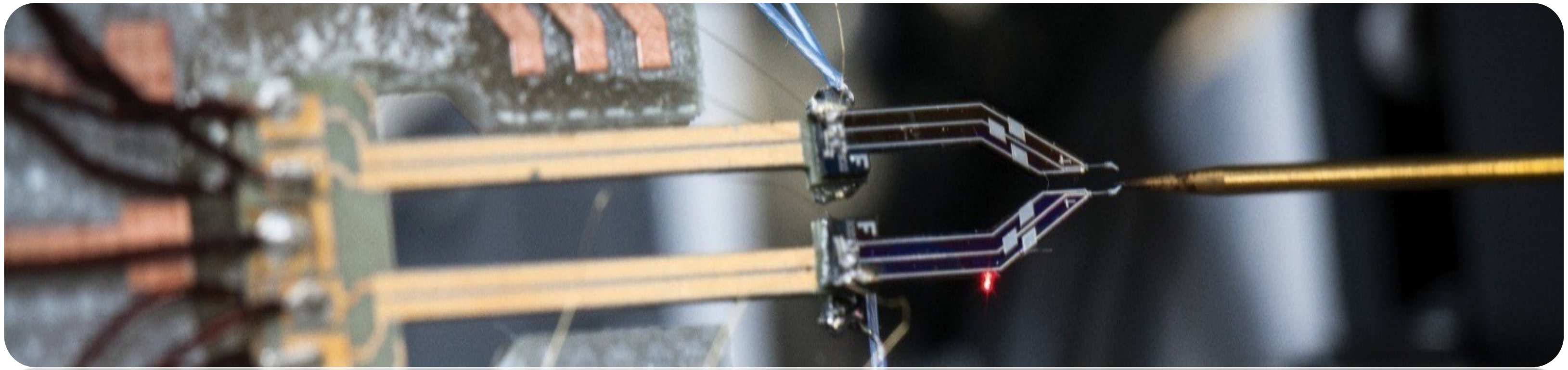
Micro and Nano Robotics:
design, fabrication and tasks



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Highlights in Microengineering Doctoral Course

June 16, 2021

1 - Introduction – scale effect

2 - Scale effect on robotics and control

3 - Actuation for microrobotics and examples of microrobotics applications

- Overview of the actuation
- Electrostatic / capacitive actuation
- Electrothermal Thermal Actuation
- Piezoelectric Actuation

4 - Sensing

5 - Microrobot architecture : 2D – 3D

1 - Introduction – scale effect

2 - Scale effect on robotics and control

3 – Actuation for microrobotics

Overview of the actuation

Electrostatic / capacitive actuation

Electrothermal Thermal Actuation

Piezoelectric Actuation (M2)

4 – Sensing

5 - Microrobot architecture : 2D – 3D

Size

100 nm | 1µm | 10µm | 100µm | 1mm

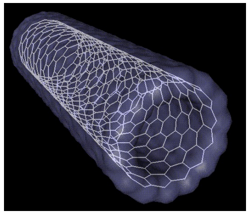
Microfabrication | manufacturing

Electronic scanning | Optical microscopy

Surface effects are predominant

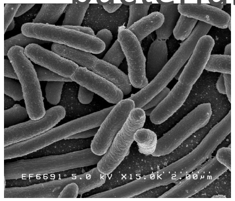
1 mm 100 µm 10 µm 1 µm

carbon nanotube



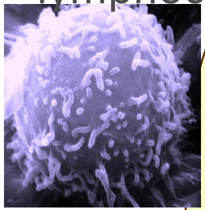
Diameter: 100 nm

bacterium



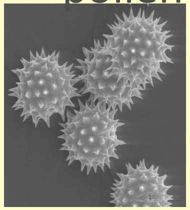
2-6 µm

lymphocyte



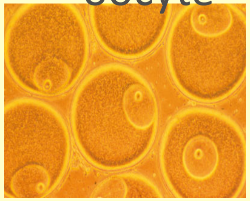
6-15 µm

pollen



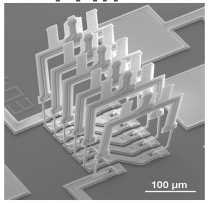
20-40 µm

oocyte



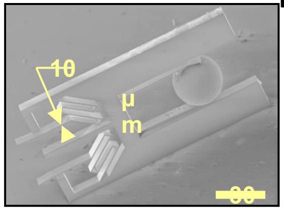
200 µm

coil



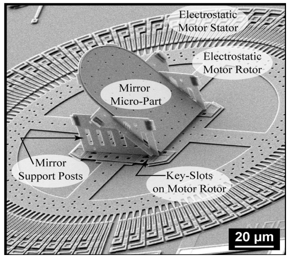
130 µm

Lens with its support

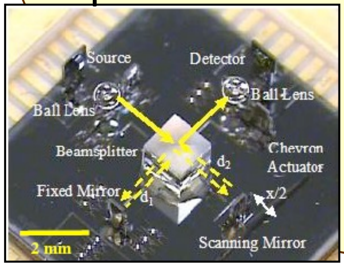


500 µm

mirror



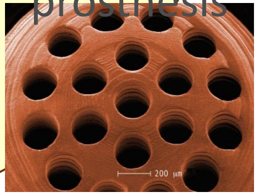
spectrometer



Gear wheel

800 µm

Hearing prosthesis



1 mm

Assembled systems

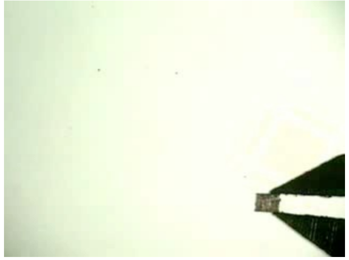
Why using robots?

