities of the air also result in higher piston velocities. If a hydraulic cylinder does its job at a maximum speed of 60 m / min, the pneumatic cylinder does it at 300 m / min. In terms of energy density, however, the hydraulics are at a pressure of 210 bar (industry standard) before the pneumatics, which are set to 6 - 10 bar, max. 15 bar (limit).

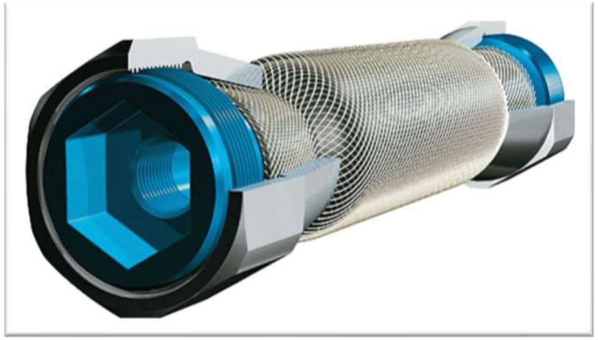
Pneumatics

- ## Advantages
  - The forces and speeds of the cylinders are infinitely variable.
  - High achievable working speeds (standard cylinder 1500 mm / s; high-performance cylinder 3000 mm / s, engines up to 100.000 min-1)
  - Compressed air devices can be overloaded to a standstill without damage.
  - Compressed air can be stored in pressure tanks.
  - With pneumatics, waste heat is only generated centrally at the compressor, not at decentralized electric drive units.
  - Air is free of charge and always available (however, energy consumption at the compressor is required to compress the air; the efficiency is comparatively low).
  - Clean, environmentally friendly medium.
  - The exhaust air can escape directly into the environment, return lines can be omitted.
  - Explosion safety of the medium is guaranteed.
  - Compressed air is insensitive to magnetic impulses.
  - Sealing and throttling technology possible (sine cylinder).

- ## Disadvantages
- Without fixed stops, precise positions are not possible due to the compressibility of the air.
- Compressed air escapes causing noise. Countermeasures are silencers.
- Compressed air treatment is required to remove dirt and moisture.
- Gases are compressible. Bursting pneumatic accumulators release large gas volumes. This can have a devastating effect, especially in closed rooms. For this reason, pneumatic containers are subject to regular inspection (costs) from a certain size.

Artificial muscles (mcKibben actuators)

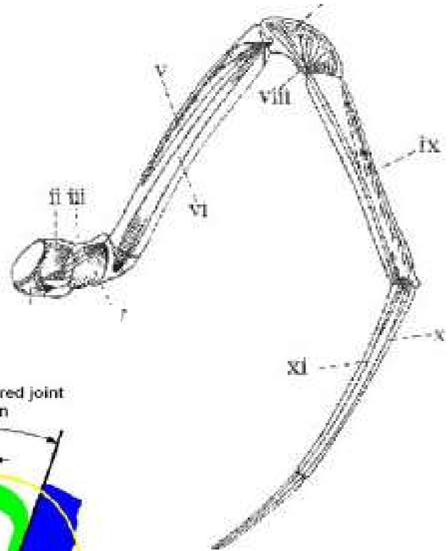
- Advantages:
  - lightweight
  - Environmental friendly
  - Simple and direct integration
  - The acutator is very near to its biological inspiration

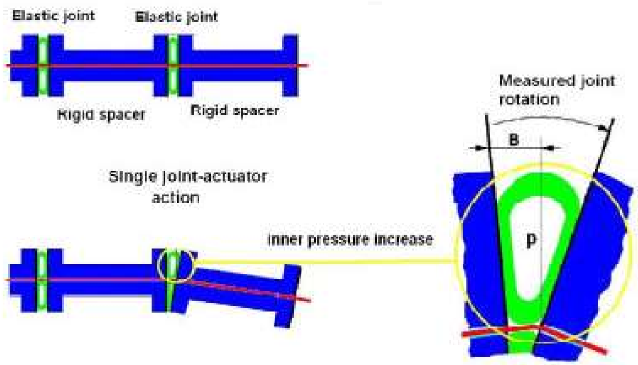


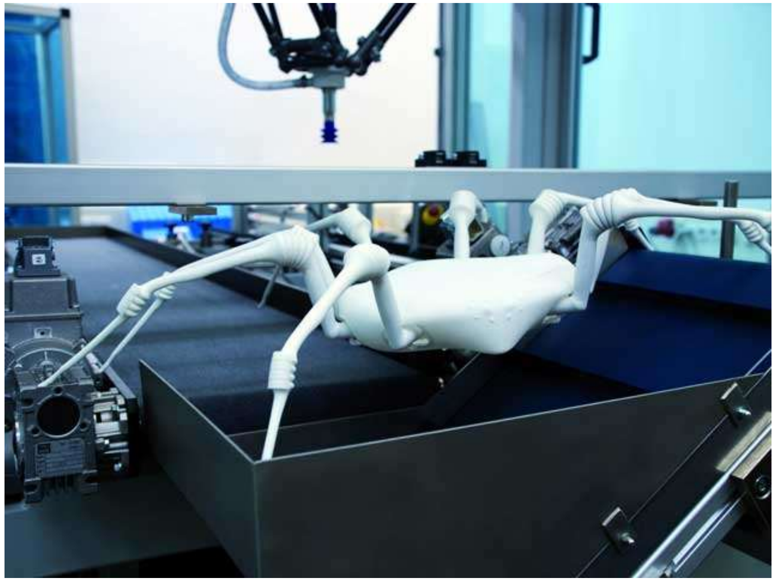
- Disadvantages:
  - Non linear behaviour -> control
  - Force depends on:
    - pressure
    - Status of the bladder
  - Delays while using big muscle bladders due to air compressivity
  - Damage of the bladder leads to uneven deformation or cracking of the bladder

