Week 02: Electromechanical Actuators 1

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Lecture Overview

- Piezoelectric Materials
- Shape memory alloys

- Next week: Dielectric elastomers and electrostatic actuators

First Assignment

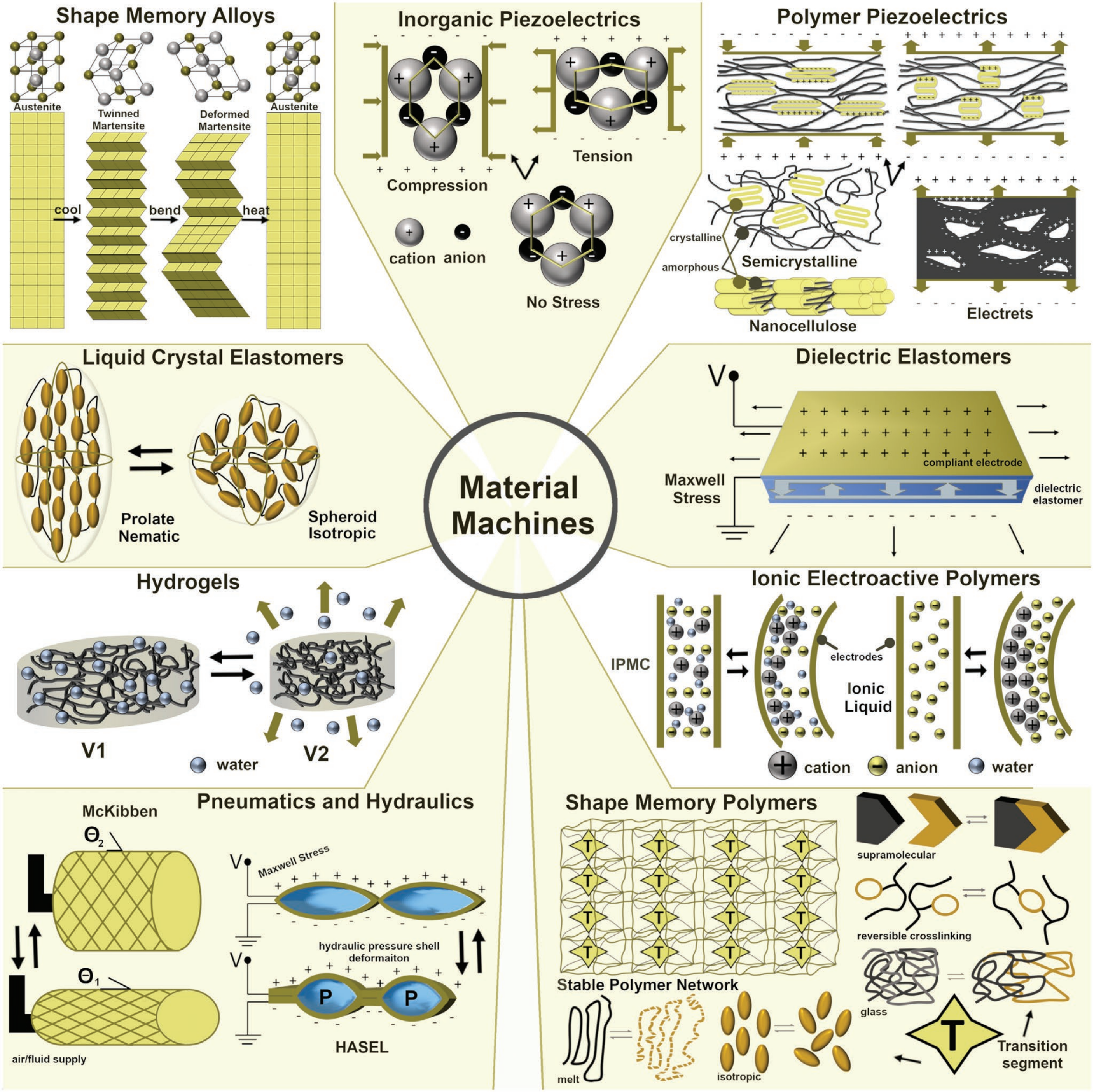
- **2 Questions per Person**
- Direct entry of text

- First deadline: February 27th, Thursday at midnight

Insect-scale jumping robots enabled by a dynamic buckling cascade

Electricity and Actuators

- Electrostatic
- Electrochemical
- Electromechanical
- Electromagnetic



Material Machines
Shape Memory Alloys
Austenite
Twinned Martensite
Deformed Martensite
Austenite
cool
bend
heat
Inorganic Piezoelectrics
Compression
Tension
cation anion
No Stress
Polymer Piezoelectrics
crystalline
amorphous
Semicrystalline
Nanocellulose
Electrets
Liquid Crystal Elastomers
Prolate Nematic
Spheroid Isotropic
Dielectric Elastomers
V
compliant electrode
Maxwell Stress
dielectric elastomer
Hydrogels
V1
water
V2
Ionic Electroactive Polymers
IPMC
electrodes
Ionic Liquid
cation
anion
water
Pneumatics and Hydraulics
McKibben
Θ2
Θ1
air/fluid supply
Maxwell Stress
hydraulic pressure shell deformaiton
P
HASEL
Shape Memory Polymers
supramolecular
reversible crosslinking
glass
Stable Polymer Network
melt
isotropic
Transition segment

Electricity and Actuators

- Piezoelectric effect: Crystals materials (e.g. tourmaline, topaz, **quartz**, cane sugar, **Rochelle salt**) producing electrical charges across their boundaries in response to applied mechanical stress

- Discovered in 1880 by Jacques and Pierre Curie brothers

- First practical application: sonar device, World War I

- Ferroelectric materials (man-made) exhibit piezoelectric constants many times higher than natural piezoelectric materials
  - Barium Titanate and Lead ZirconateTitanate (PZT)

Inversion Symmetry in Crystal Structure and Electrostrictive Effect

- Centrosymmetric dielectric materials
  - When subjected to external electric field, the movement of cations and anions are such that extension and contraction get canceled out between neighboring springs and the net deformation is zero.
  - There are second order effects (chemical bonds are not perfectly harmonic) which lead to a small net deformation
  - Deformation is proportional to the square of the electric field (electrostrictive effect)

- Non-centrosymmetric dielectric materials
  - When subjected to external electric field, there will be asymmetric movement of the neighboring ions, resulting in significant deformation of the crystal
  - Deformation is proportional to the applied electric field (piezoelectric effect)
  - Second order effects are also present but negligible

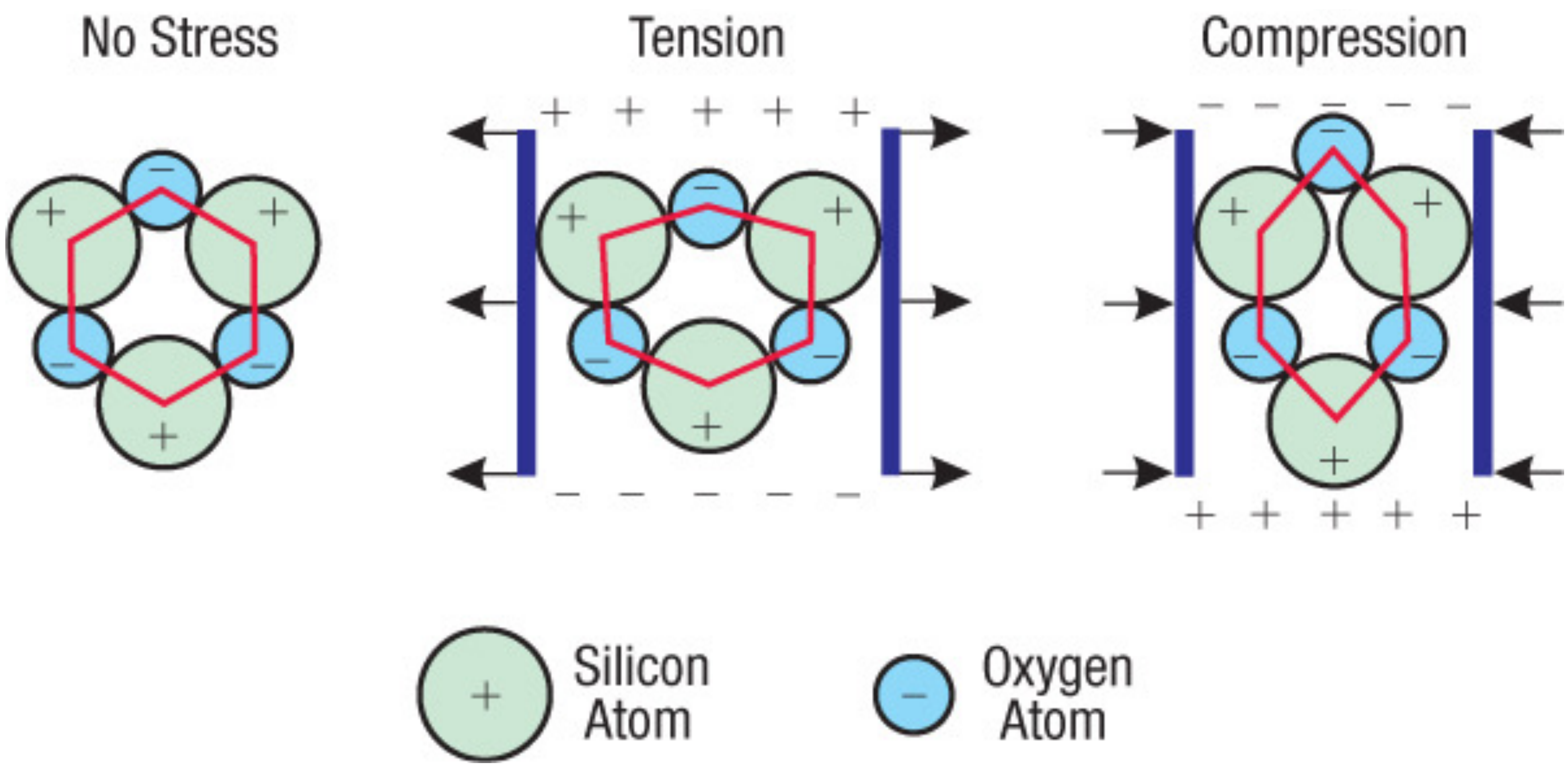
Ferroelectric materials

- Spontaneous polarization
  - Inherent alignment of dipoles in the absence of external electric field

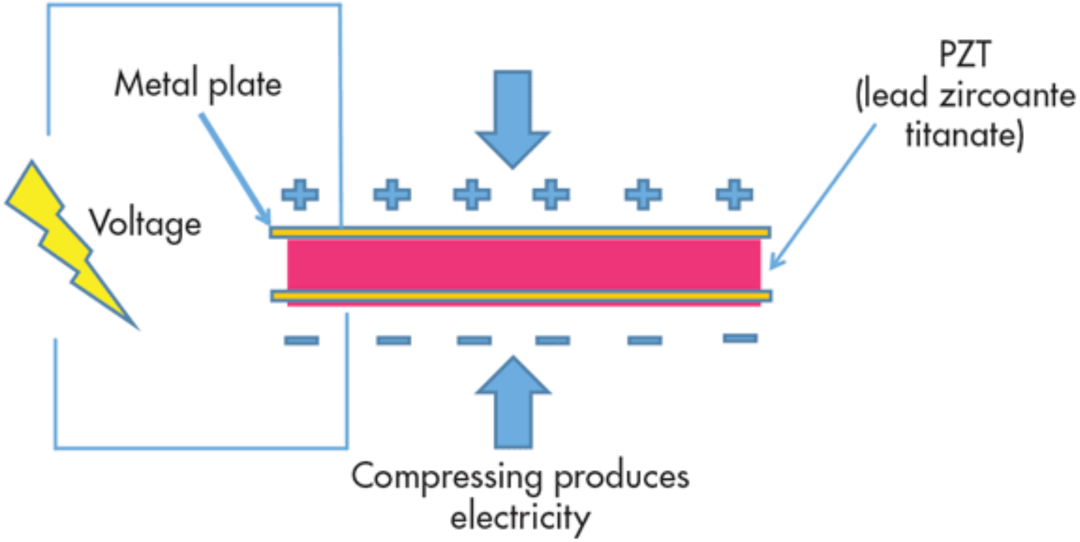
- Reversible polarization
  - Spontaneous polarization can be reversed by applying an external electric field

- Ferroelectric domains: small microscopic regions within which all the electric dipoles are oriented in the same direction due to a short range electrostatic interaction
- When an external electric field is applied, the domains tend to get oriented in the direction of the applied field
- Eventually the material consists of a single domain (saturation polarization)

Piezoelectric Effect

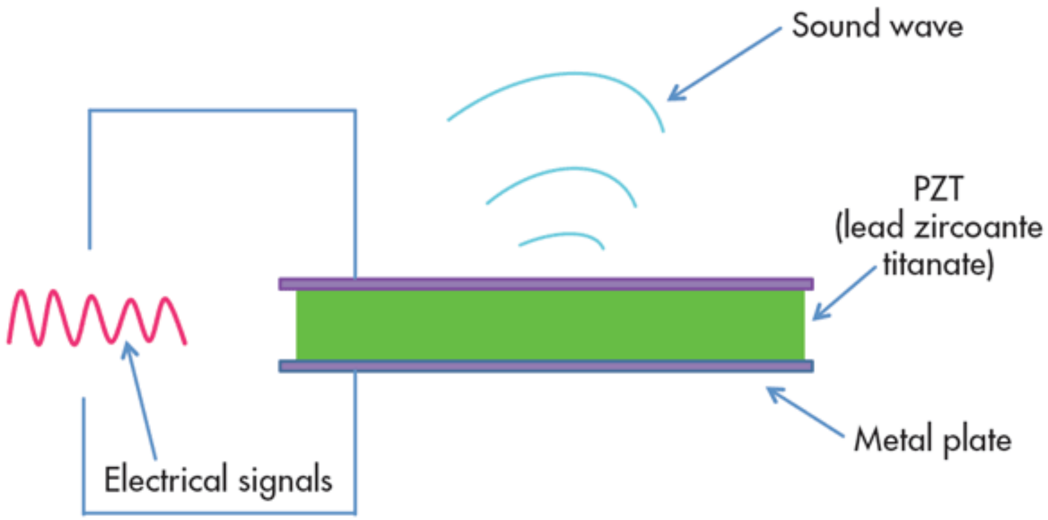


Piezoelectric Effect



- Piezoelectric crystal is placed between two plates. The material is in perfect balance and does not conduct an electric current.
- Mechanical pressure forces electric charges within the crystal out of balance. Excess negative and positive charges on both sides.
- Metal plates collect these charges to produce a voltage.