- microscale is not accessible directly by human
    - micro-objects are too small
    - micro-objects are sometimes placed in vaccum

  combine robot precision and human intelligence in micro-cobots

- micro-objects have unpredictible behaviour
    - high impact on environemental conditions
    - unpredictible surface properties

  robot can change their behaviour in function of the object behaviour



- production of complex assembled micro-systems
    - small inertia enables high speed manipulation
    - human is not able to perform fast manipulation

  robot can generate high speed and controled trajectories

Miniaturization changes everythings

- **Scale effect**
  - impact of miniaturisation on physical effects

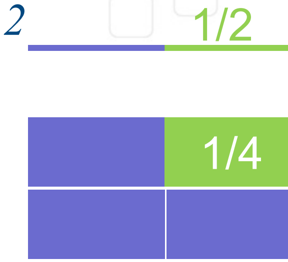
    modification of the relative weigth of each phenomena

- **Examples**
  - mass m, inertia I, weigth P : volume effects
    proportionnal to volume L^3
  - electrostatic force : surface effects
    proportionnal to surface L^2
  - Capillary force Fc, adhesion force : linear effects
    proportionnal to dimension L

  - Miniaturisation dividing the typical size by ten:
    inertia is divided by 1000,
    electrostatic force is divided by 100,
    surface tension is divided by 10

⇒ **Importance of electrostatic effects and surface tension in small scales !**

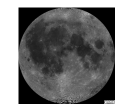
dimension divided by *2*
surface divided by 2^2
volume divided by 2^3



Earth

r = 1 m ⇒ A/V = 3 m^{-1}

Moon



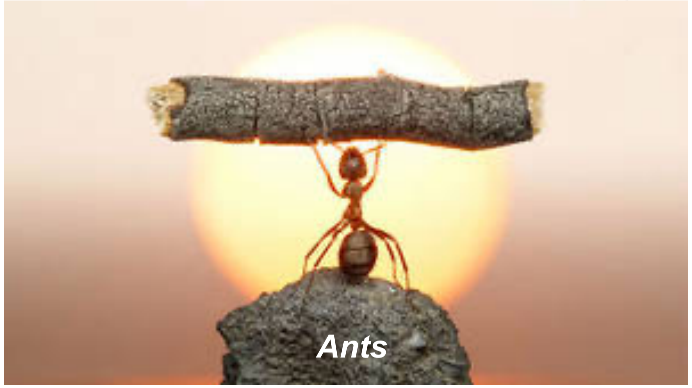
r = 100 µm

⇒

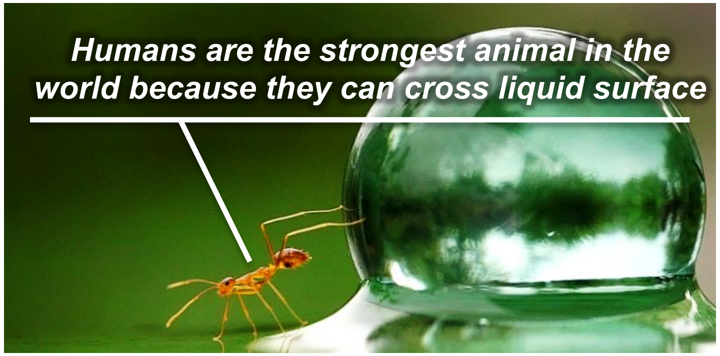
A/V = 30 000 m^{-1}

two scales : two worlds

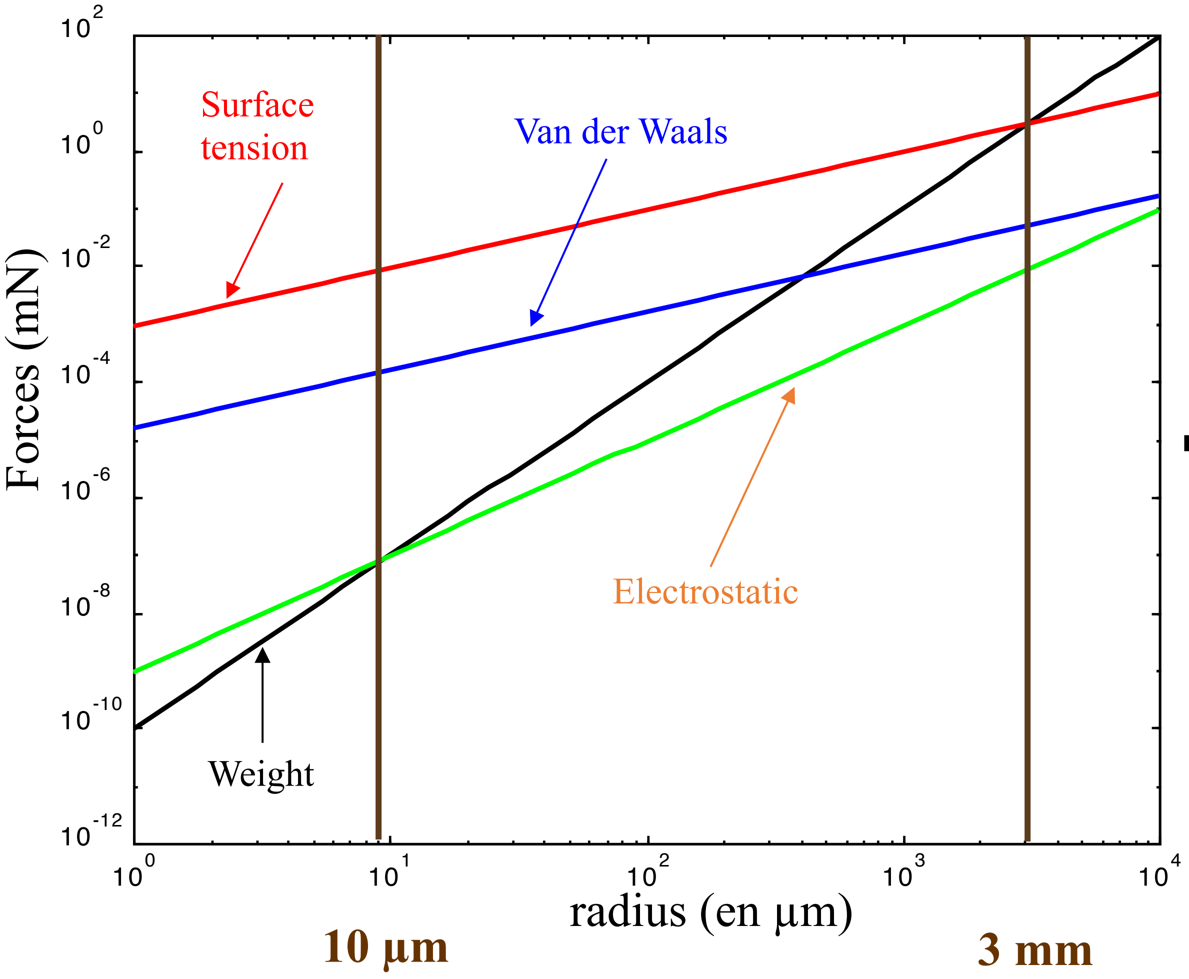
• In macroscale, weigth are predominant



• In microscale, surface tensions are predominant.