Pneumatic Muscles I

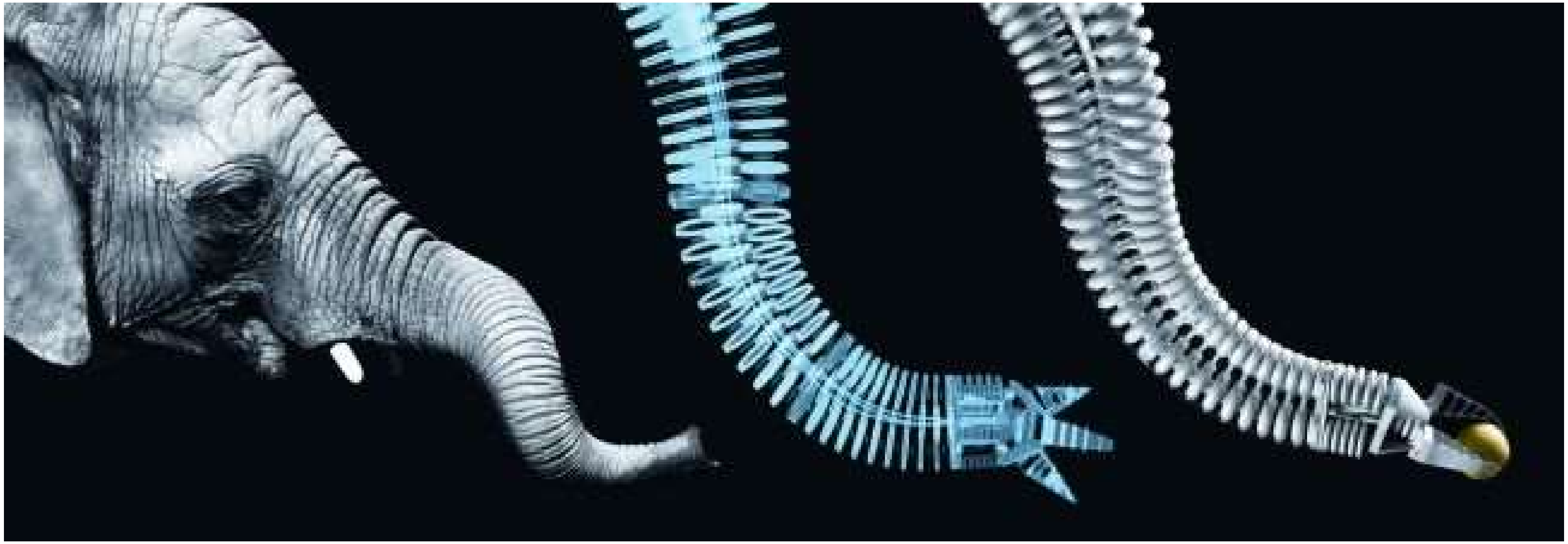
- IFAM spider-robot
  - Integrated pneumatic cells within the 3D printed structure
  - Usage of different materials during the printing process
  - Built aufer biological inspired spider actuation: combination of muscles and fluidactuators (pressure pads)