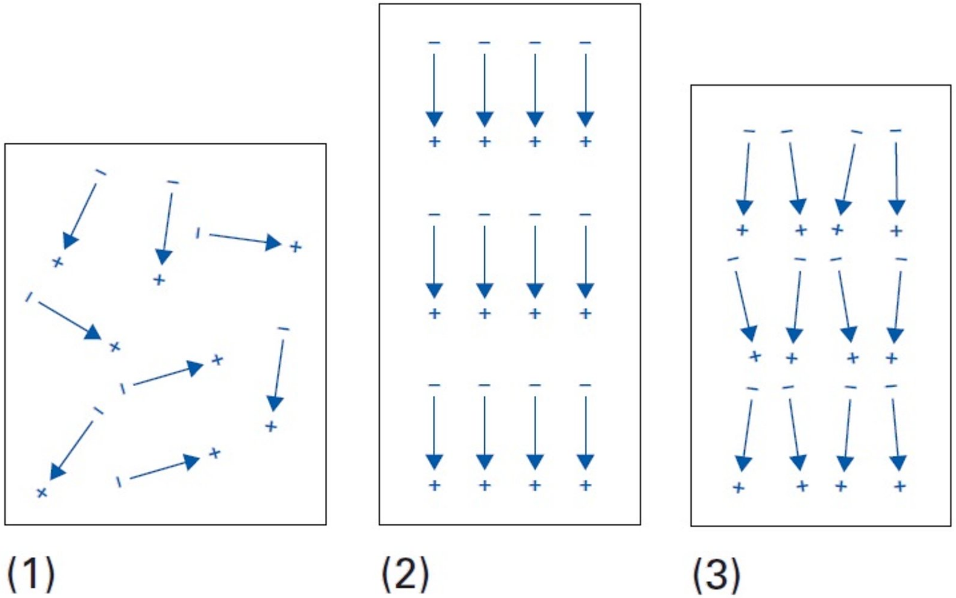
Piezoelectric Effect



- Piezoelectric crystal is placed between two plates. The material is in perfect balance and does not conduct an electric current
- Electrical energy is applied which shrinks or expands the crystal
- Deformation of crystal released mechanical energy in the form of sound

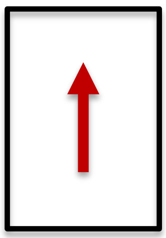
Poling

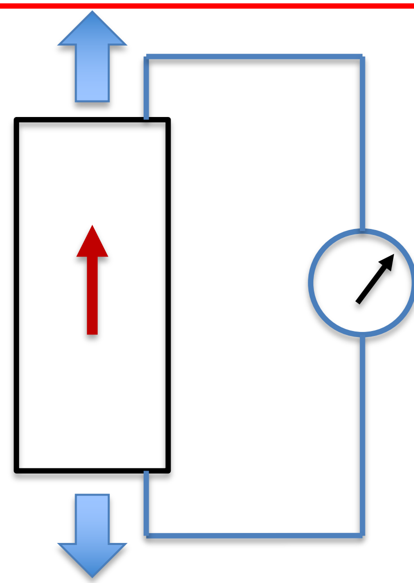
- The process of generating net remnant polarization by applying sufficiently high electric field (to attain saturation polarization) at a temperature slightly less than the transition temperature
- 2-3h of electric field application (several kV/mm)
- Most of the domains remain frozen in the oriented state even after cooling to room temperature (remanence)

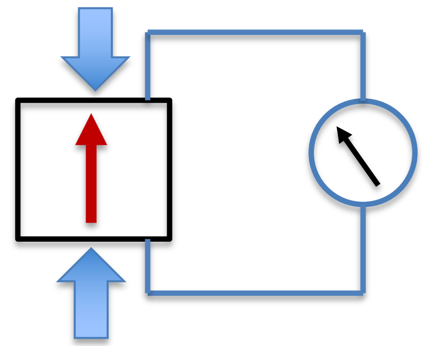


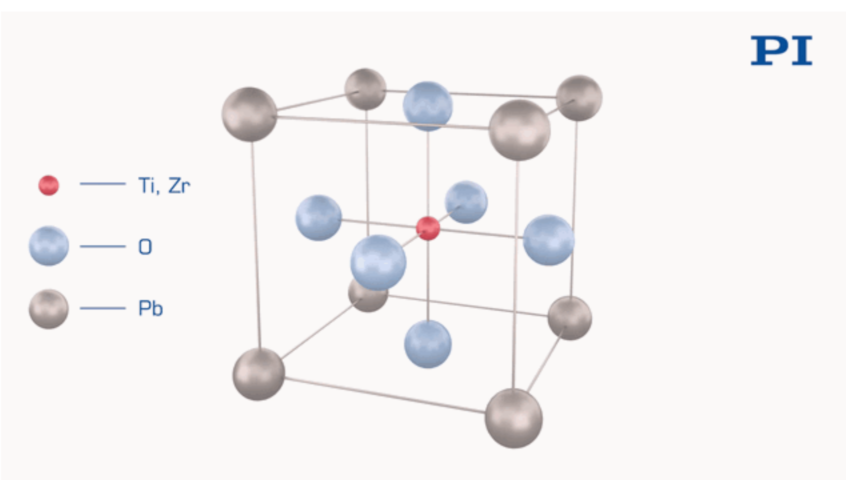
Piezoelectric Effect

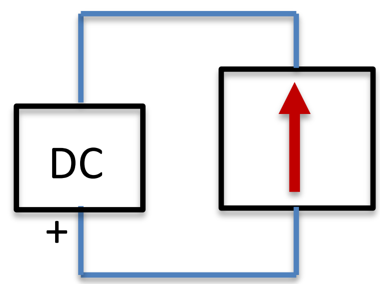
Poled piezoelectric material

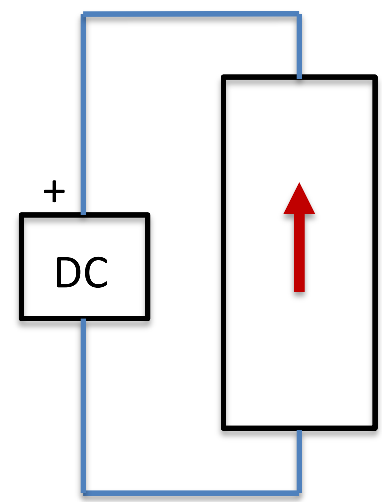












Electromechanical coupling

$$D = d \times T + \varepsilon^T \times E$$

$$S = s^E \times T + d^t \times E$$

D: electric flux density

E: electric field

T: mechanical stress

S: mechanical strain

d: piezoelectric charge coefficient [C/N or m/V]

ε^T: permittivity (dielectric constant) for constant stress [F/m]

s^E: elasticity coefficient for constant electric field

Piezoelectric Materials

- Quartz (crystalline form of silicon dioxide, natural)
  - Crystal cut, chemical etching, watches, computer clocks
- Lead zirconate titanate ($PbZr(Ti)O_3$, PZT).
- Electromechanical coupling coefficient

$$k^2 = \frac{\text{Converted mechanical energy}}{\text{Input electrical energy}}$$

$$k_{33}{}^2 = \frac{d_{33}{}^2}{\varepsilon_{33}{}^T s_{33}{}^E}$$

Property	PZT	PMN–PT	PZN–PT
Strain [%]	0.2	0.6	1.7
Stress [MPa]	110	>100	130
Efficiency [%]	90	90	90
Electromechanical coupling (k_{33})	0.7	0.92	0.95
Piezoelectric coefficient (d_{33}) [pC N^{-1}]	750	2500	2500

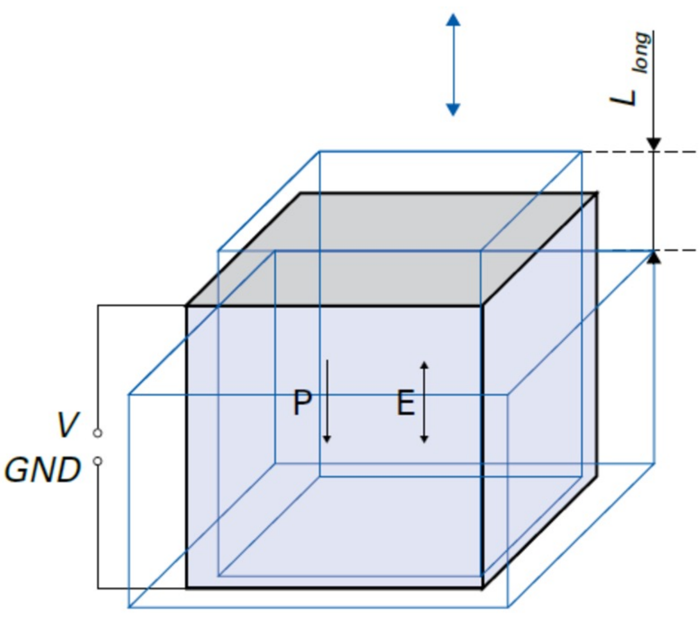
Piezoelectric Characteristics

Piezoelectric charge constant

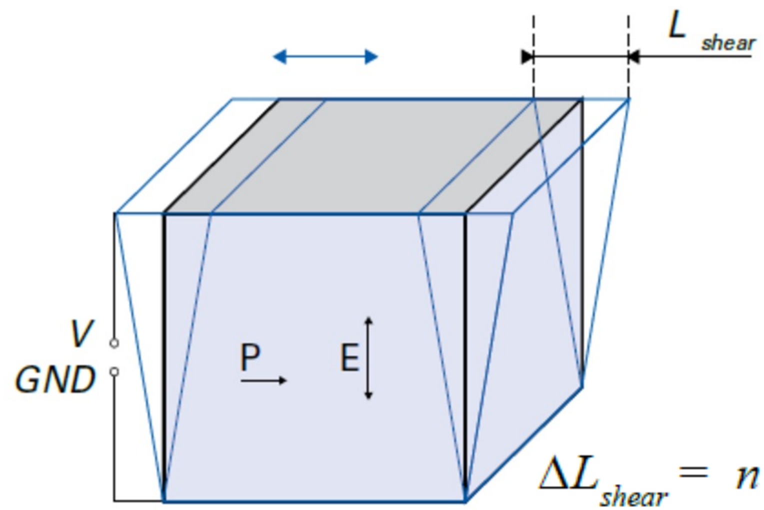
d_{33}

Induced strain is in direction 3

Electrodes are perpendicular to axis 3

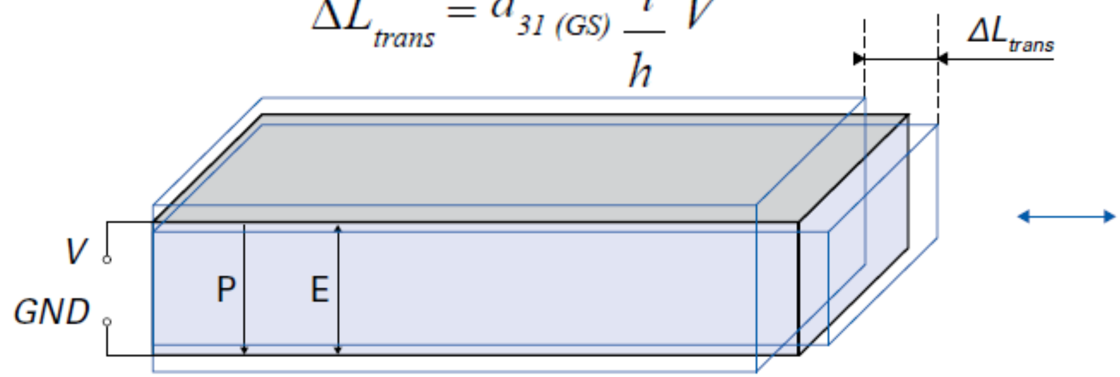


$$\Delta L_{long} = n\, d_{33(GS)}\, V$$



$$\Delta L_{shear} = n\, d_{15(GS)}\, V$$

$$\Delta L_{trans} = d_{31\,(GS)} \frac{l}{h} V$$

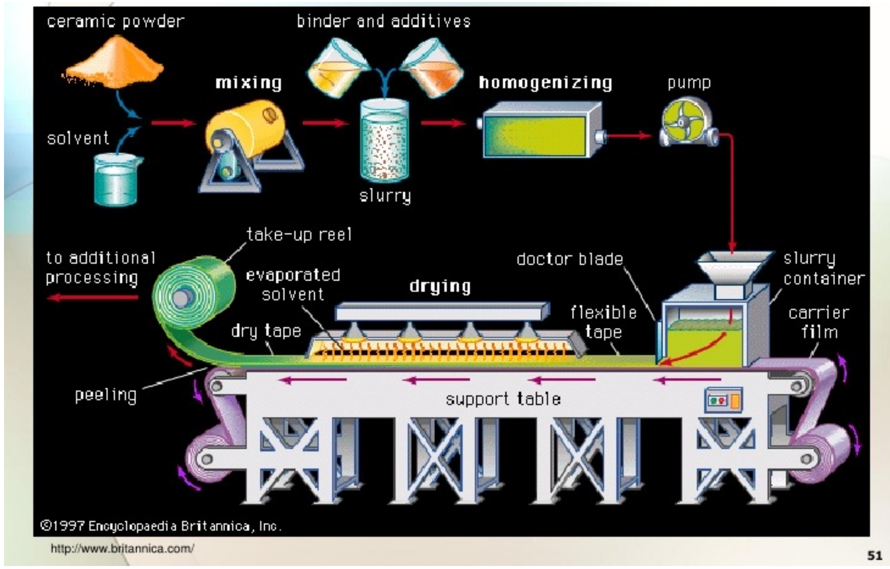


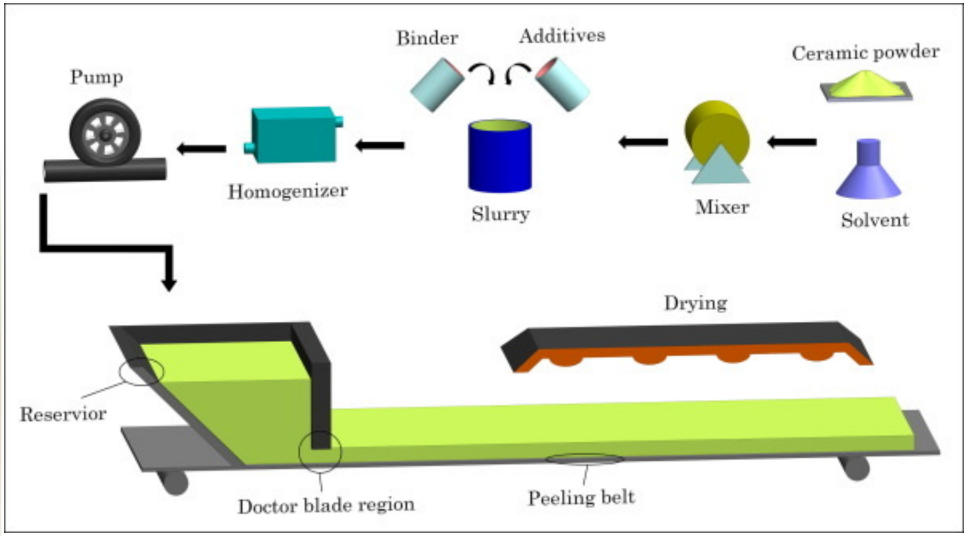
Fabrication Techniques

- Powder form
  - **Solid-state reaction** technique: Oxides PbO, TiO_2, and ZrO_2 are mixed, heated to 650℃ for 2-3h, the product is heated to about 850℃ (calcination process), the mixture is milled (ball milling) to obtain microscale particles.
  - **Coprecipitation** of the oxides from solution. Filtration of the precipitate, drying, thermal process.
  - **Sol-Gel Technique**: Formation of a gel with polymerization. The gel is dried, ground to get fine powders.

Fabrication Techniques

- Shape forming
  - Mix powder with a polymer binder and process in molds using high pressure (press).
  - Tape casting: A fine powder is suspended in aqueous solution consisting of solvents and binders to form a slurry. The slurry is allowed to flow on a cellulose sheet spread on a carrier. The carrier is passed under a doctor blade. The solvent is allowed to evaporate.



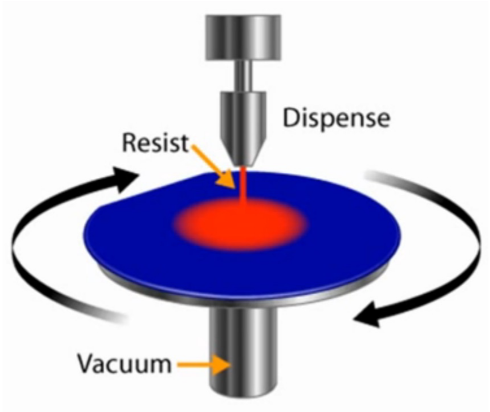


Fabrication Techniques

- Thin film formation
  - **RF Sputtering deposition (PVD)**: plasma is generated in a low-pressure chamber using an inert gas (argon) by applying high-frequency voltage across two electrodes. Energetic ions of the plasma strike target PZT plate and dislodge the molecules. Molecules travel through the plasma as vapor and get deposited on the substrate.
  - **Spin Coating** of PZT slurry
  - **Chemical Vapor Deposition (CVD)**: Vaporization of molecules at high temperature (>500 C) with precursors (halides), diffusion of molecules to the substrate, adsorption, formation of solid films.

Coating

- Surface conditioning
  - Preparation of the wafer surface to improve or reduce adhesion
  - Dehydration + HMDS (HexaMethylDiSalizane) – Hydrophobic surface
- Resist deposition
  - Critical step as it determines thickness and uniformity
  - Spin Coating: resist is dispensed on top and wafer spins at a certain speed
  - Balance between centrifugal force and viscous forces
  - Higher speed and lower viscosity → thinner layer
- Soft bake
  - Step to remove solvent from the slurry
  - Solidifies the ceramic layer



Lithium Niobate (LiNbO3 or LN)

- Grown as a crystal
- MOCVD (metalorganic vapor-phase epitaxy) process
- Can be bought as wafers
- Transparent material
- High-speed sound processing with surface acoustic wave devices
- Wireless communication

Thin film PMUTs

- Piezoelectric Micromachined Ultrasound Transducers
- Applying direct current (DC) voltage across the piezoelectric layer tends to strain it due to the d_{31} piezoelectric effect.
- This strain is then restricted by the underlying device layer, leading to in-plane normal stress
- Since plate PMUTs are thick, the neutral axis rests in the device layer
- The difference (lever arm) between the piezoelectric layer's centroid and the neutral axis, results in a bending moment M that bends the structure in an out-of-plane manner.
- Thus, applying an AC voltage makes the structure vibrate.