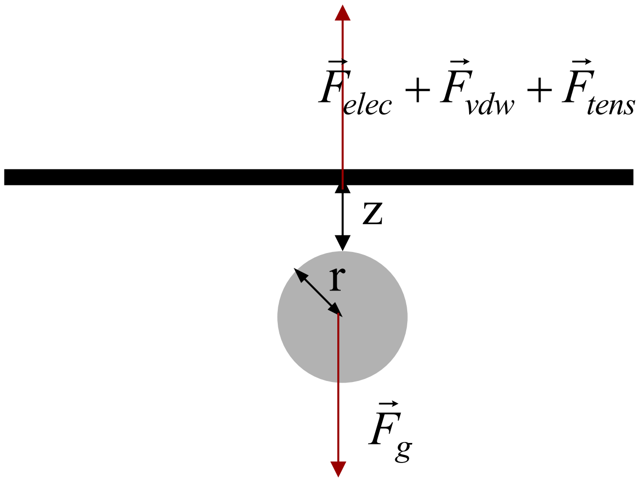


Relative influence of the forces



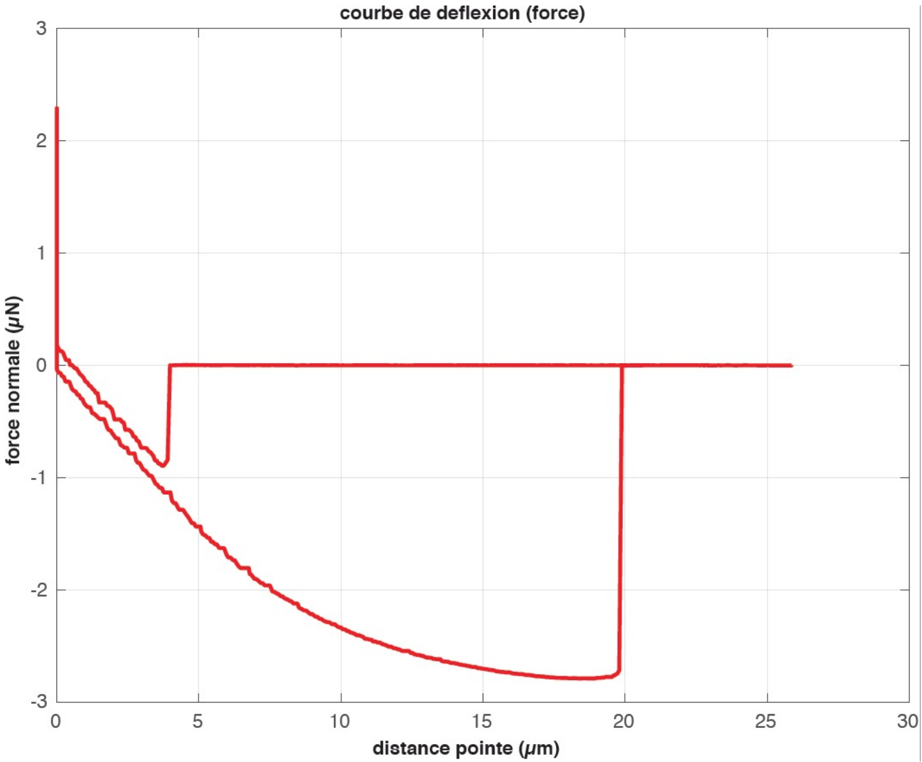
Example:

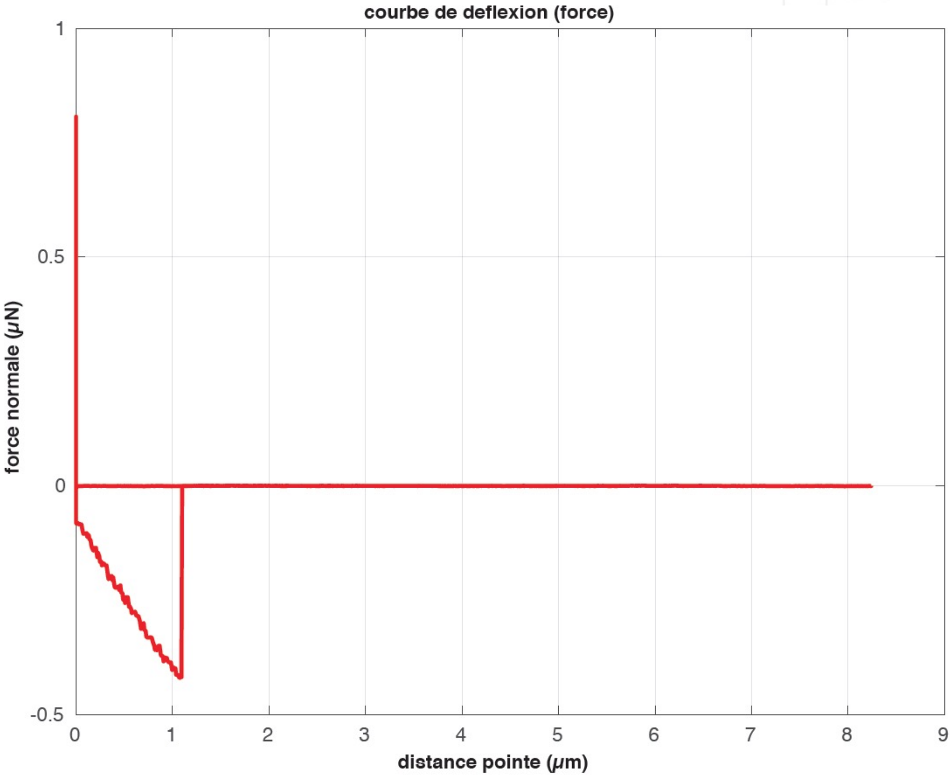
interaction sphere-plan



Attractive – Repulsive Force

Deflection curve of an AFM cantilever





approach-remove on a gold substrate covered with Pani polymer
--> attraction and adhesion

approach-remove on a piece of tungsten --> no attraction

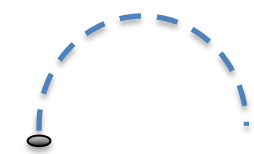
Scale effect on physics

- **Dynamics:** resonance frequency

  resonance frequency ~ L^{-1} Higher dynamics in smaller scale

- **Mobility:** going up to an obstacle having your own size

  Ep= H.mg -> Ep ~ L^4 Better mobility in smaller scale



- **Magnetic actuation**: electromagnetic torque

  T ~ L^3 à L^5 magnetic torque cannot be used in small scale

- **Thermal effects:**

  Response time: T ~ L à L^2 Low thermal inertia

- **Energy :** batteries, gaz, petrol : E ~ L^3 difficulty to store energy in small scales'