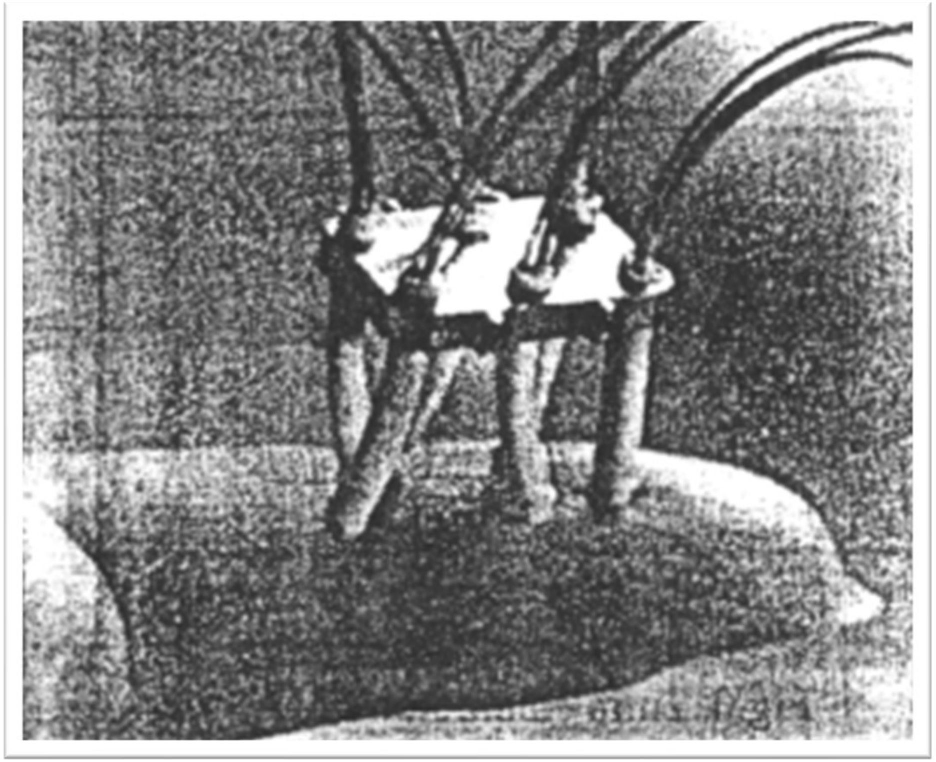


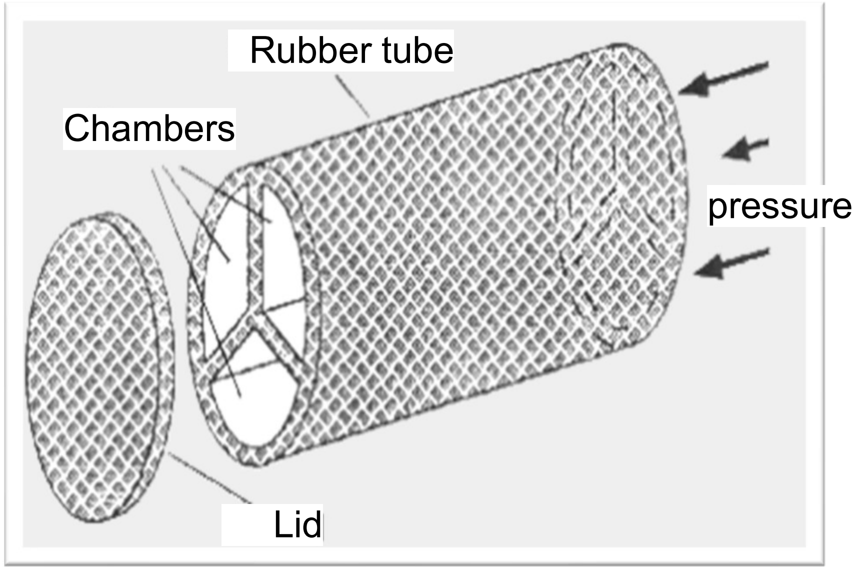


Pneumatic muscles II



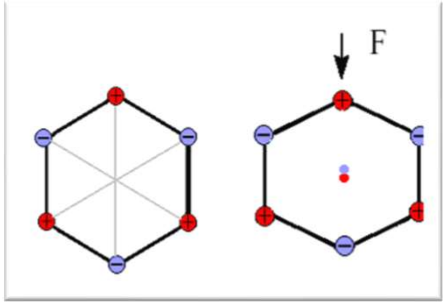
Fluidic microactuator





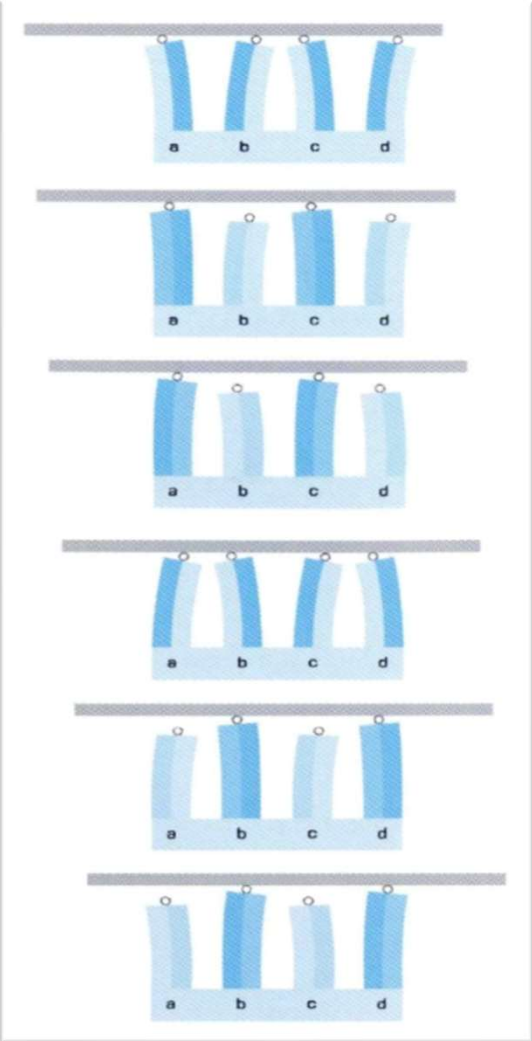
Piezo - actuators

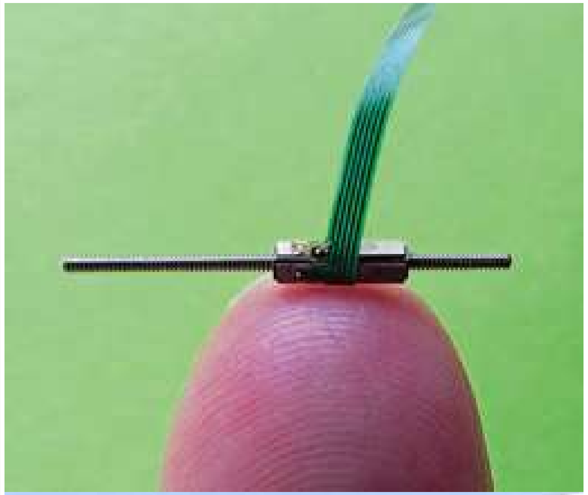
- „piezein“ – (greek) to press
- Atomic electro-deformation-phenomenon
- Certain cristalls generate electric charges if their structure is beeing deformed
- The effect is bidirectional useable
- Very low travel / very high forces

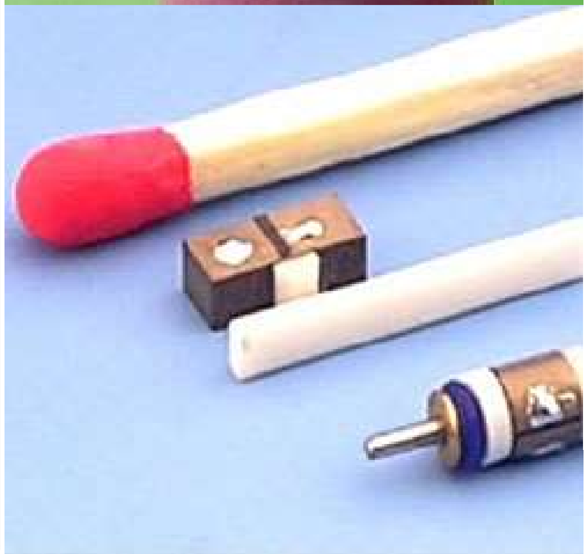


  - The spartial arrangement of the crystals is important to archieve longer travel ranges