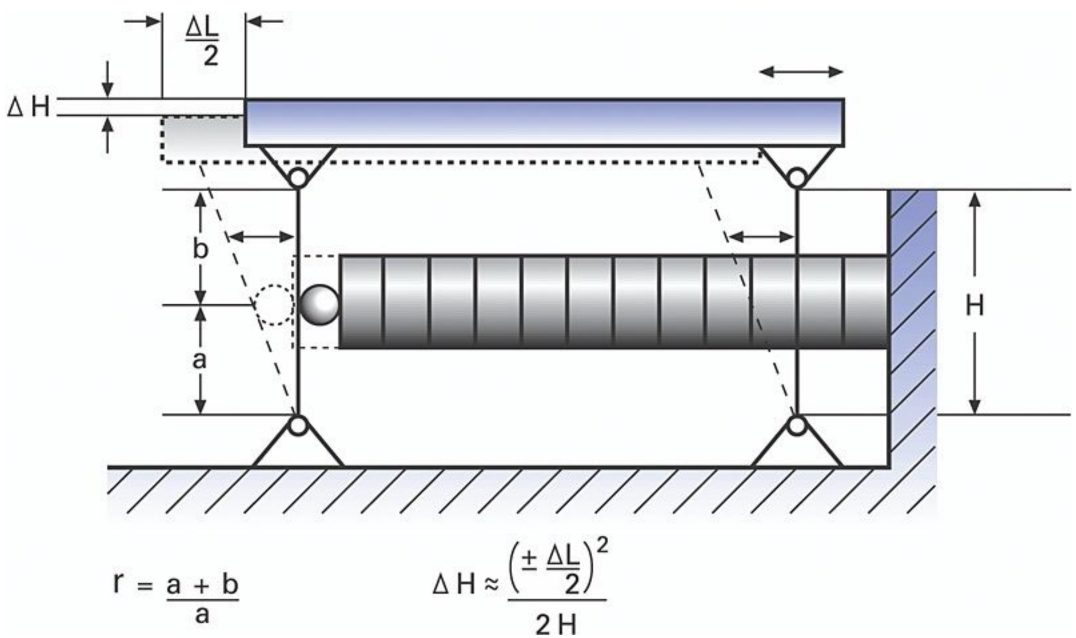
Why Use Piezo?

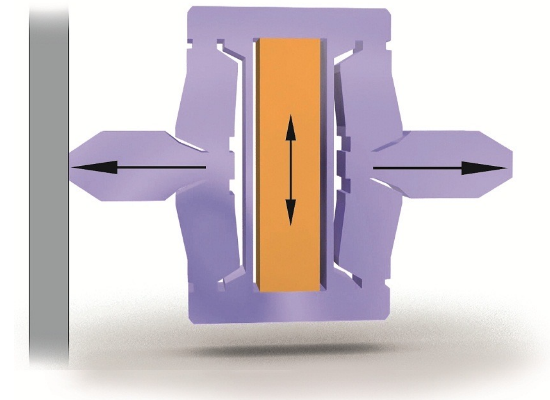
- Position precision
  - Almost linear dimensional change free of stiction effects
  - Down to sub-nanometer range
- Speed
  - Solid-state actuation: speed of sound (kHz)
  - Can respond to an input in milliseconds (valve control)
- High Force
- Reliability, generate little heat, nonmagnetic, vacuum compatible, few mechanical components (wear)

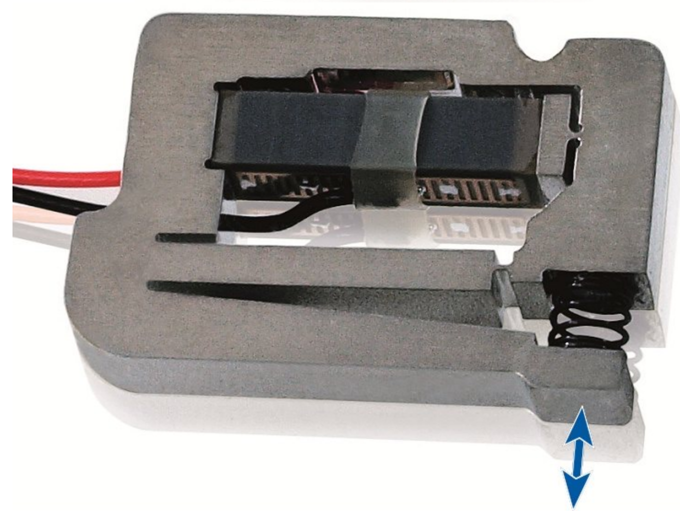
- Small actuation strain
  - Typically, 0.1 percent of the length at max voltage
  - Lever amplifiers
- Brittle ceramics and large excitation field (MV/m range)

Amplification Mechanisms

- Flexure-guided (flexure linkages, flextensional mechanism)
- With increasing amplification ratio, both stiffness and responsiveness are reduced (preloading?)
- Bending actuators





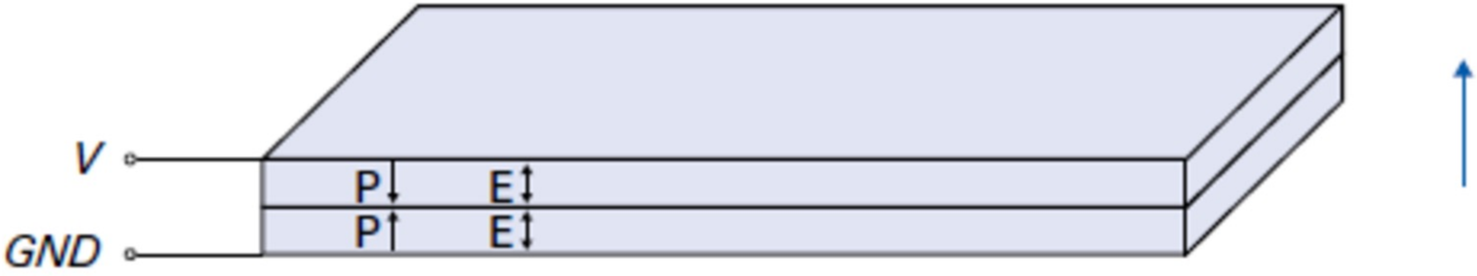


Bimorph configuration

- Bonding two strips with opposing piezoelectric expansion axes
- For a cantilever mounted bimorph, the unloaded deflection δ of the beam resulting from the applied voltage V

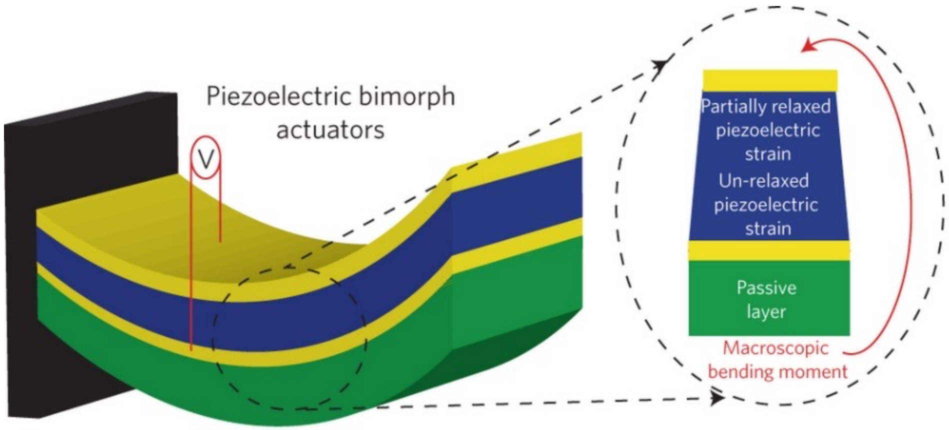
$$\delta = \frac{3}{5} d_{31} V \left(\frac{L}{a}\right)^2$$

Where a is the width of each strip, L is the length, $d_{31} = 2\text{x}10^{-11}$ m/V for PVDF. As an example, $a = 0.5$ mm, $L = 30$ mm, $V = 300$ V then $\delta = 13$ μm.



Bimorph configuration

- Coupling with a passive layer



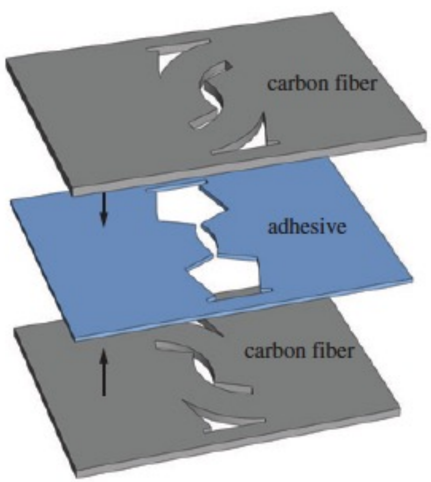
L = Bending displacement [m]
d_{31} = Transverse deformation coefficient
n = Number of stacked layers
V = Operating voltage
l_f = Bender length
h_p = Height of piezo
R_h = Ratio of substrate height and ceramic height
R_E = Ratio of elastic moduli of substrate and ceramic

$$\Delta L_{bend} = \frac{3}{8} n \, d_{31(GS)} \frac{l_f^2}{h_p^2} \frac{2R_h R_E (1+R_h)}{R_h R_E (1+R_h)^2 + 0.25(1-R_h^2 R_E)^2} V$$

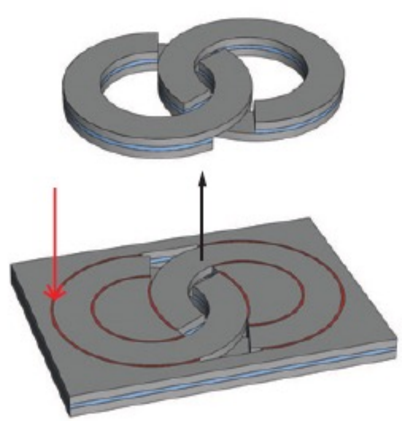
Timoshenko Beam Theory

Monolithic Fabrication of Mechanisms

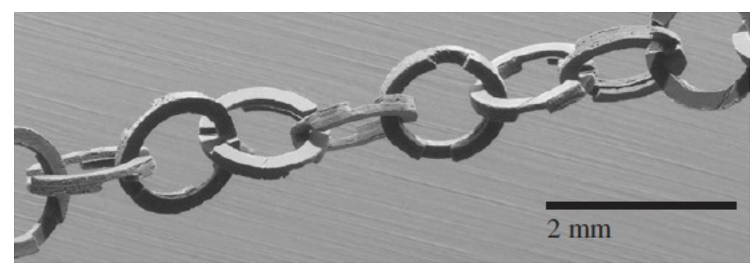
- Printed circuit board techniques
- Multilayer laminates, alignment pins,
- Leaving small tabs or bridges connecting parts to the bulk material
- Laser micromachining (355 nm): 1-150 um thickness, 8um beam
- Electropolishing, ultrasonic cleaning, plasma treatment
- Acrylic sheet adhesive for lamination



Machining/Lamination

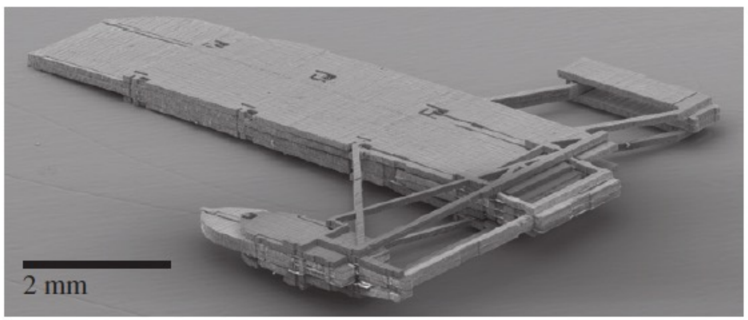


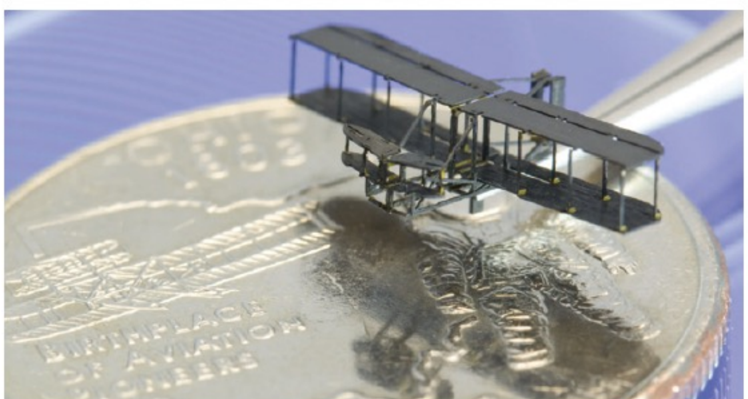
Singulation

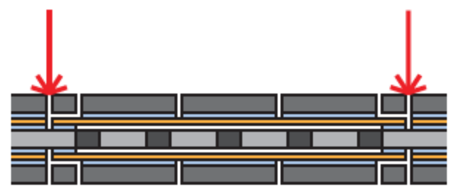


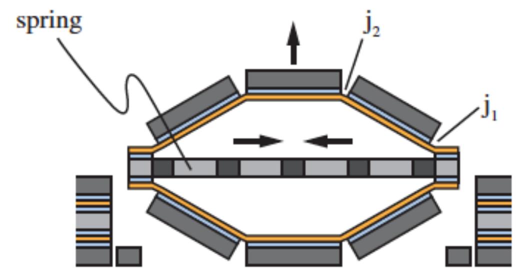
Monolithic Fabrication of Mechanisms (video)

- Pop-up book folding: multiple rigid-flex folding layers are stacked and bonded together.
- Model is released by trimming each bridge and opening the mechanisms like a book.
- Springs to perform self-folding of pre-strained layer