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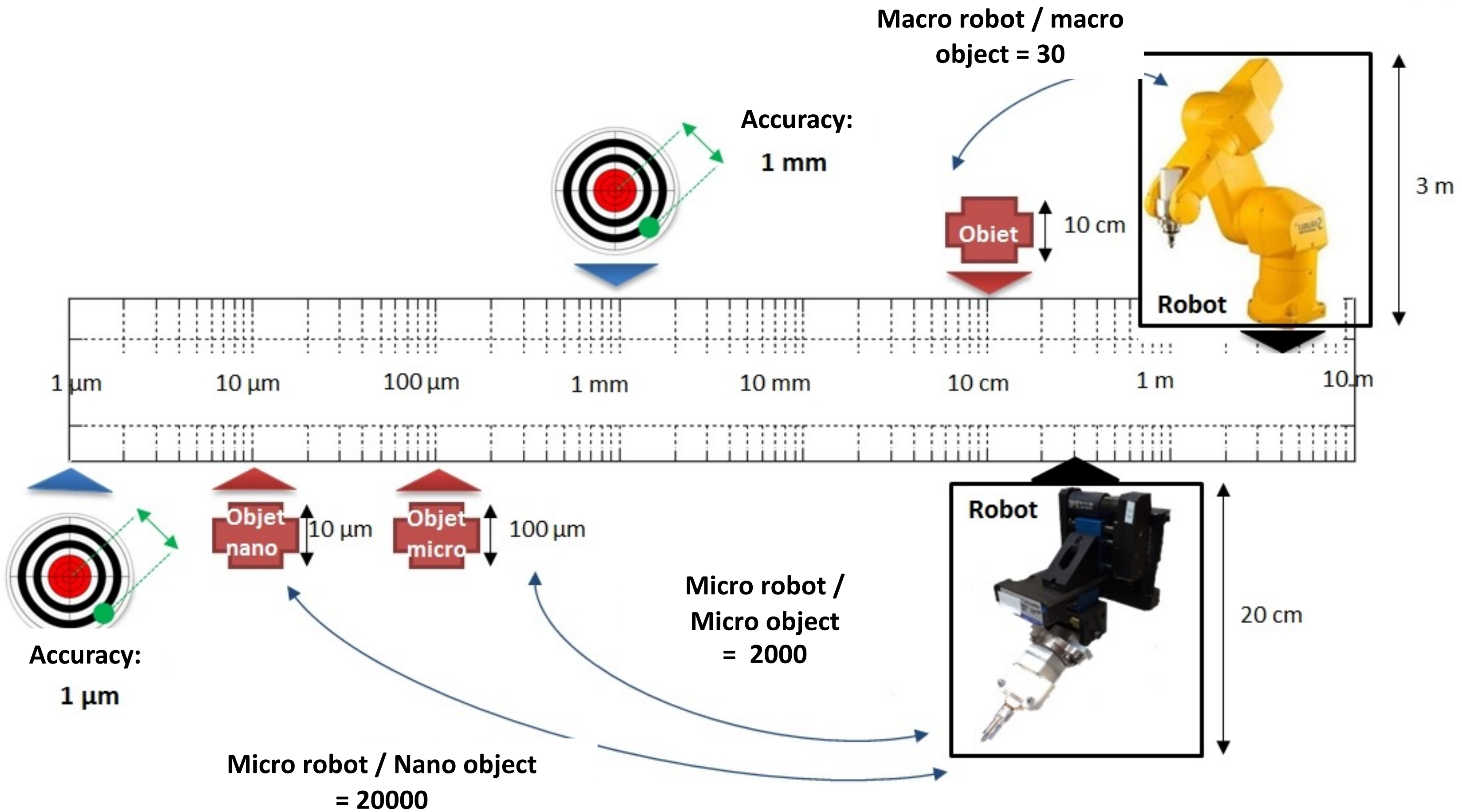
Scale effect on robotics

- Why small robots are needed for micro-nano manipulation



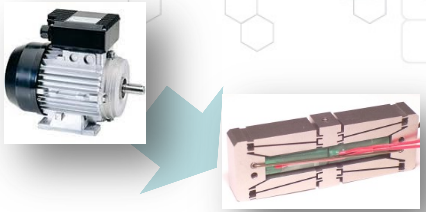
From C. Clévy HDR

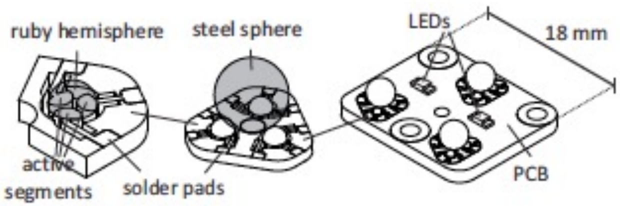
Scale effect on robotics

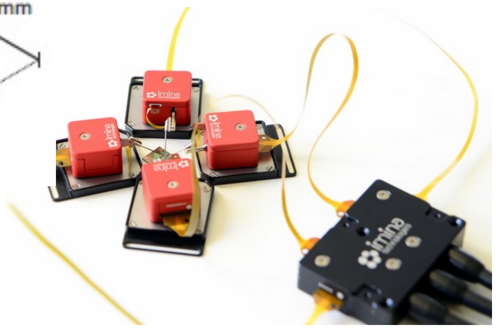
- actuation

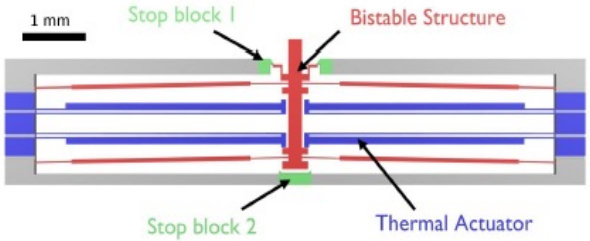
  High required precision, impact of friction on sliding surface