  - First approximation of the movement is proportional to the stored electrical charge
  - No additional energy is required to hold a position unter load

Linear piezo-actuators



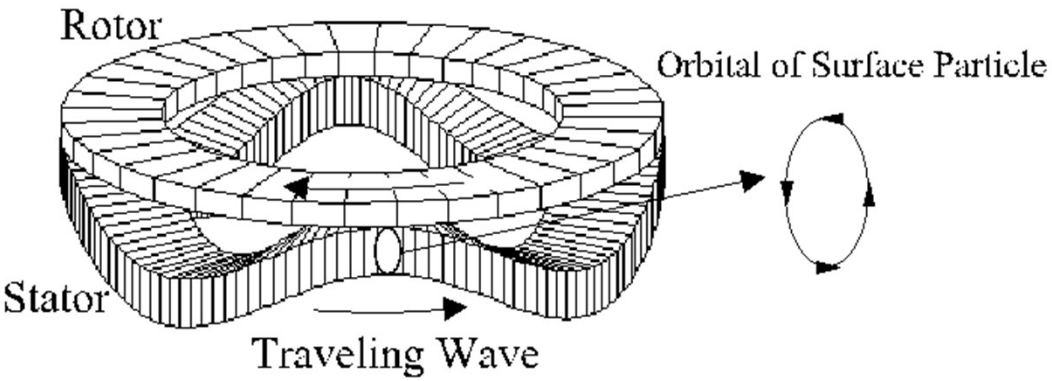




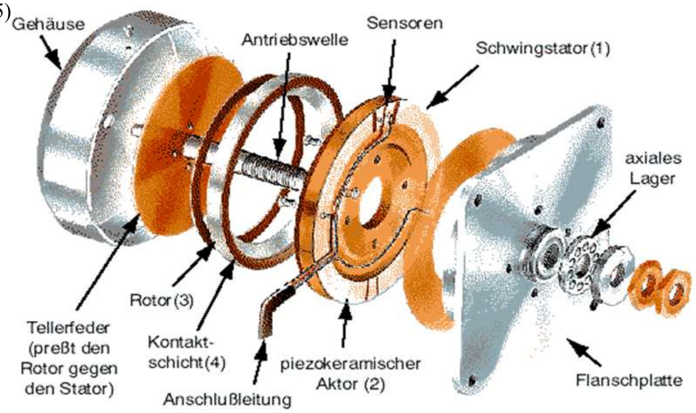
Piezo LEGS®
Linear

Rotative piezo-actuators

Ultrasonic – travelingwave-motor



(Source: jpl.nansa.gov, 2015)

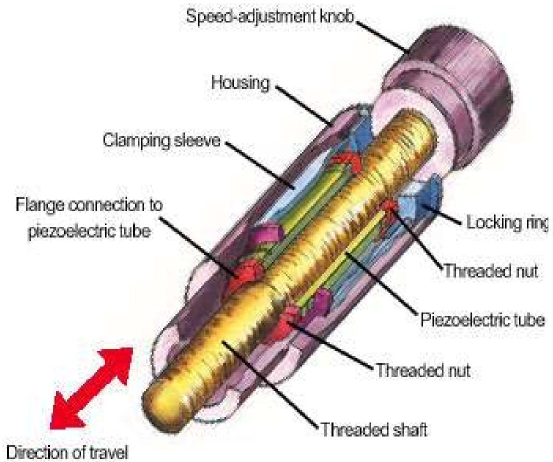


(Grafik: Daimler-Benz Forschung)

- The stator is excited by piezo-actuators at approx. 45 kHz.
- An approx. 1µm high traveling wave is created on the stator.
- This sets the motor in motion.