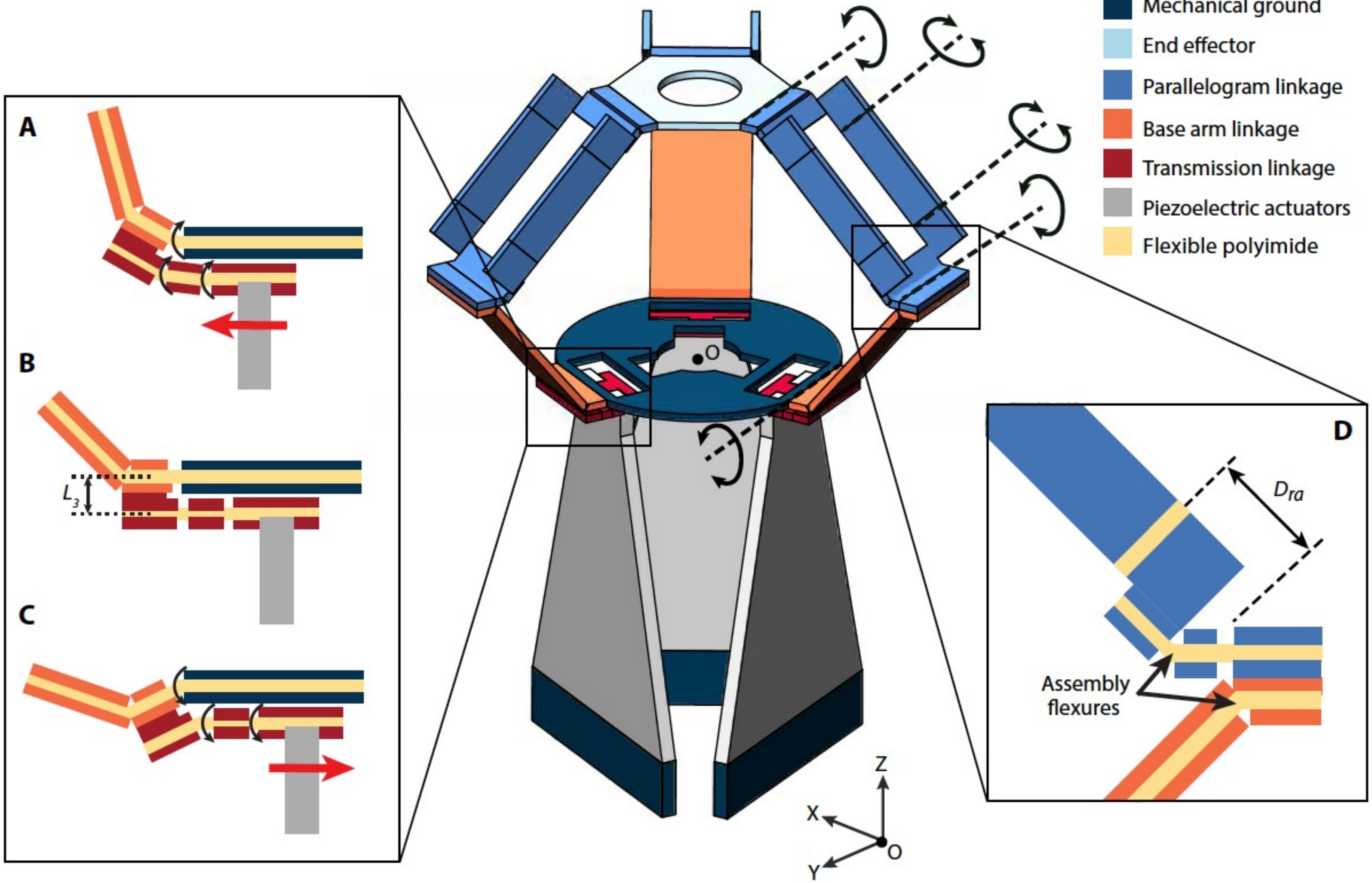








Example: milliDelta Robot



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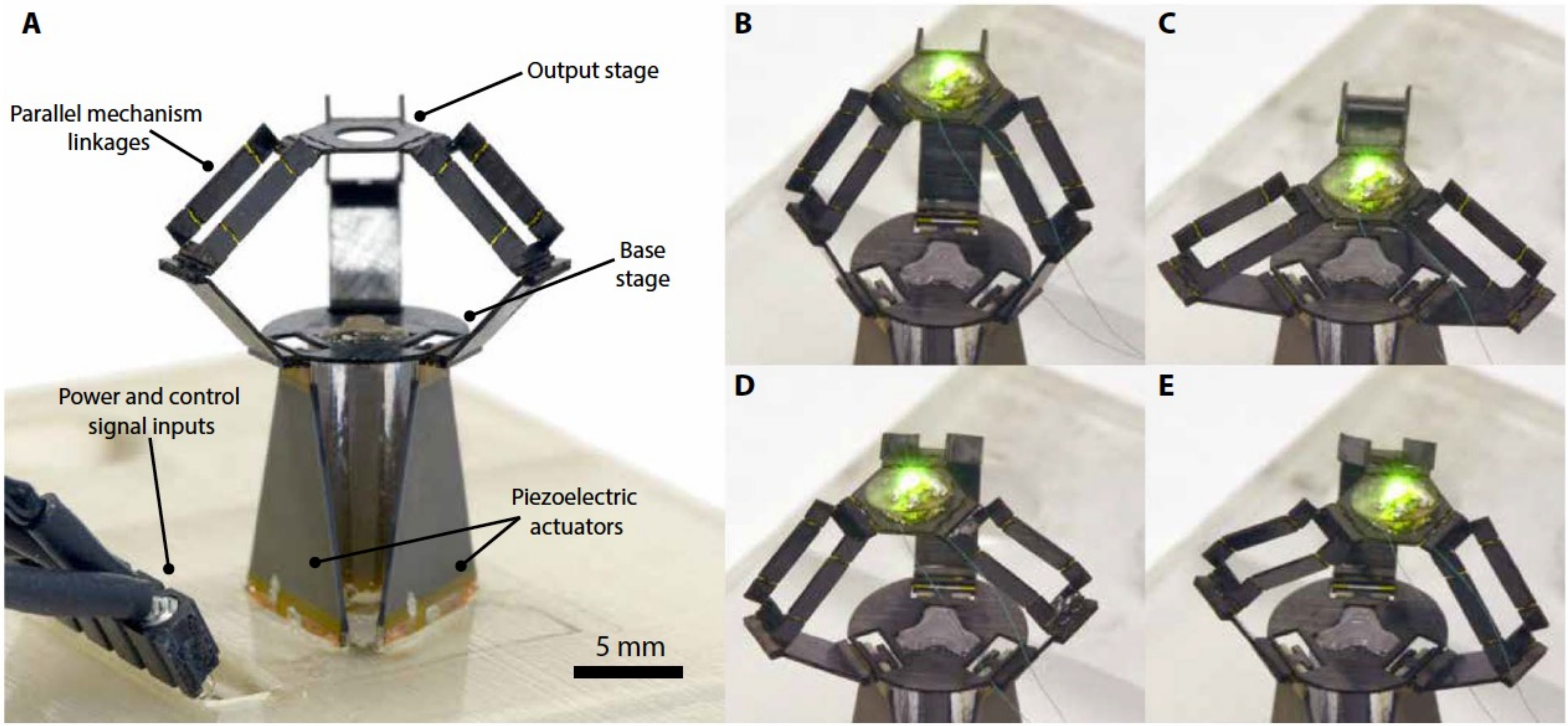
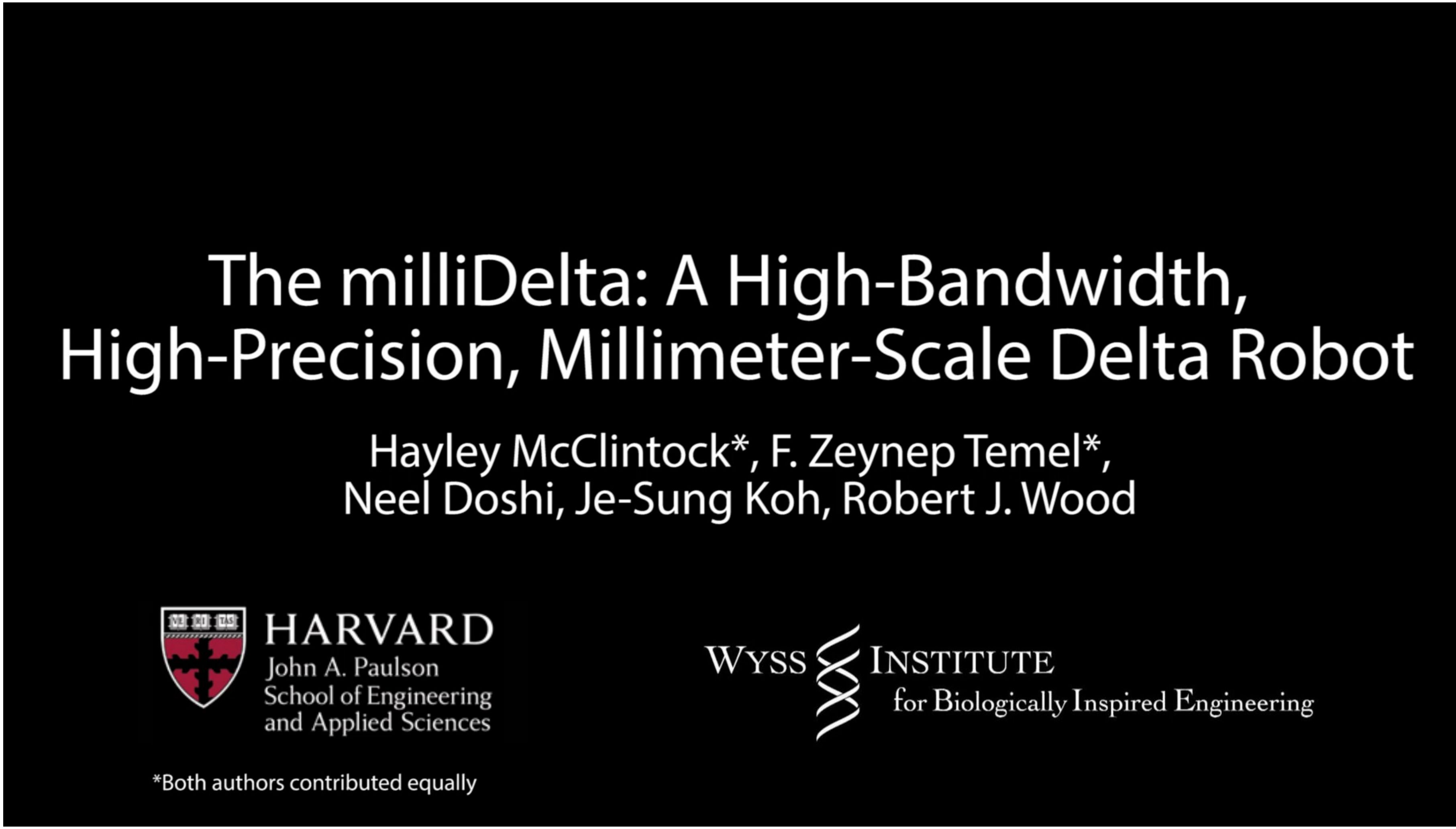
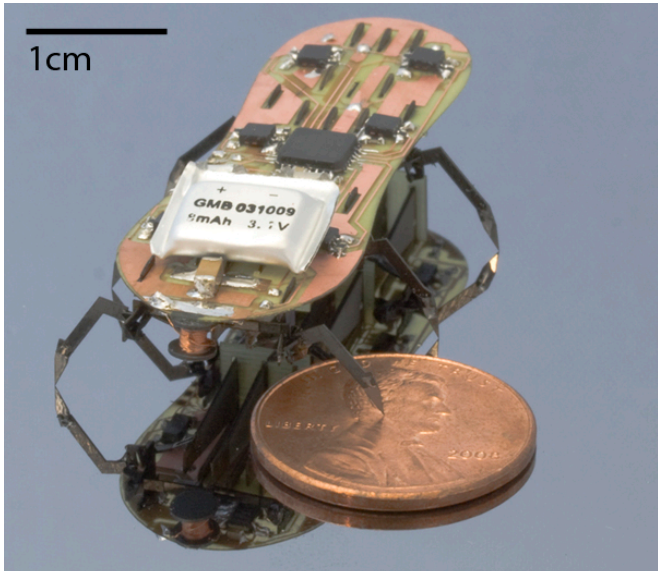


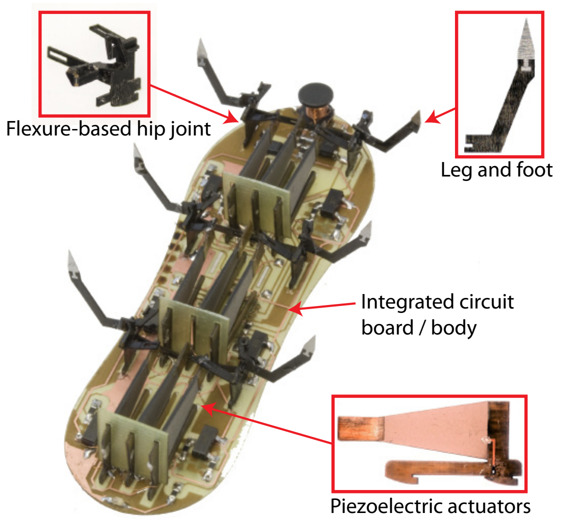
Example: milliDelta Robot

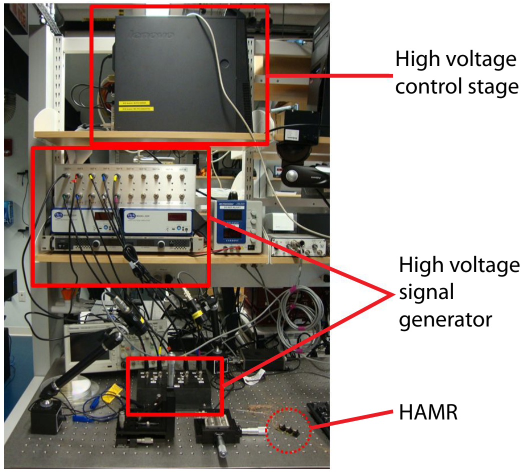


Example: HAMR

- Harvard Ambulatory MicroRobot
- HAMR3 is 1.7g and 48 mm long
- Max speed: 4 cm/s

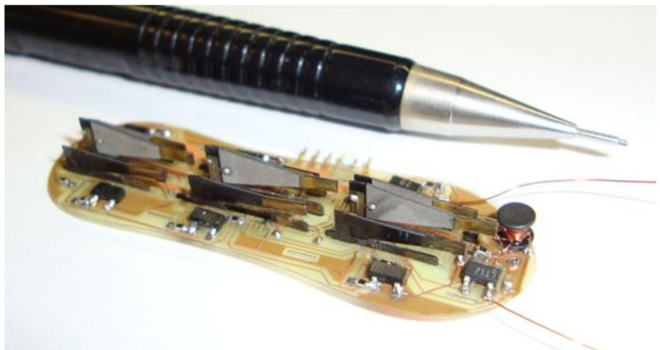


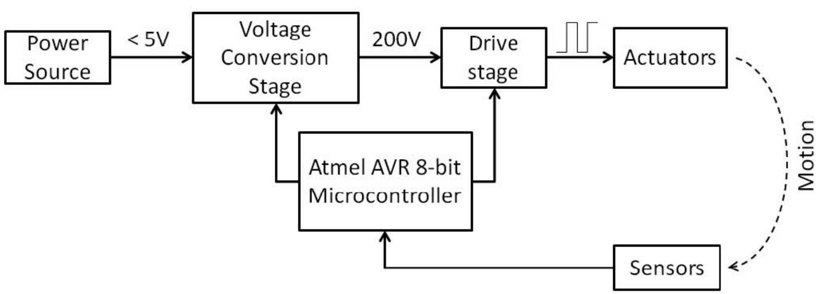


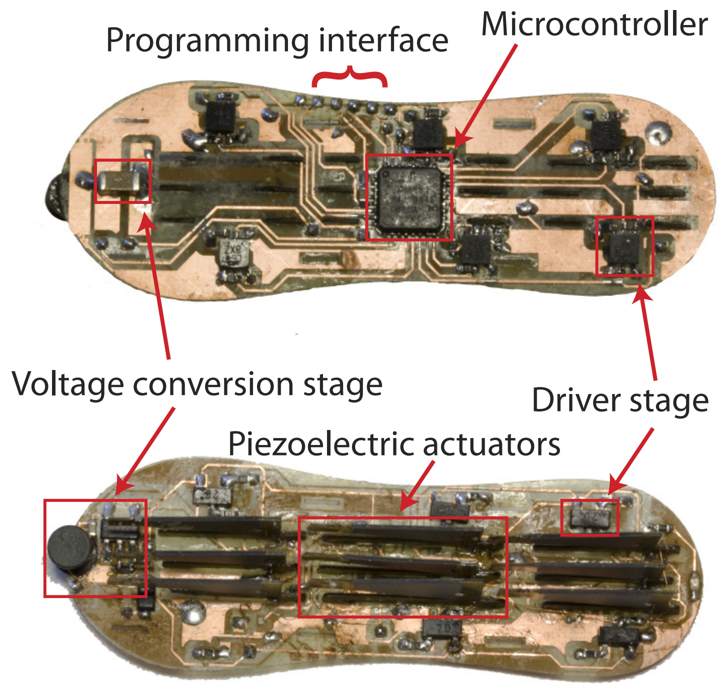


Example: HAMR

- Harvard Ambulatory MicroRobot







Example: HAMR (video)

- HAMR-F is 2.7g and 45 mm long
- Powered by 8 mAh lithium battery

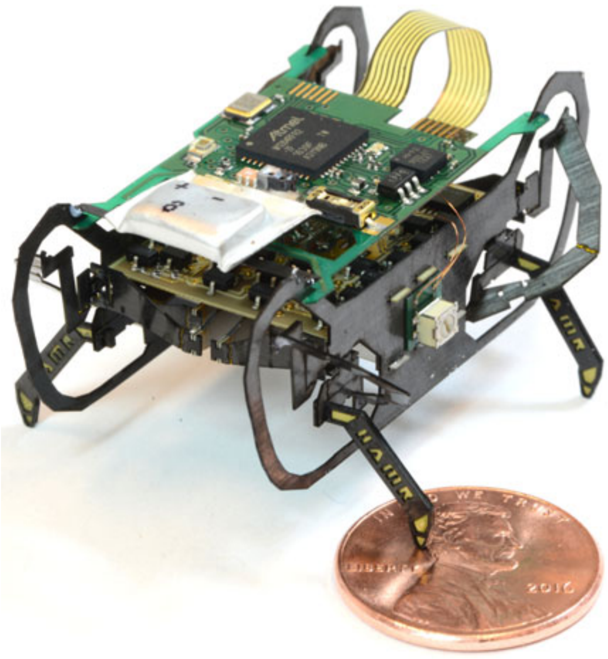
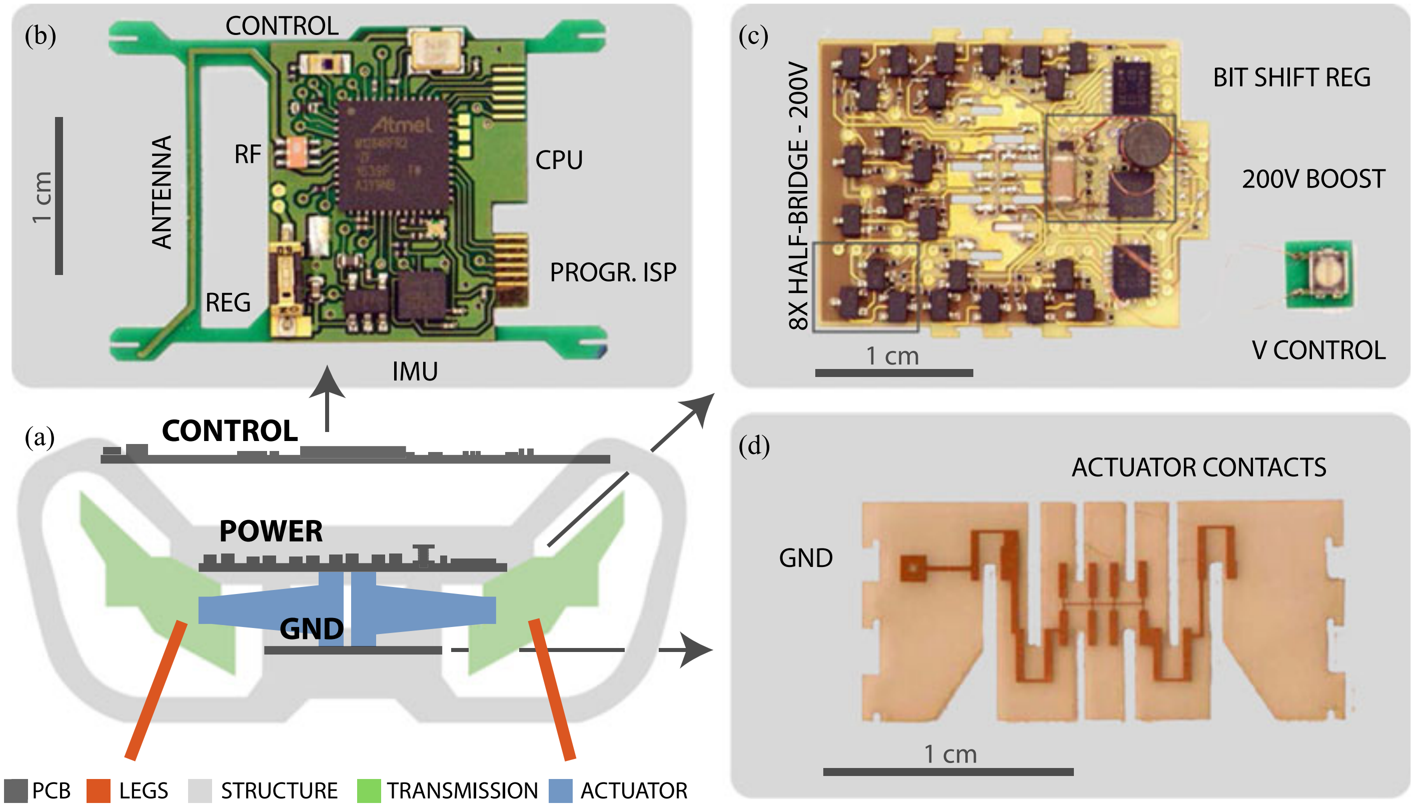