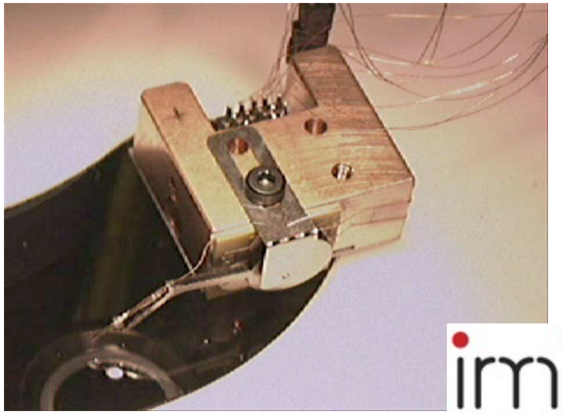
  →Compliant mechanisms and active materials











imina technologies

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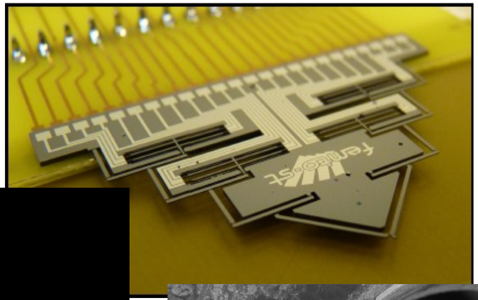
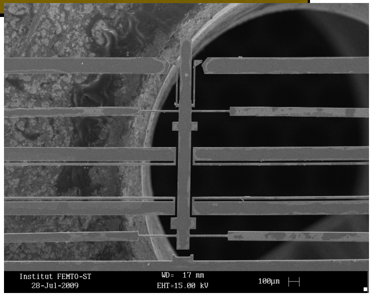
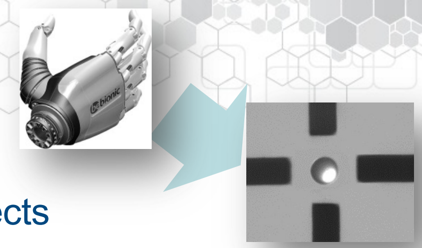




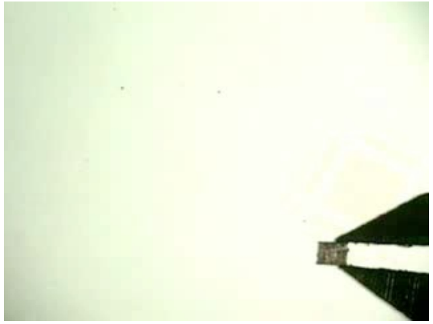
Scale effect on robotics



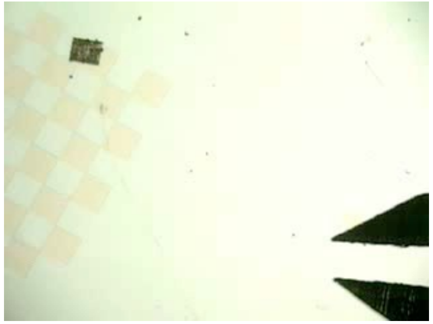
- grasping

  Inertia of objects is negligible, adhesion between tweezers and objects

  → Require new hanlding principles



Electrostatic disturbances



Adhesion disturbances

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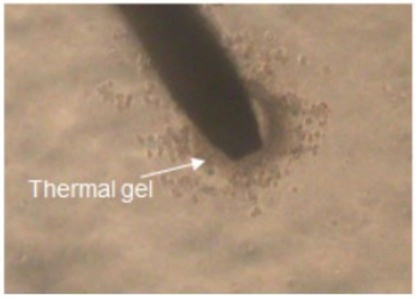

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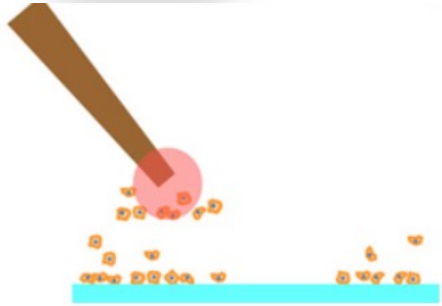
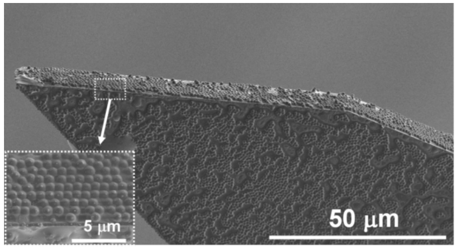
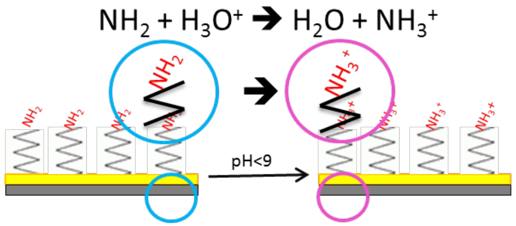


Phase change



Roughness control



Surface functionnalisation

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Non-contact manipulation

Compliant mechanisms

It involves transmitting the movement, force or energy generated by the actuator

- A compact, lightweight mechanism chosen from a suitable material is inherently more precise than a large and heavy mechanism.

- Un bras de 10 cm de long avec une précision de 10 nm … c'est comme …
un bras de longueur « Besançon-Paris » avec une précision de 4 cm …

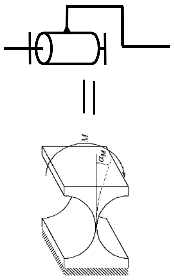
- ΔT=1° C correspond à ΔL=480 nm pour une poutre de 40 mm

- Augmenter des fréquences de résonnance

$$f \;\alpha\; \sqrt{\frac{k}{m}} \;\alpha\; \sqrt{\frac{E}{\rho}}$$

materiau	$E/\rho.10^7$ m^2/s^2
acier	2,66
aluminium	2,62
kevlar	9
silicon	15

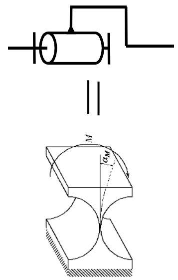
- Friction is the mortal enemy of resolution (and therefore of precision)
- ***Deformable mechanisms, non-contact bearings***

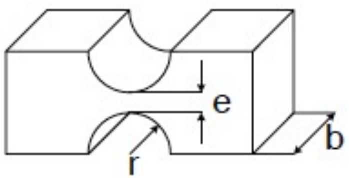


Actuation for microrobotics

Association of an actuator with a compliant structure

Thermal actuators sometimes have sufficient strokes or piezoelectric bimorphs to which high voltages are applied, but most of the time it is necessary to amplify the movement.
As seen in another part of the course, to avoid problems resulting from friction, the guiding and amplification mechanisms will be mainly based on deformable or compliant structures.