Squiggle - motor

- Various piezo elements are coupled to a nut that drives a shaft.
  - Resolution is in the nanometer range
  - Up to 10 mm/sec. or 12.000 RPM
  - 5 Newton linear or 3 mN-m rotative
  - Dimensions: 1.8 x 1.8 x 6 mm

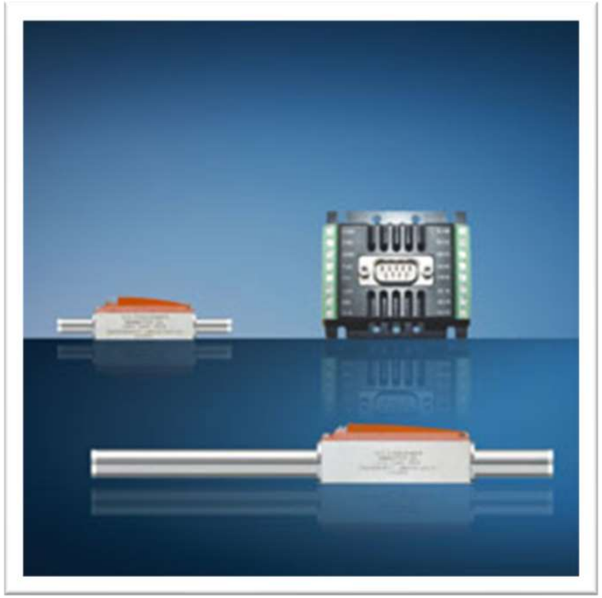


(Quelle: machinedesign.com, 2015)

(Source: newscaletech.com, 2015)

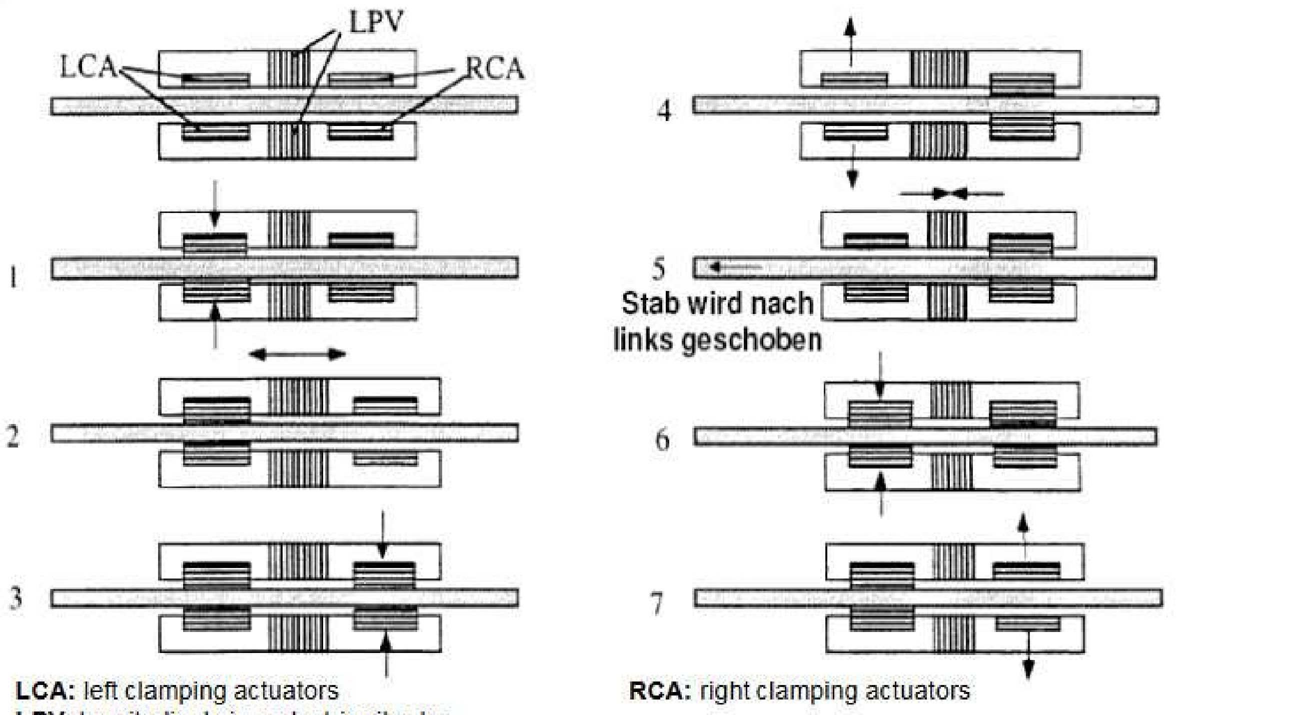
Quickshaft actuator

- Linear motors
  - Elektromagnetic drive
  - 10 – 27 N positioning force
  - Max. lift 120 mm
  - Positioning accuracy +/- 0.05 mm
  - Available bus-systems:
    EthreCAT, POWERLINK, PROFINET,
    SRECOS III, TCP/IP, Profibus-DP,
    CANOpen, DeviceNet