TABLE I
MASS DISTRIBUTION OF HAMR-F

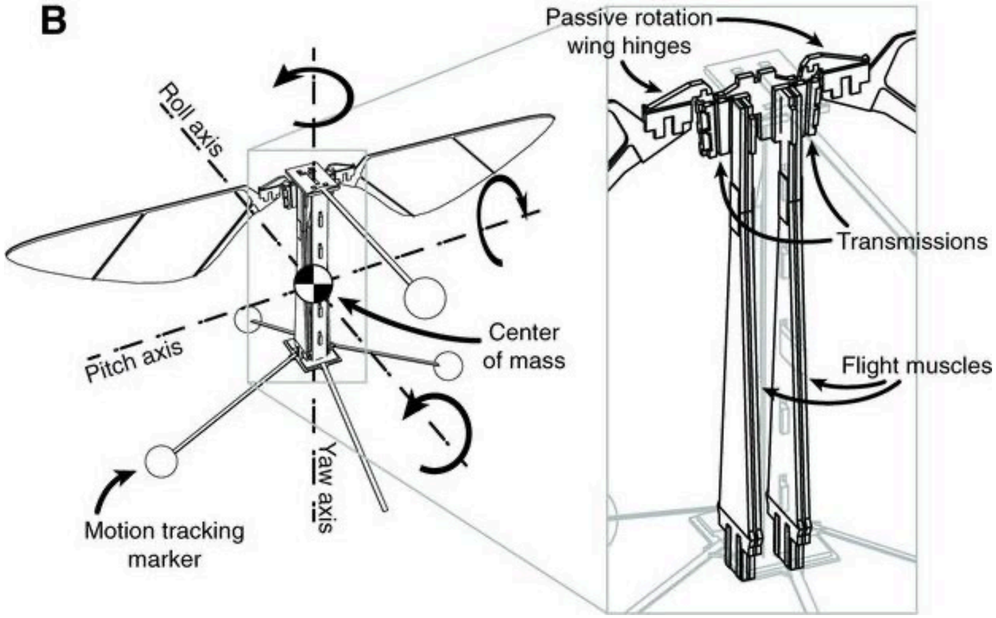
Component	Mass (mg)
Control Board	450
Power Board	563
Transformer	47
Battery	330
Actuators	$8 \times 109 = 872$
Chassis	528
Total Mass	2790

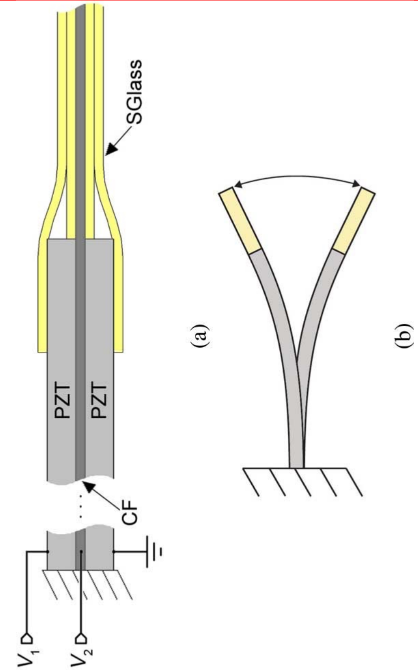
Example: HAMR

- HAMR-F is 1.7g and 48 mm long
- Powered by 8 mAh lithium battery



RoboBee

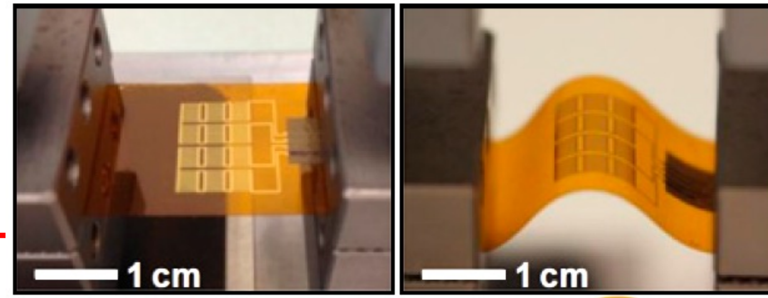




Part	**Material**	**Average thickness [μm]**
Wings	Titanium alloy	50
Structure	Carbon fiber	500
Transmission (joints)	Polyimide film	15
Actuator	PZT	127
Locking joints	Brass	25

RoboBee (video)

Energy Harvesting



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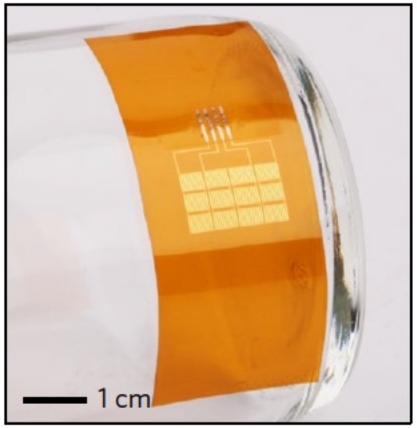

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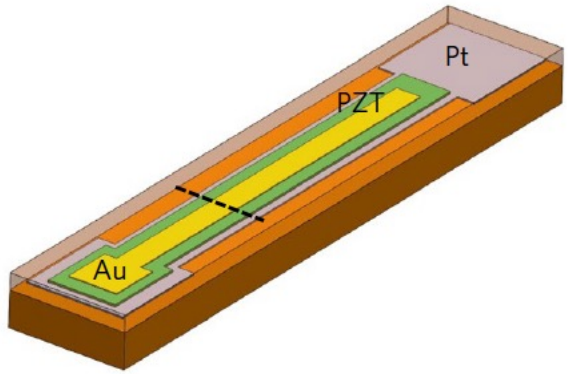
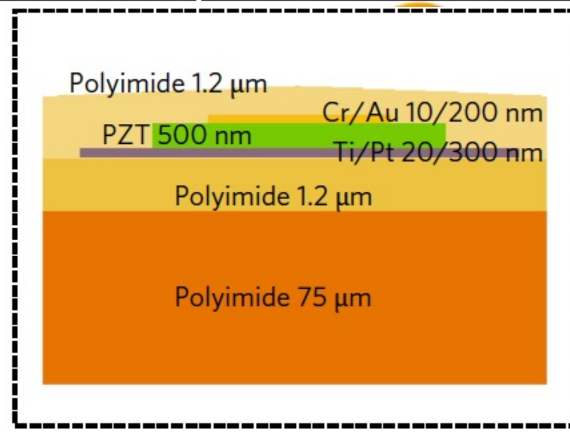
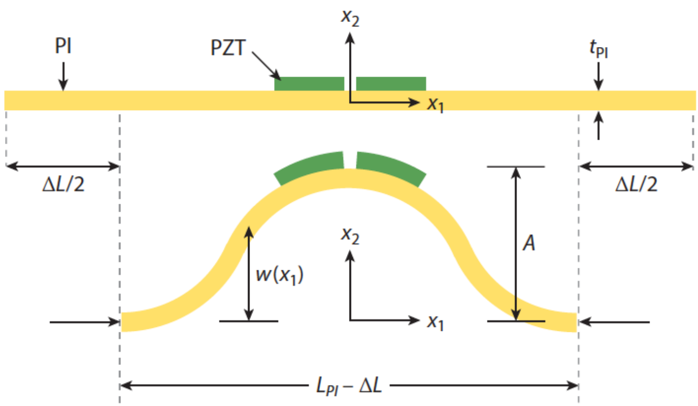
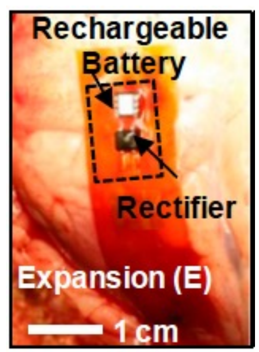
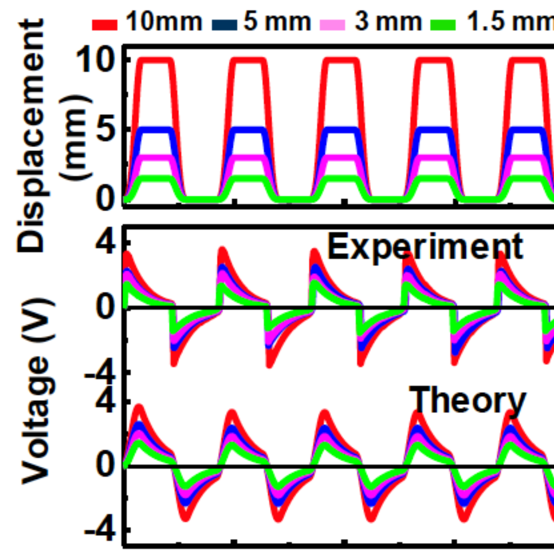




Material	Kapton	Ti	Pt	PZT	Au	Cr
Elastic modulus (GPa)	2.5	116	168	63	78	279
Poisson's ratio	0.34	0.32	0.38	0.3	0.44	0.21

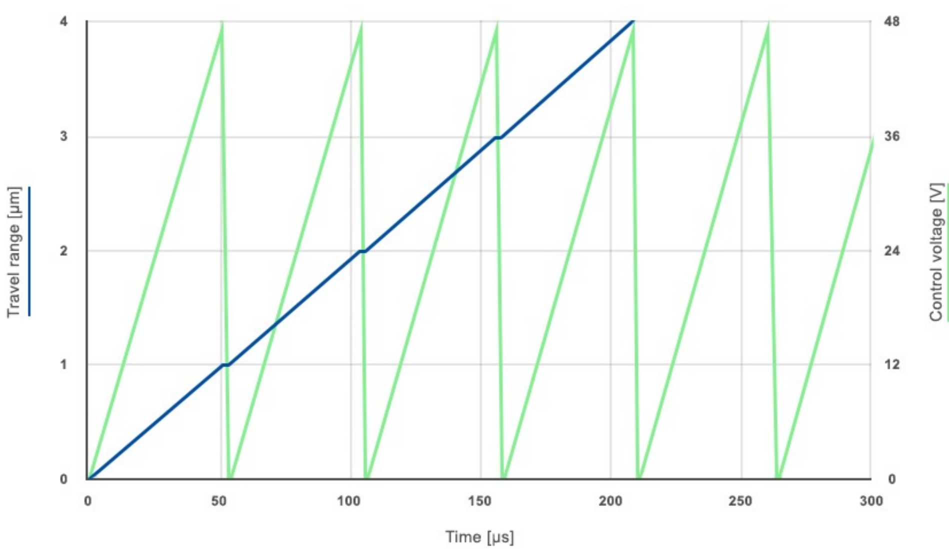


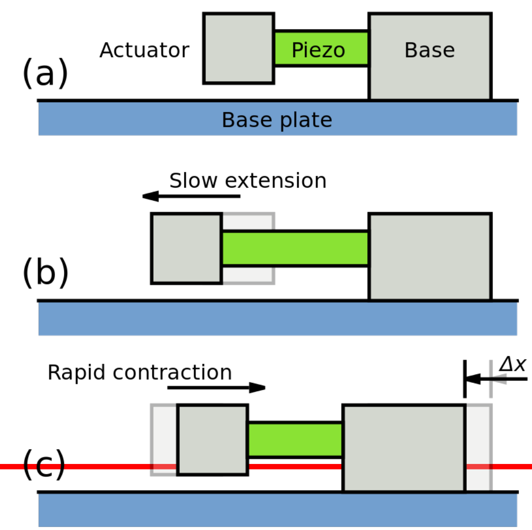




Piezo Motors

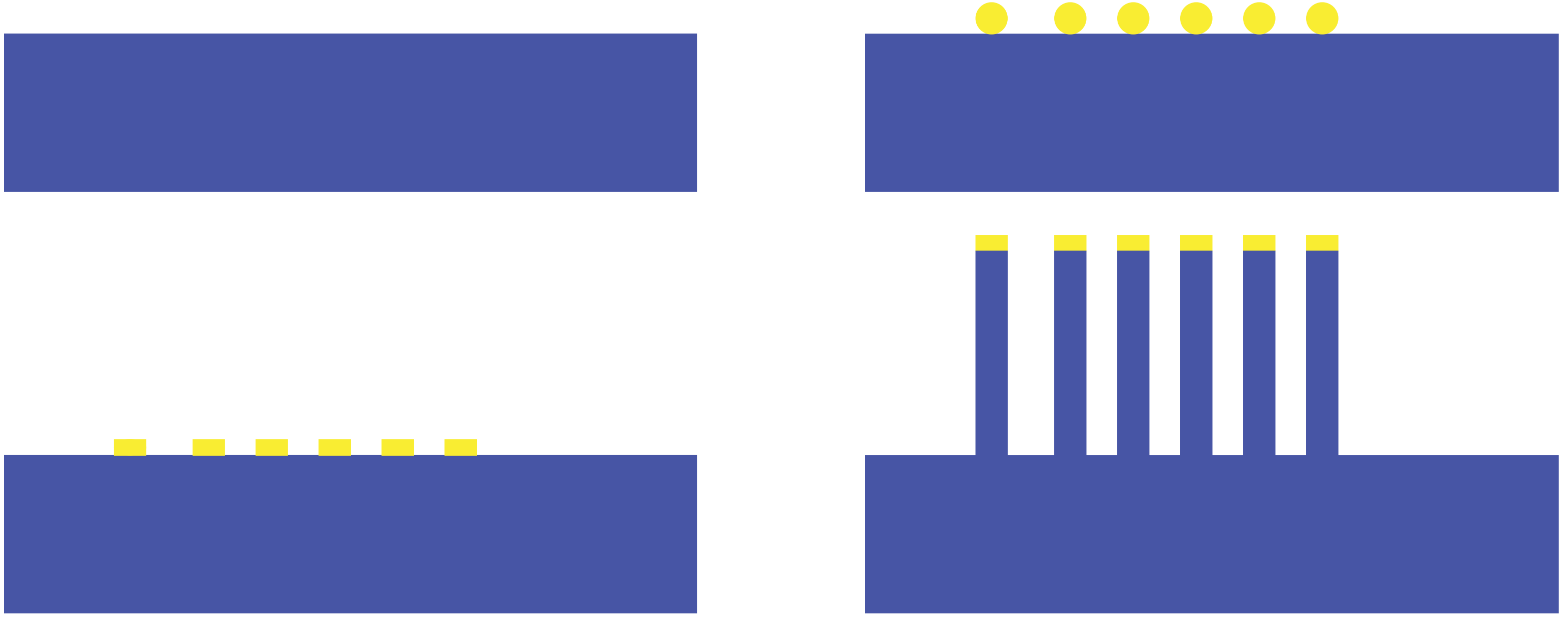
- Stick-slip mechanism (inertia motor, impact drive)
- A platform makes frictional contact with the ground, and on the platform is a piezo element and attached mass
- Reaction forces resulting from rapid acceleration of the mass by the piezo cause the platform to make a step (slip)
- The mass is then slowly retracted so that friction prevents return motion of the platform (stick)
- Saw-tooth shape signal (slow expansion, fast contraction)