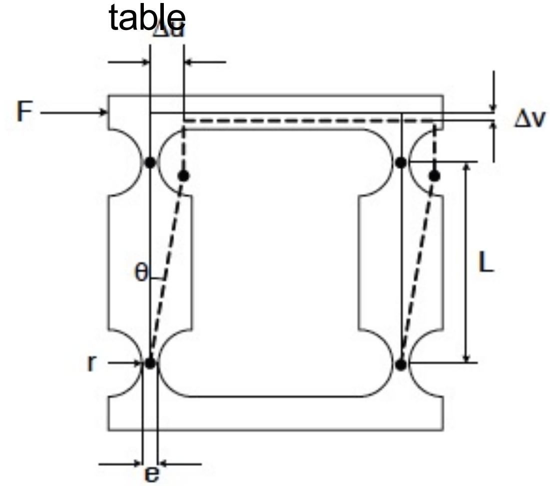




Flexural stiffness $K = \frac{2Ebe^{2.5}}{9\pi\sqrt{r}}$

Maximum angular stroke before plastification $\alpha = \frac{3\pi\sigma_{max}\sqrt{r}}{4E\sqrt{e}}$

Calculate the translation stiffness K_t of the table

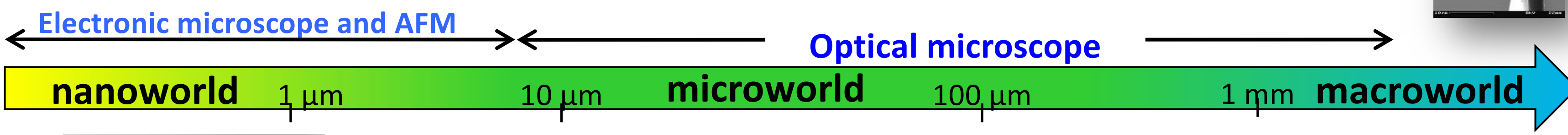


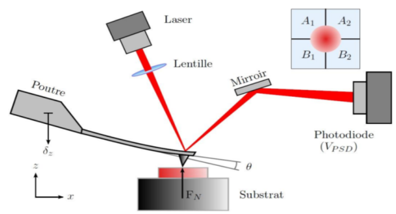
$$K_t = 8\,\frac{E\ b\ e^{2,5}}{9\ \pi\ L^2\ \sqrt{r}}$$

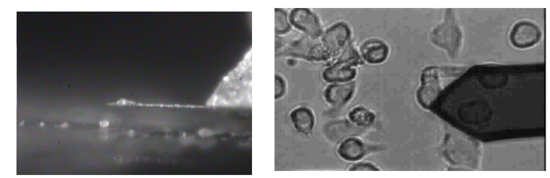
Scale effect on robotics

- sensing

  Mainly based on vision based on optical vision, near field vision or electronic vision

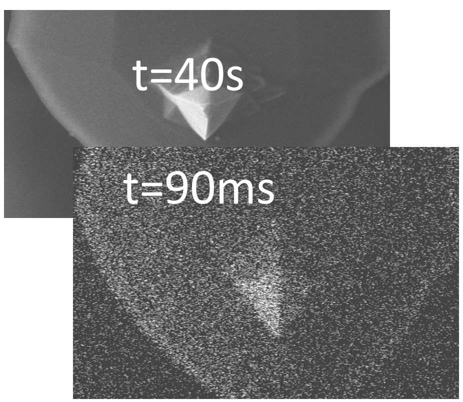


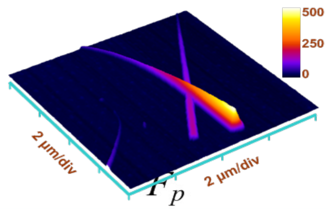




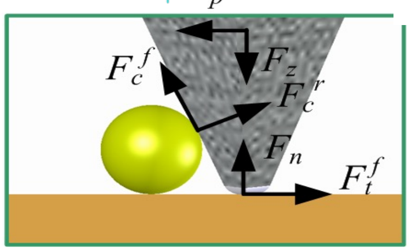
Atomic Force Microscope (AFM)

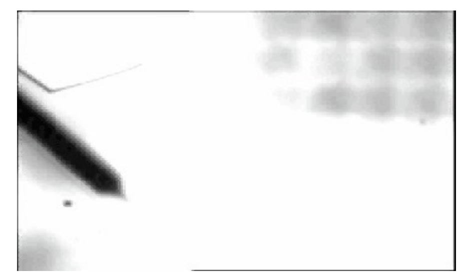
Scanning Electron Microscope (MEB)





Optical Microscope





strong additive noise due to fast image acquisition

Tool

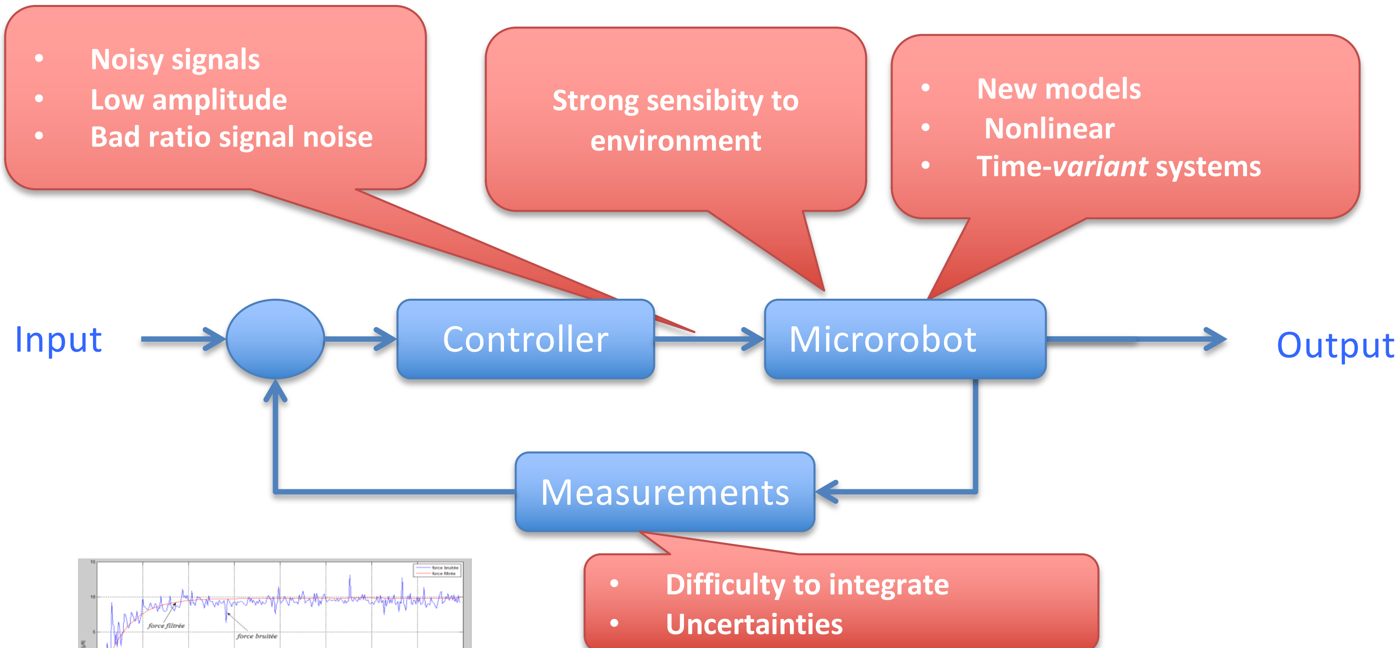
Fast tracking algorithms
Vision sensor for 3D visual servoing