(Source: motionshop.com, 2015)

Inchmotor / Caterpillar-motor



David Newton et al., A linear piezoelectric motor, Smart Mater. Struct. 6 (1997) 295–304

(Source: schmetterling-raupe.de, 2017)

Smart materials

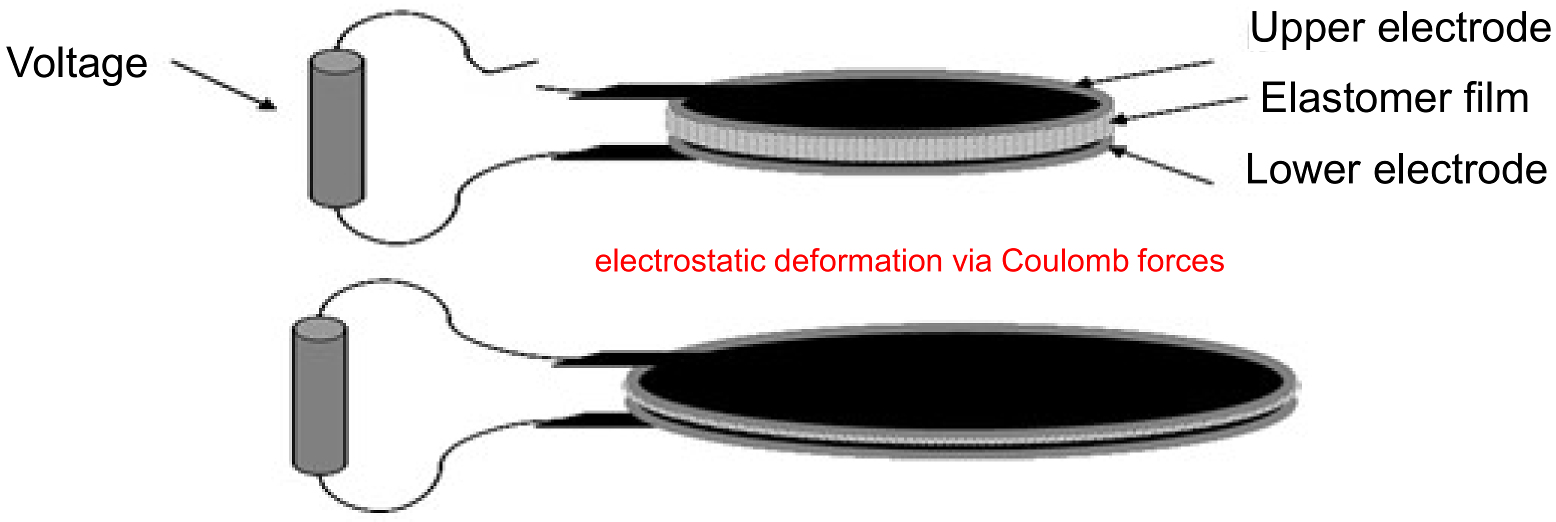
- EAP
  <u>electroactive polymeres</u>
  - Dielectrical EAPs
    - Electrical charge transport
    - High stretch possible
    - Need of high electrical voltage
    - Low electrical power consumption
    - Energy free position keeping
  - Ionic EAPs
    - Diffusion of ions
    - Higher electrical energy consumption
    - Positioning requires energy

Property	EAP	SMA	EAC
Actuation strain	Over 300%	<8% (short fatigue life)	Typically 0.1-0.3%
Force (MPa)	0.1-25	200	30-40
Reaction speed	µsec to min	msec to min	µsec to sec
Density	1-2.5g/cc	5-6g/cc	6-8g/cc
Drive Voltage	IonicEAP: 1-7V Electronic EAP: 10-150V/µm	5V	50-800 V
Consumed power	Mwatts	Watts	Watts
Fracture behaviour	Resilient, elastic	Resilient, elastic	Fragile