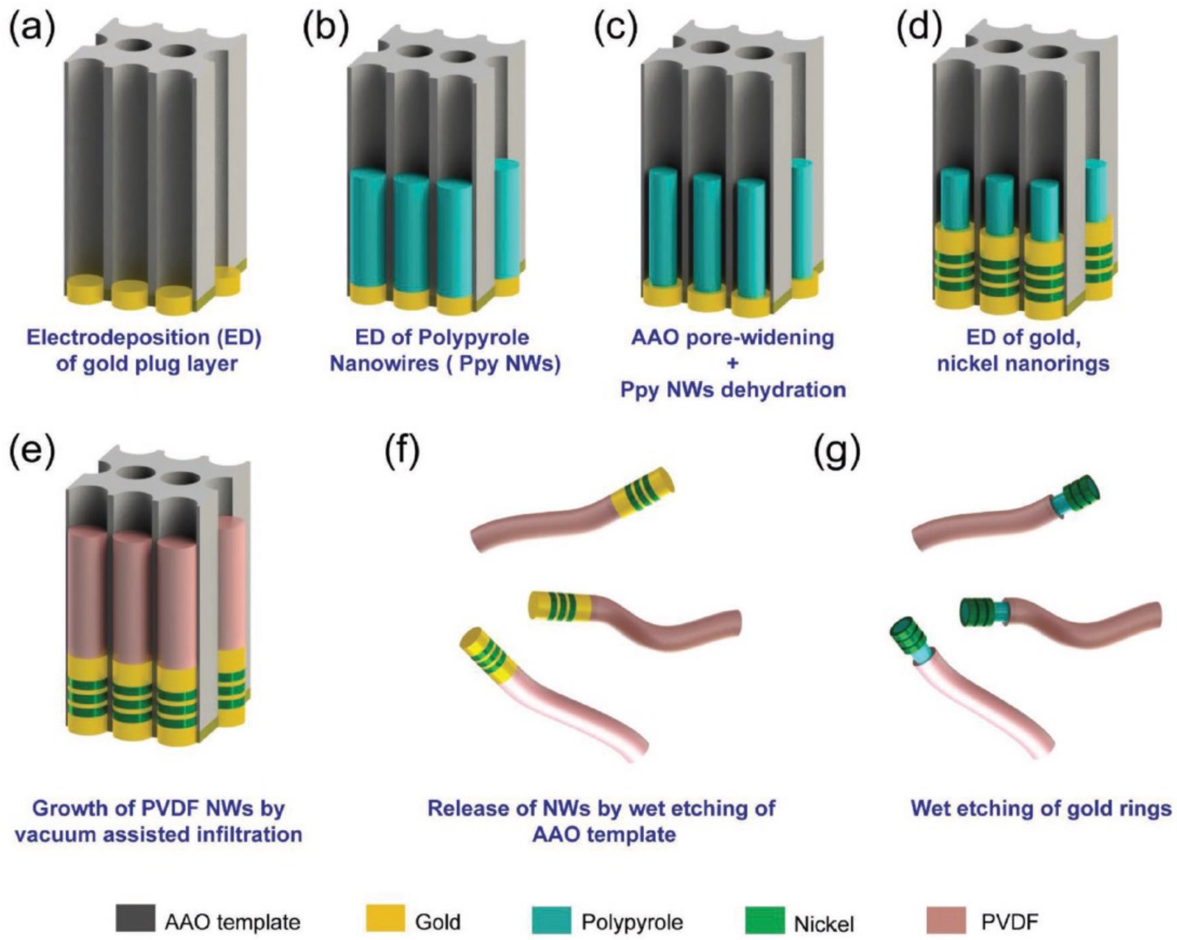
Piezoelectric Nanowires

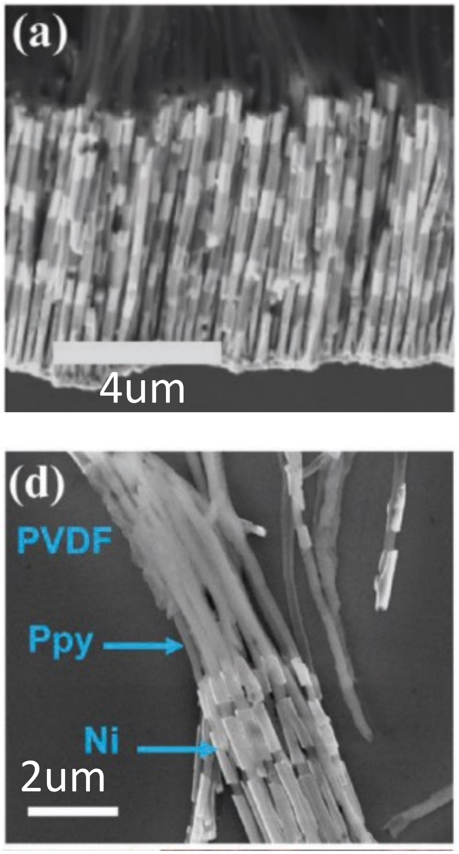
- Growing ZnO (zinc oxide) Nanowire arrays
- Vapor-liquid-solid growth (VLS)
- Metal catalyst, gases as precursors



Piezoelectric Nanowires

- Magnetic rotation to generate electricity





Magnetostrictive Materials

- Generation of strain in response to magnetic field
- Terfenol-D (Terbium, iron, Naval Ordnance Lab, dysprosium), Galfenol (gallium-iron alloy)
- Strains up to 0.25% under 400 kA/m field (500 mT)
- Stress up to 20 MPa with bandwidths up to 20kHz
- High energy density: 25 kJ/m^3 (For PZT: 1.3 kJ/m^3)

- Small strain, hysteresis, brittleness (hard to machine), high stiffness
- Large coils are required
- Material: expensive

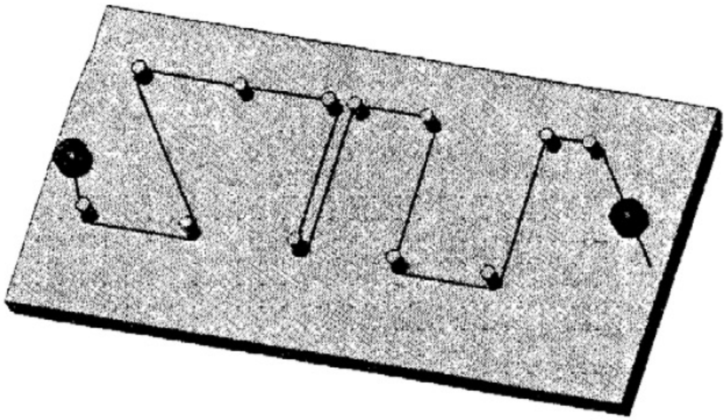
Shape Memory Alloys (video)

- Discovery in 1932 by Arne Olander.
- Alloys of nickel-titanium (e.g., NiTi or Nitinol) outperforms most other materials such as iron or copper-based alloys
- The shape memory property of NiTi alloy was discovered in 1960s in the Naval Ordnance Laboratory, hence the name Nitinol.

- Reversible transition between two phases, martensite (low-temp) and austenite (high-temp)
- Martensitic phase is yield-able (shapeable, plastic deformation)
- Deformations of the martensitic phase, occurring above a critical stress, are recovered completely during the transformation at austenite phase
- Fabrication conditions determine the shape-memory effect and phase transition temperatures

Shaping Procedure

- Start with a wire or cut pieces from a sheet using pulsed ultraviolet laser micromachining system
- Fix the structure in a jig, fixture, or mandrel to hold the desired shape
- Anneal at high temperature (400 C) for an hour
- This annealing process resets the undeformed martensitic state
- The actuator will remember its programmed shape when heated above its transition temperature (70 C)



Generation of Heat

- Joule (resistive) Heating
  - Current passing through electrically resistive material
  - Electrical conductivity of Nitinol is 1 uOhm m: uniform heating

- Convective or conductive Heating/cooling
  - The surrounding medium is heated (air, water) and used as coolant

$$\tau \sim \frac{t^2}{4\alpha} = \frac{\rho t^2 C_p}{4k} \qquad (2)$$

where t is the thickness, α is the thermal diffusivity, ρ is the volumetric mass density, C_p is the specific heat capacity, and k is the thermal conductivity. During cooling in air, convective heat transfer is the dominant process and has the time constant of

$$\tau = \rho C_p \frac{t}{h} \qquad (3)$$

where ρ is the volumetric mass density, t is the thickness, C_p is the specific heat capacity, and h is the heat transfer coefficient of free air convection at the boundary.

Generation of Heat

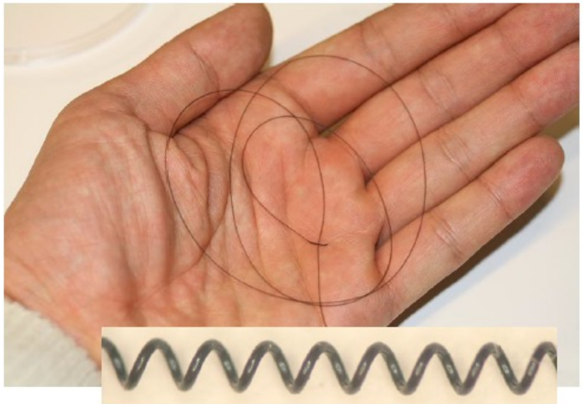
- Joule Heating
  - Current passing through electrically resistive material
  - Electrical conductivity of Nitinol is 1 uOhm m : uniform heating

- Convective or conductive Heating
  - The surrounding medium is heated (air, water)

- Photothermal excitation (absorption, plasmon resonance)
  - Surface coating with high light-absorption, high thermal conductivity
  - Gold nanoparticles and antennas

Actuation performance

- SMA wires intrinsically can contract up to 8% in length (recoverable strain)
- Increase strain to more than 100% with helix or zigzag geometry
  - Lower stress



- Bending actuators
- Torsional actuators
  - Linear actuation of several SMA wires (pulley)
  - Shape recovery of a twisted fiber or tube: untwisting of individual fibers in a yarn (small displacement)

Actuation performance

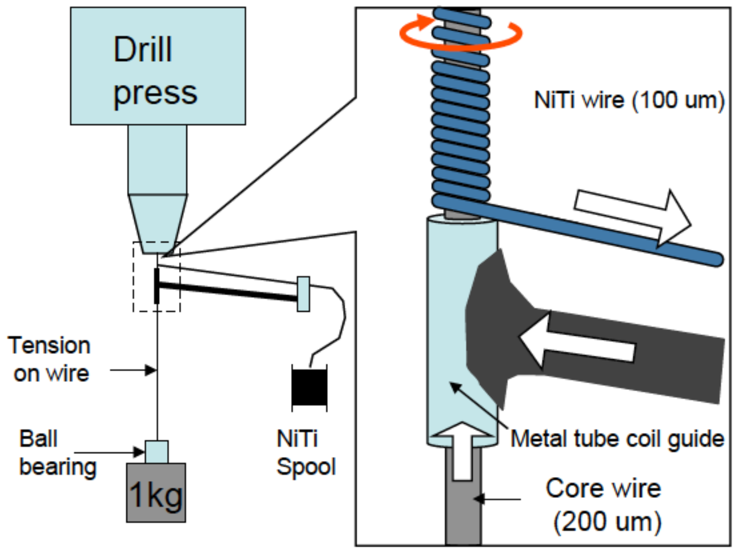
Limitations: thermal hysteresis in the strain, low cycle life, high fabrication cost, relatively low efficiency

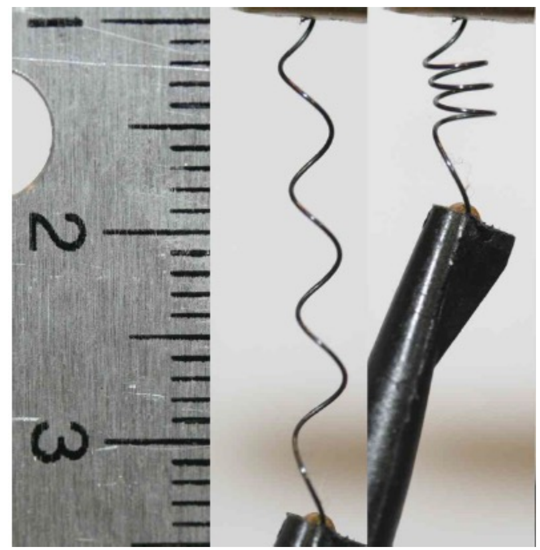
Property	Thermally activated SMAs
Stimulus	Heat (Joule heating)
Amplitude of stimulus	≈4 V (>> 4 V in short pulse excitation)
Strain [%]	<8.5
Stress [MPa]	<700
Strain rate [% s^{-1}]	<300
Work density [MJ m^{-3}]	<10
Power density [MW m^{-3}]	<30
Tensile strength [MPa]	<1900
Bandwidth [Hz]	<3 (<35 in a bending actuator)[80]
Efficiency [%]	<16%[a)]
Cycle life	300 (@≈5%) to 10^7 (@≈0.5%)

SMA Coiled Springs

- Once winding finishes, the actuator is baked in the furnace
- Annealing temperature: 300-600 C
- Actuated at 6V and 0.55 A.
- Energy density 1.2kJ/kg

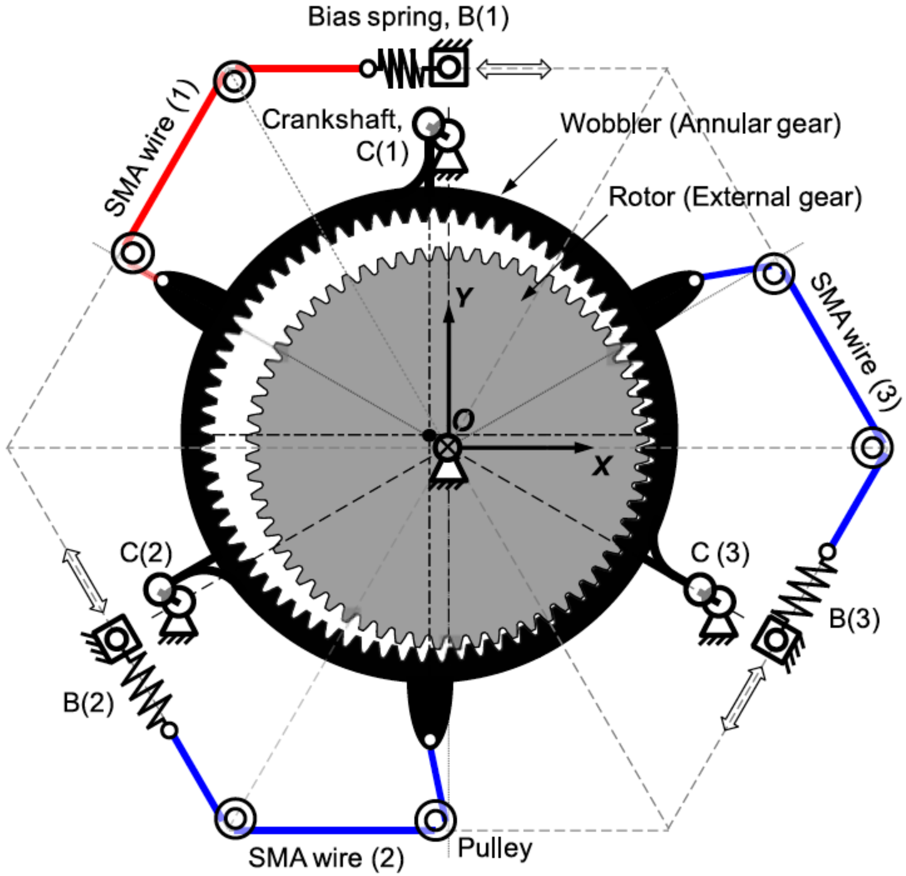
Type	Wrap	Compression (%)	Time (s)
Original	Tight	62	10
Wrap	Loose	77.81	7
Wrap	Tight	70	10.5
Tube	Loose	79.35	8
Tube	Tight	74.36	12