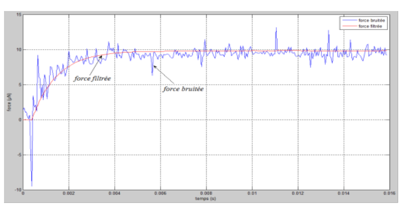
Scale effect on robotics

- automation

  Non-linear behaviour of the actuators and impact of the surouding medium

  →Require advanced control laws



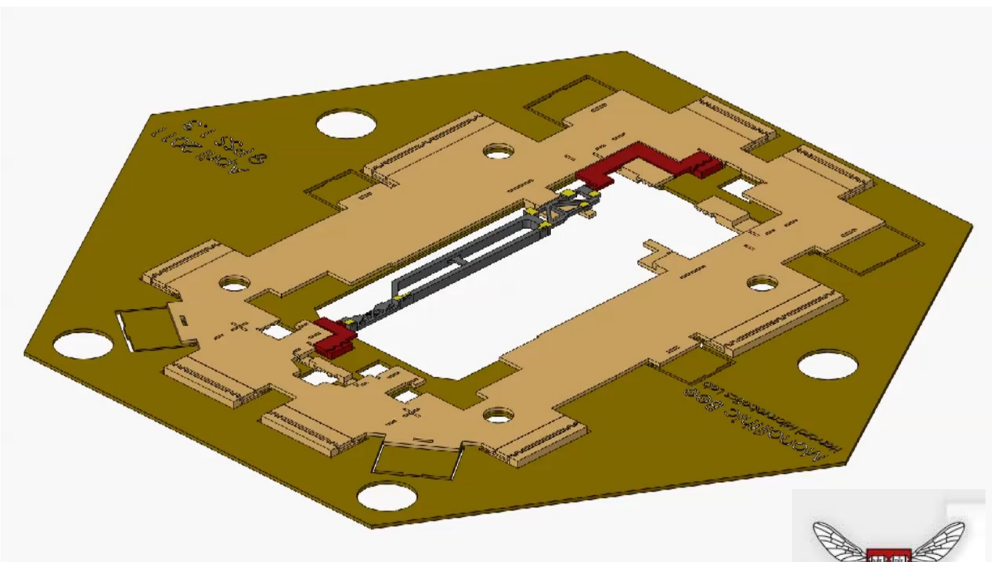


Scale effect on robotics

- fabrication vs microfabrication

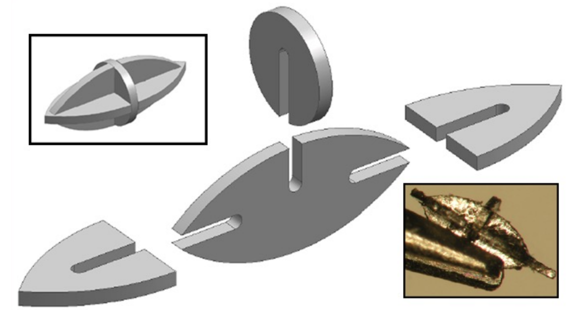
microfabrication inspired from microelectronics : 2D objects

→ Require to propose new design including the fabrication constraints



Origami principle

HARVARD
MICROROBOTICS
LABORATORY



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3D microassembly

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3 – Actuation for microrobotics

Overview of the actuation

Electrostatic / capacitive actuation

Electrothermal Thermal Actuation

Piezoelectric Actuation

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Overview of actuation in the microworld

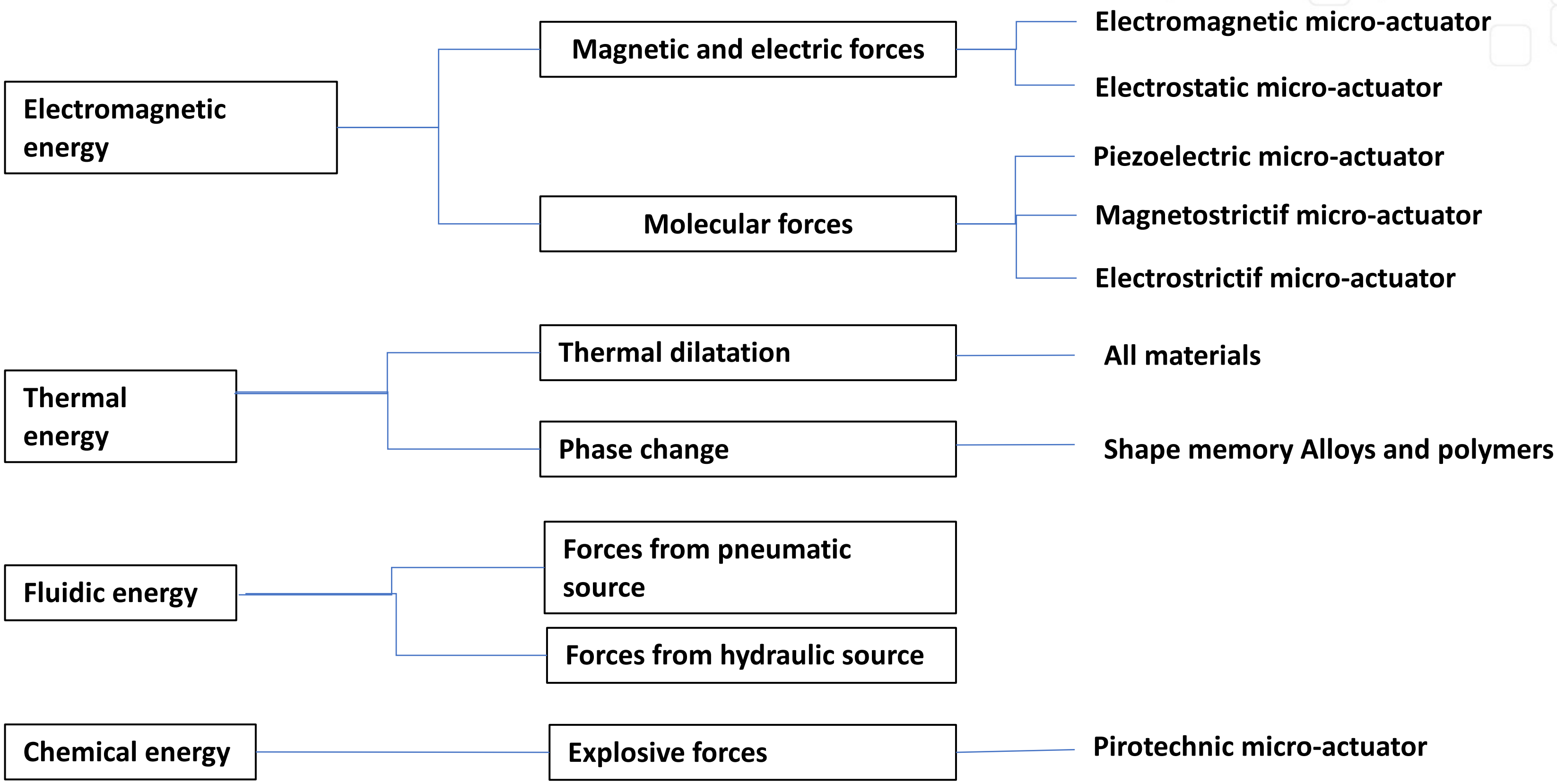
The actuator is the component in a device or system that provides the force required to perform the work desired by a control unit.