- SMA
  shape-memory alloys

- EAC
  electroactive ceramics

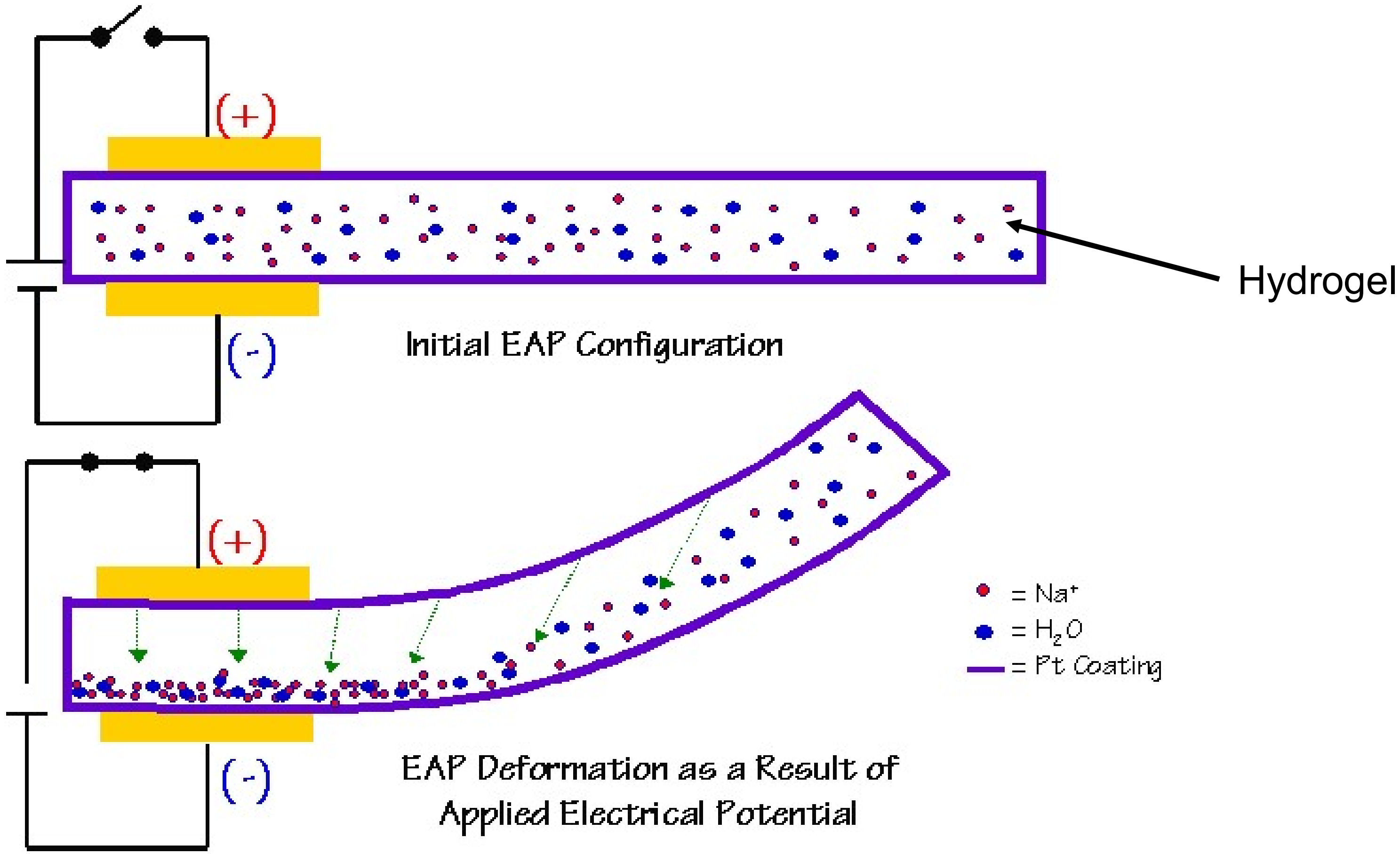
Dielectric EAP



A dielectric material must be / is polarizable.

(Source: hizoog.com, 2015)

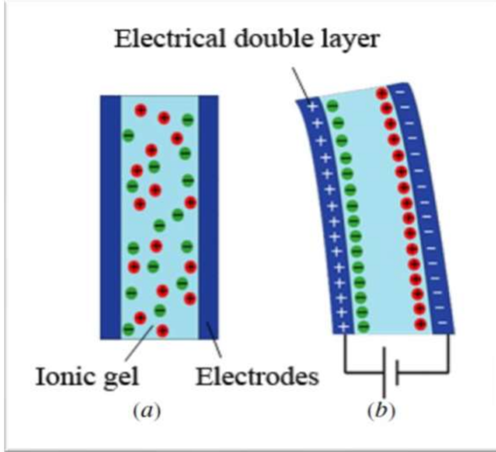
Ionic EAP



(Source: hizoog.com, 2015)

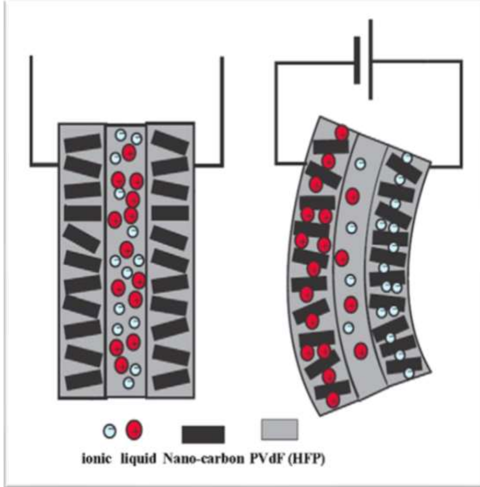
Ionic-gel actuators

(Quelle: nasa.gov, 2010)



(Source: Saito, 2008)