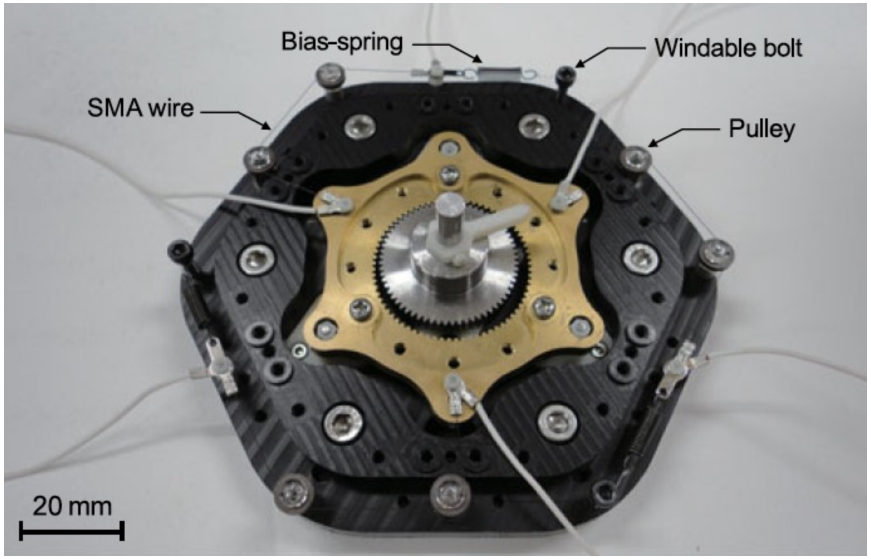


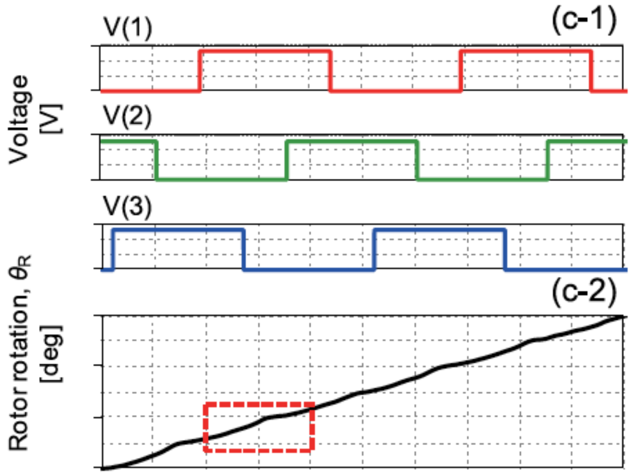


SMA Rotary Actuator

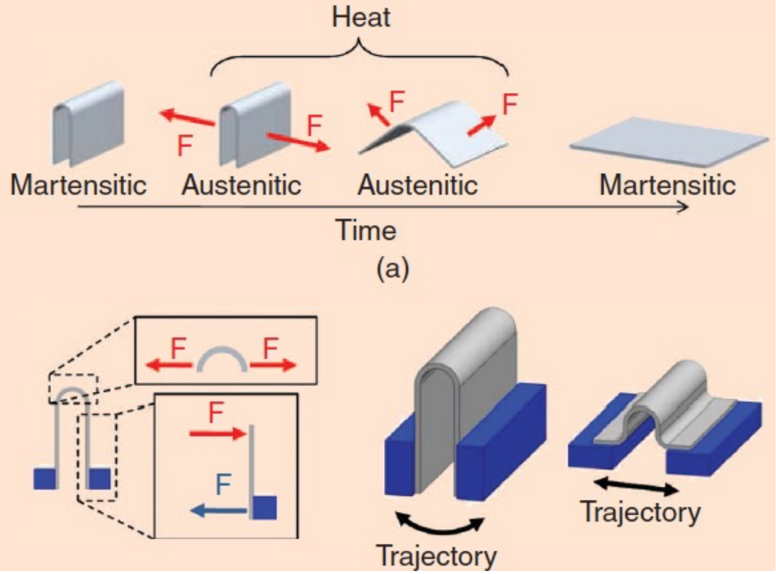
- Sequentially activated SMA wires

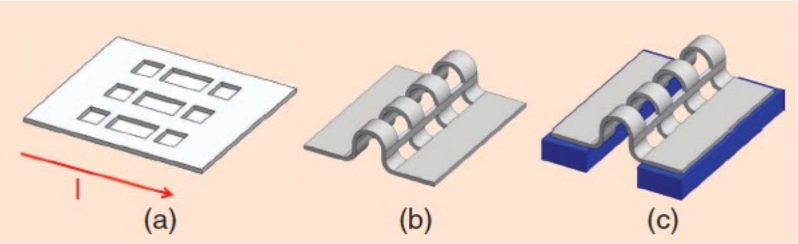




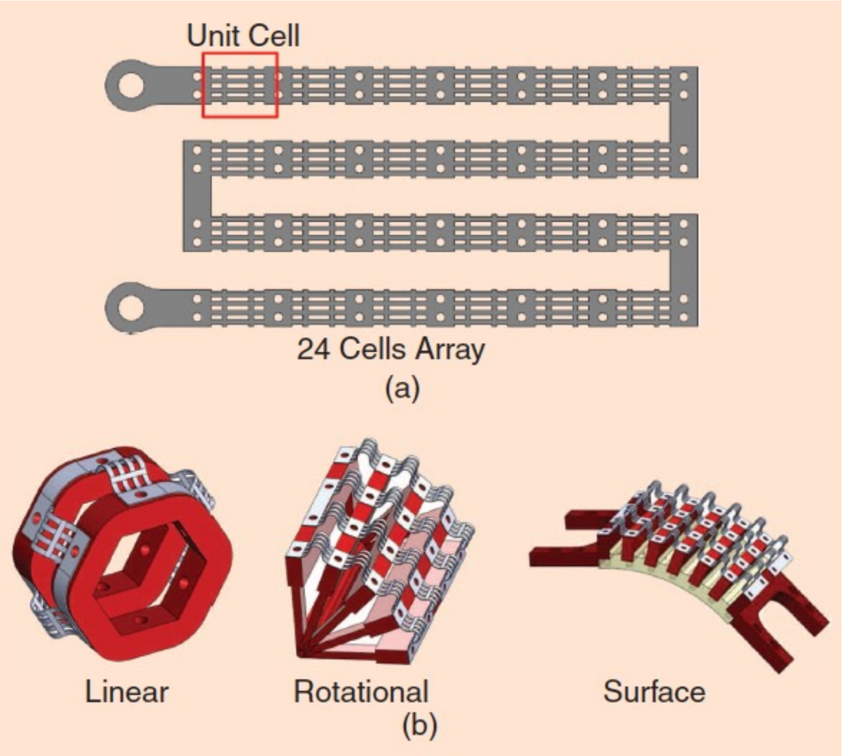


Modular SMA Sheet Actuators

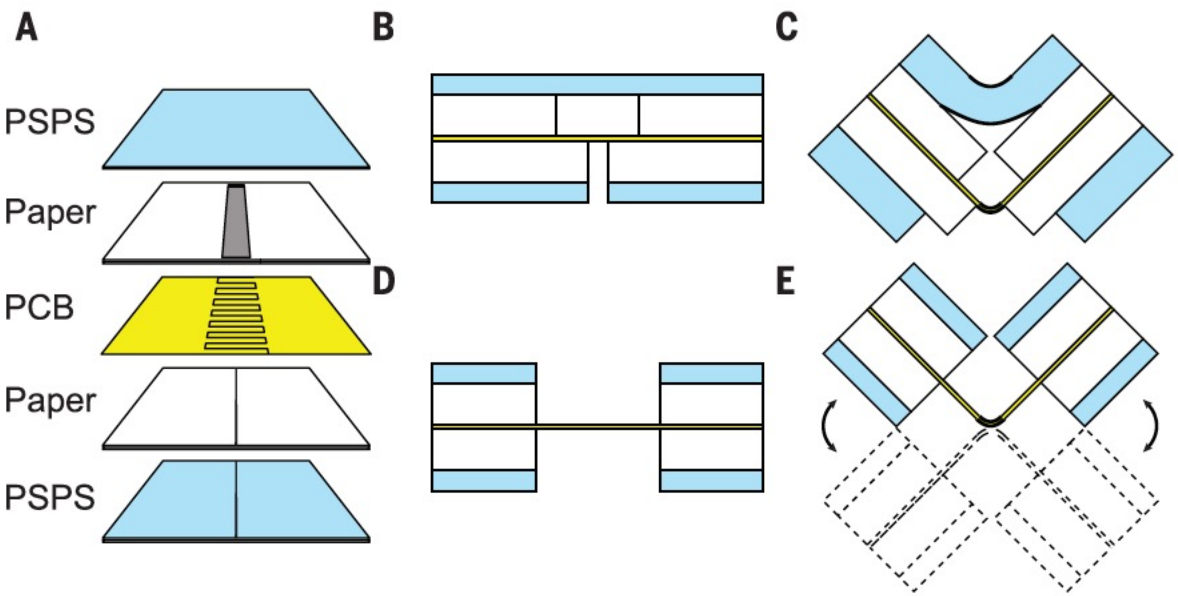


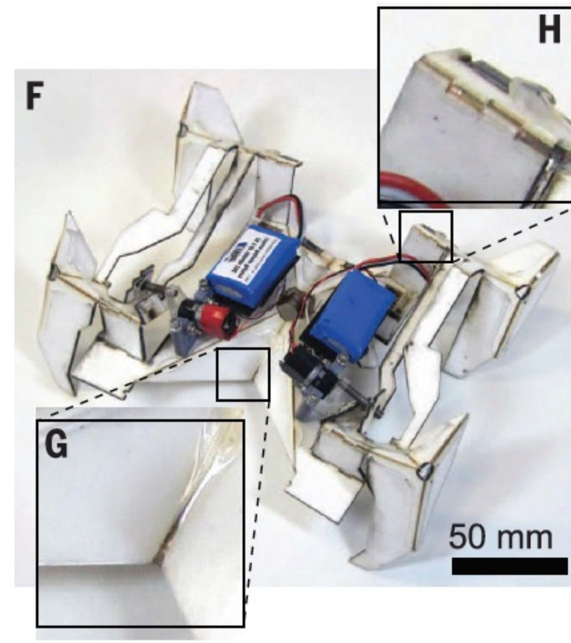


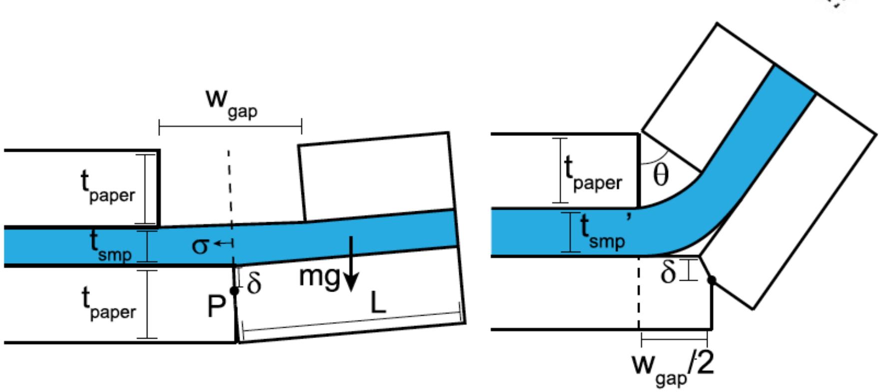
	Units	Micromo 1624006S	Maxon A2516	SMA Actuator
Diameter	mm	16.00	16.00	13.00
Length	mm	23.80	17.40	18.25
Torque	mN.m	1.50	0.76	5.10
Power	W	1.31	0.80	6.00
Weight	g	21.00	12.40	0.50
Torque/ power	mN.m/W	1.15	0.95	0.85
Torque/ weight	mN.m/g	0.07	0.06	10.20



Self-folding Machine



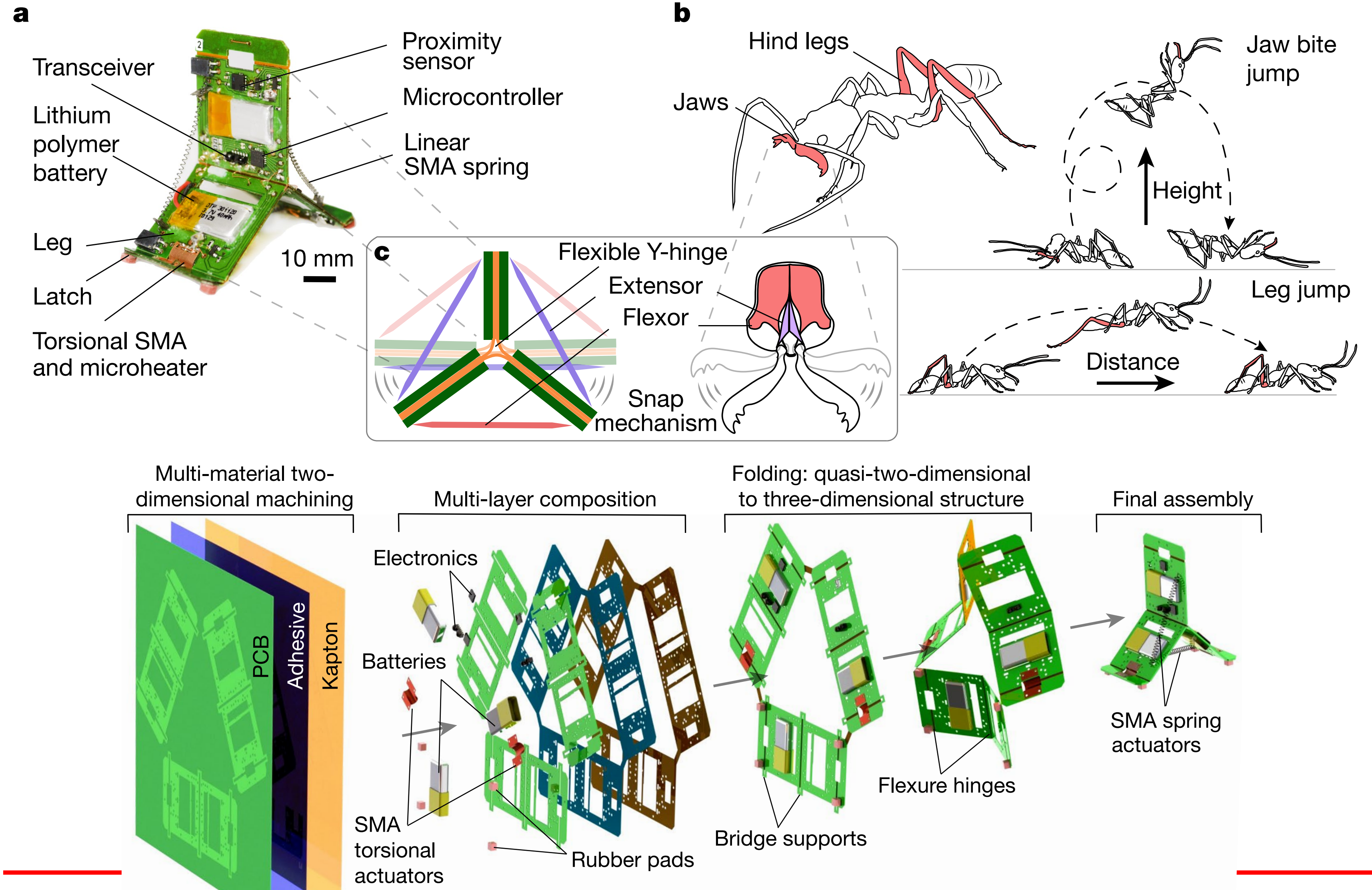




$$T = \frac{\sigma_a}{1-\nu} W t_{smp} \left(\frac{t_{smp}}{2} + \delta \right)$$