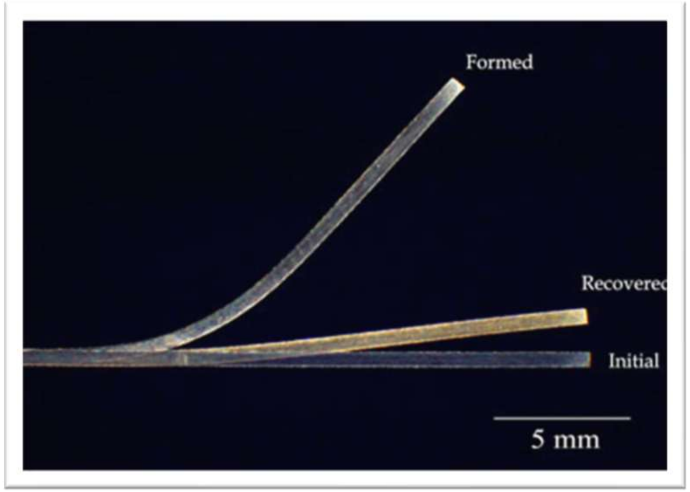
- Compareable with Ionic-EAPs with a gel-like substance
- Transformation by ion diffusion



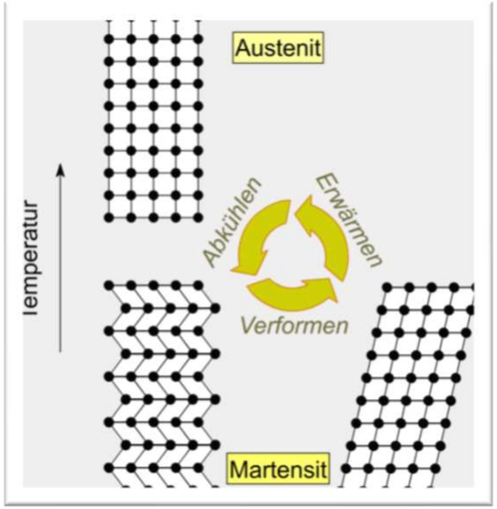
(Source: Mukai, 2009)

Shape memory alloys (SMAs)

- Deformation possible at room temperature
- (Back-)transformation due to heating
- „burning in“ the shape at approx. 500 degrees Celsius
- Deformed martensite is returned to its original austenite phase by energy supply.
- High specific work capacity
- > 100.000 movement cycles without fatigue
- One-way (memory)effect
  - Reshaping when heated
  - Used as an actuator, an restoring force is nedded. (f.e. a spring)
- Two-way (memory)effect
  - Reshapeing when heated
  - (Back-)transformation after cooling (into trained cold-shape)
  - No work can be done on the cold backtransformation
- Use in nano or micro robotics



(Source: nasa.gov, 2010)



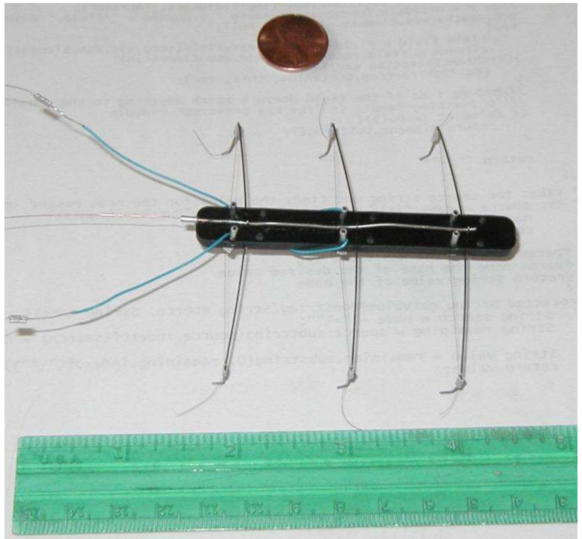
(Source: de.academic.ru, 2010)

Muscle wire (Flexinol / Nitinol)

- Nickel-Titanium alloy
- **N**ickel **T**itanium **N**aval **O**rdnance **L**aboratory → NITINOL
- Linear actuators
- Also a shape memory alloy
- Small diameter – high forces
  (250 µm / 930 g / 9,11 N)
- Long cycle times
- Use in nano or micro robotics

(Source: muskeldraht.de, 2015)

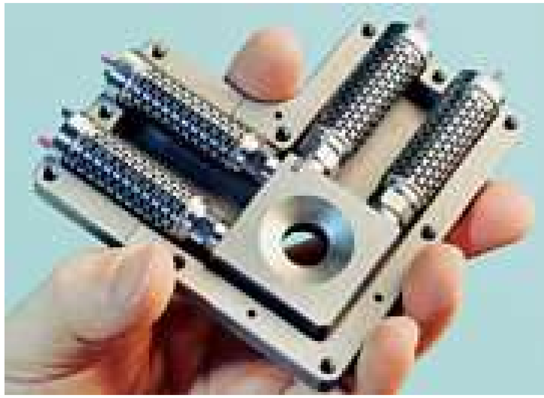
(Source: heurekablog.com, 2015)



(Source: hizook.com, 2015)

Electroactive ceramics (EACs)

- Ceramics with piezoelectrical effects
- → Sub-area of the allready mentioned piezo-actuators
- Short range in travel
- High forces
- An additional controller is needed
- Usage in linear and rotative motors



Positioning actuator with electroceramic elements. (Source: Simens.com 2015)

recap slide

- Common and innovative motor concepts
- General overview on DC motors
- General overview on hydraulics and pneumatics
- Parameters that are needed to find the right actuator for the application
- Experimental actuators for further (robotic) applications
- Bioinspired actuators
- Atomic force driven actuators

Thank you for your attention!

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