Self-folding Machine

SMA Millirobots

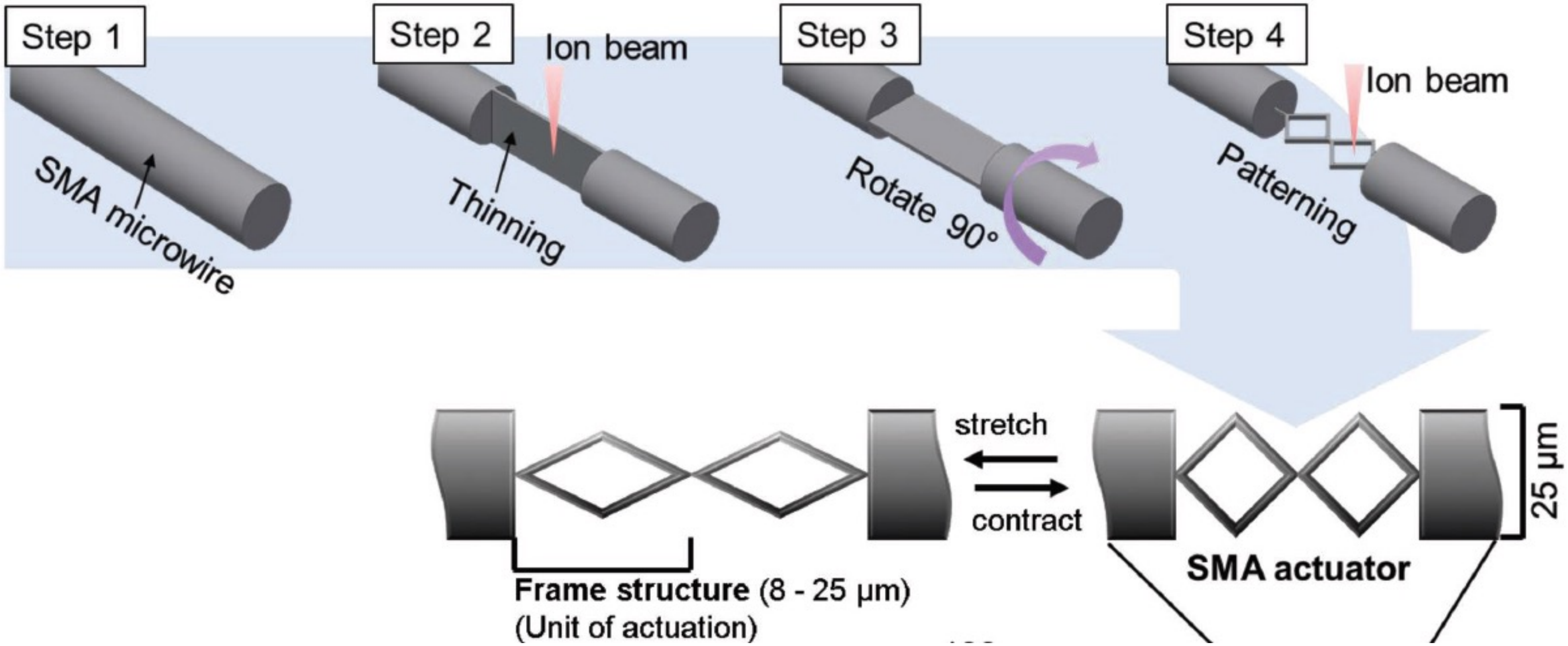


SMA Millirobots

SMA Millirobots

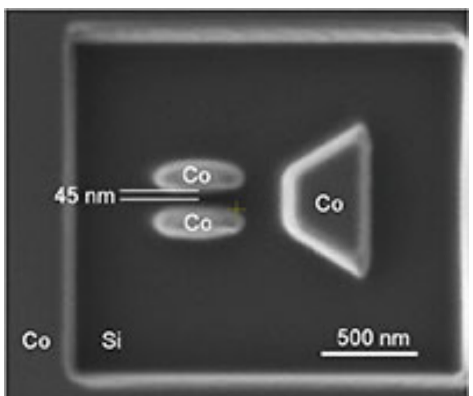
SMA Microactuators

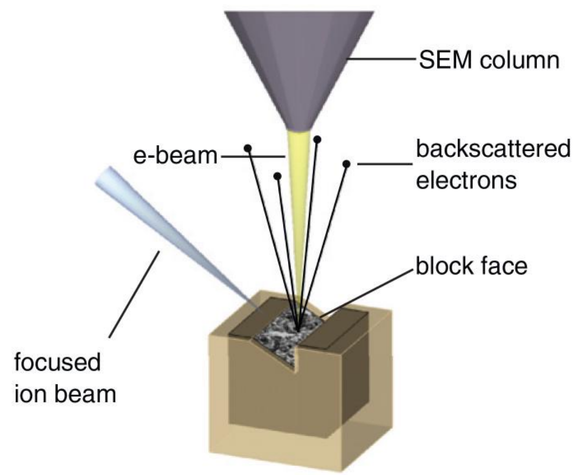
- Focus Ion Beam milling of 25 μm wire
- Activation with UV laser (high absorption coefficient for metals)



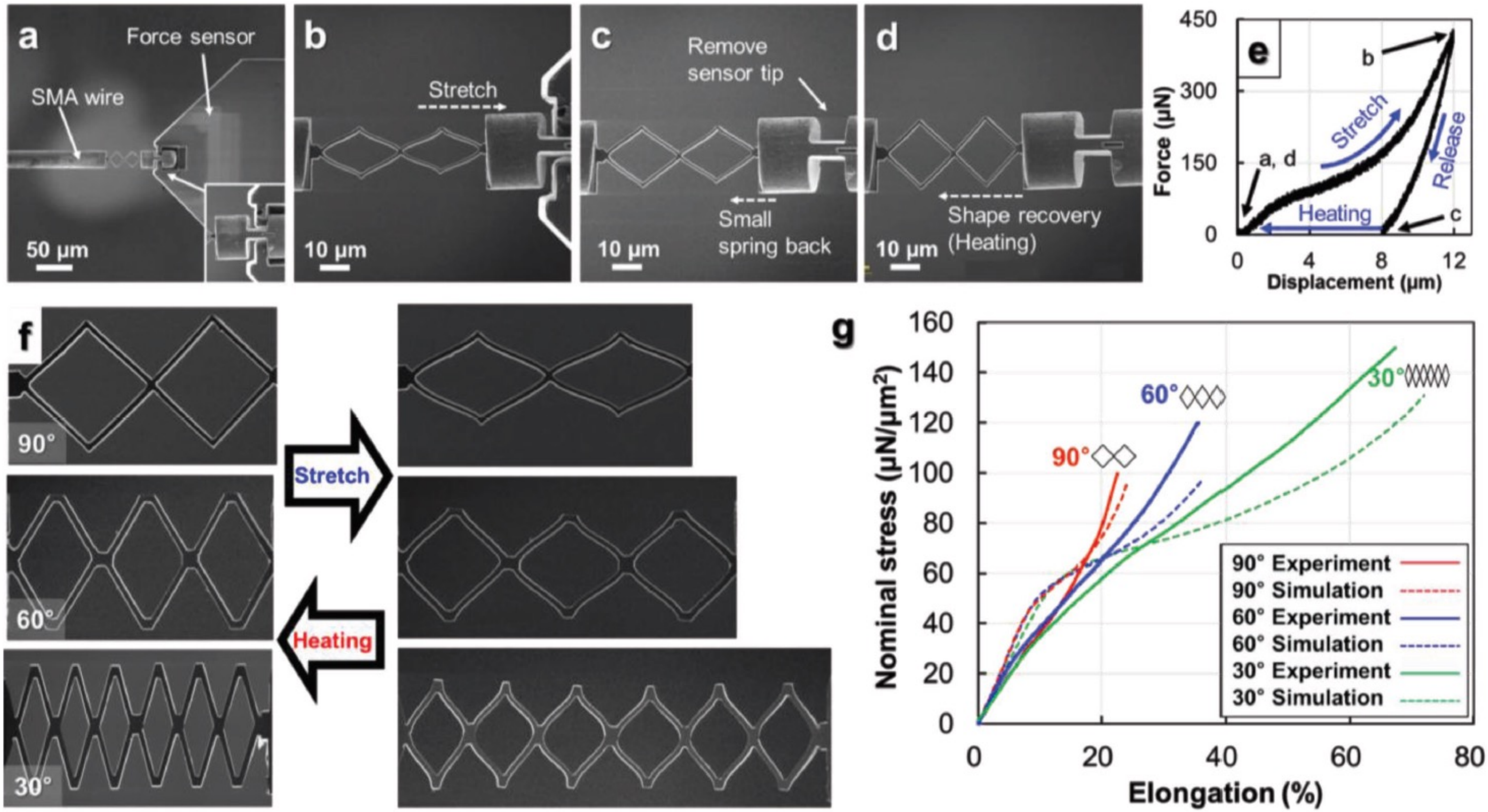
Focused Ion Beam Milling

- In electron microscopy, relatively low-mass electrons interact with a sample non-destructively to generate secondary electrons which, when collected provide high-quality images (sub nanometer res)
- Focused ion beam (FIB) instrument uses a beam of ions
- Lightest ion has 2000 times the mass of an electron
- Control the energy and intensity of the ion beam
- Capable of cutting away or building up structures on a surface with a resolution of 50 nm. Structures can be imaged in real-time using scanning electron microscopy mode.

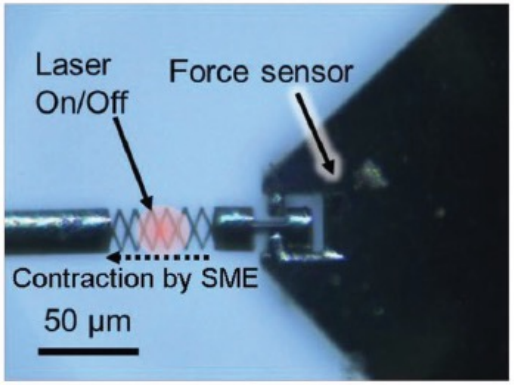


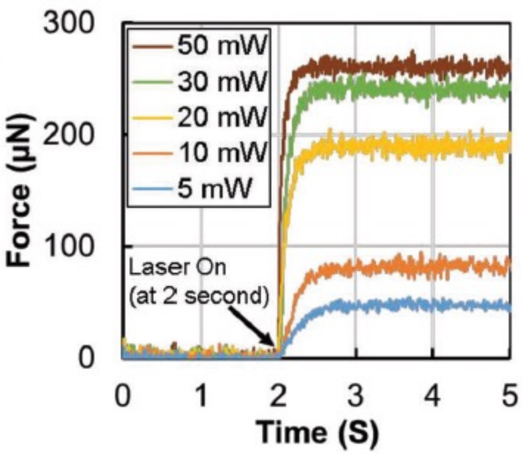


SMA Microactuators



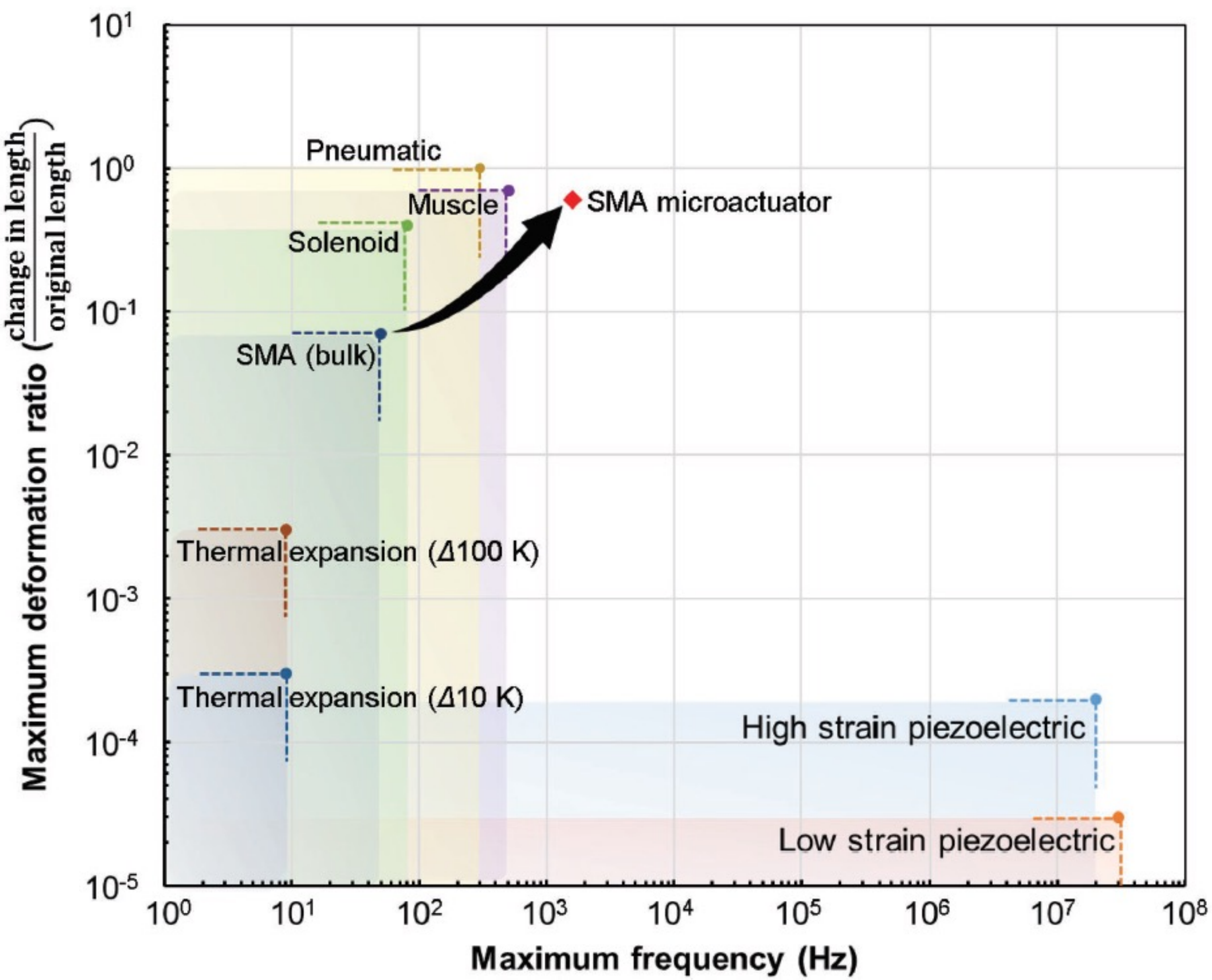
SMA Microactuators



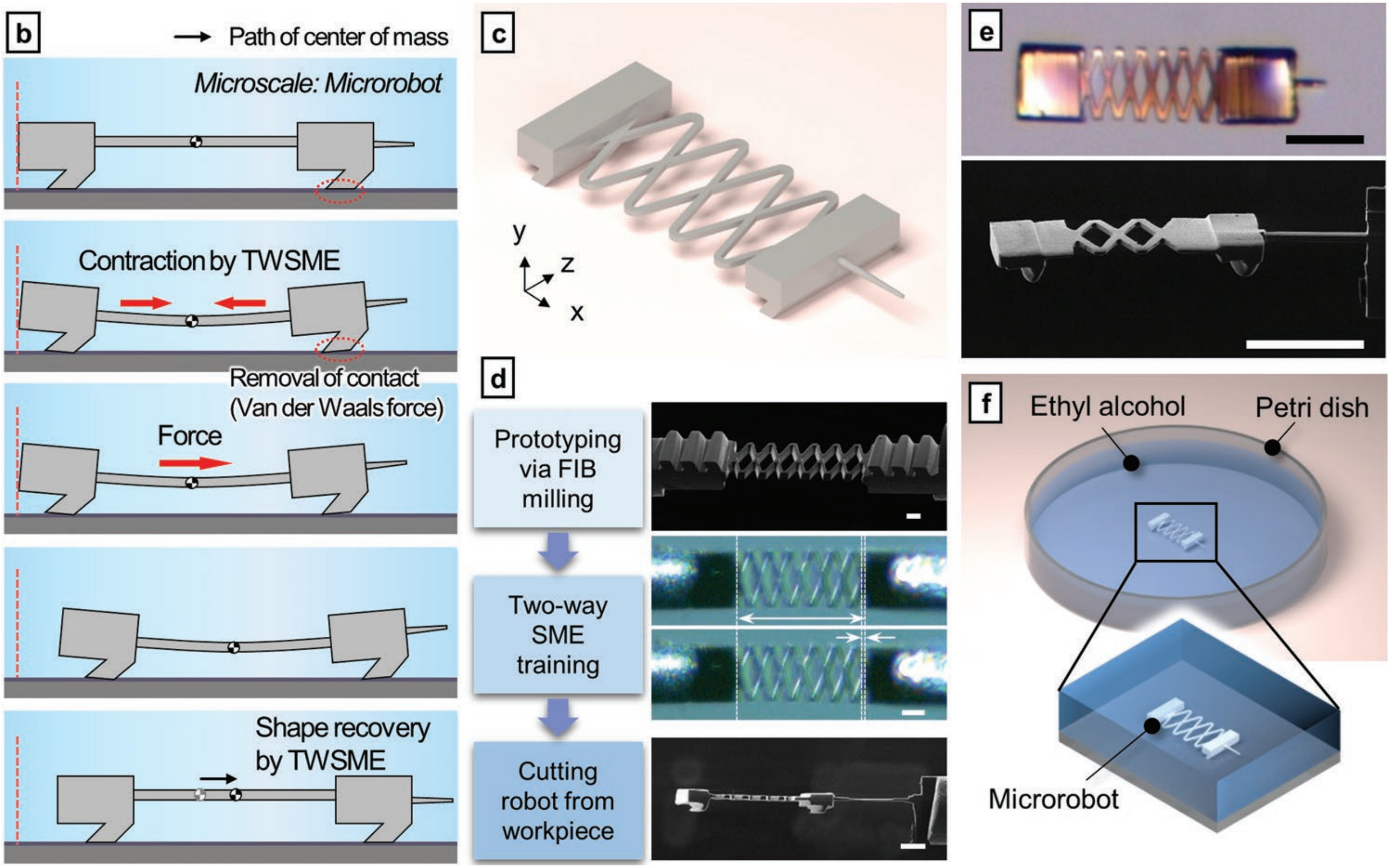


Specification	Muscle fiber	SMA microactuator [unit cell]
Maximum frequency [Hz]	500[2]	1600
Maximum actuation stress [MPa]	0.1–0.4[2]	0.75
Diameter [μm]	24.4 ± 1.1[29] (myofibril)	25
Length [μm]	1.6–2.5[30] (length of sarcomere)	8–25
Maximum deformation ratio	0.25–1.4[31,32]	0.15–0.6

SMA Microactuators: Performance



SMA Microrobot



SMA Microrobot