Actuators based on hydraulic, pneumatic and electric motor-based technologies are widely used on a macroscopic scale but are not necessarily transferable to micro and millimetre scales due to insufficient performance or efficiency during miniaturisation.At the microscopic level, different types of active materials and alloys are generally used, which are capable of providing a consistent work on this scale.

Most commonly used actuation principles in microobotic:

- piezoelectric actuators
- electrostatic actuators
- thermal actuators
- electromagnetic actuators
- shape memory alloy actuators (AMF)
- electro-active polymer actuators.

Overview of actuation in the microworld



Overview of actuation in the microworld

	SMA	Piezoelectricity
Physical phenomenon	Solid phase transformation	Dipole orientation
Actuating principle	Thermal	Electric field
Energy density ($J.m^{-3}$)(order of magnitude)	10^6 to 10^7	10^6 (PZT), 10^3 (PMN)
Bandwidth	Small (10^2 Hz)	High (100 kHz)
Operating mode	Flexion, torsion, torsion, tension, compression	Depend on the electric field orientation
Deformation	1 - 8 %	0,12 – 0,15 %

	Thermal Bimorph	Conductive polymer
Physical phenomenon	Solid phase transformation	Oxydation and reduction, ions diffusion
Actuating principle	Difference between thermal dilatation coefficient	Voltage difference
Energy density ($J.m^{-3}$)(order of magnitude)	10^5 Ni/Si	10^3
Bandwidth	small	Small (10Hz)
Operating mode	bending	Bending, tension, compression
Deformation	5,23 x 10^{-4} %/°C	1 – 5 %

	Giant magnetostrictive
Physical phenomenon	Magnetic dipole orientation
Actuating principle	Magnetic field
Energy density ($J.m^{-3}$)(order of magnitude)	10^4 to 10^5 (Terfenol D)
Bandwidth	High (100 kHz)
Operating mode	Depend on the magnetic field orientation
Deformation	0,58 – 0,81 %

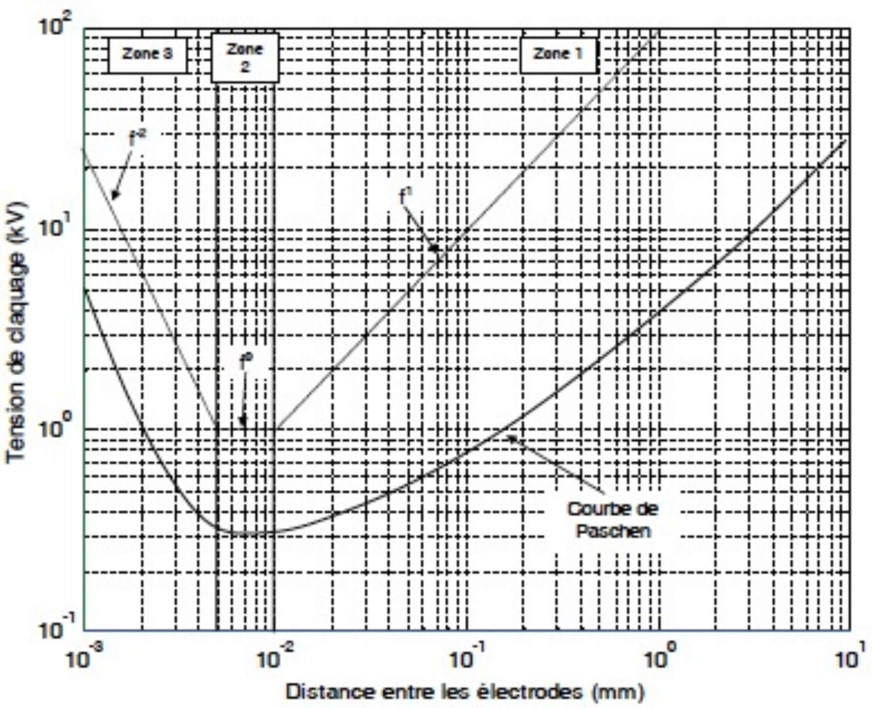
Actuation for microrobotics

Electrostatic / capacitive actuation

and

examples of microrobotics appication

Electrostatic / capacitive actuation



Paschen curve (in air, at atmospheric pressure and 20°C)

U_d: breakdown voltage
f : scale factor
d : distance between electrodes

- Zone 1: d>10µm - U_d increases with d. It is possible to approximate that U_d is proportional to d. Under these conditions, the scale factor on U_d is: $U'_d/U_d=f^0=1$

- Zone 2: 5<d<10µm - U_d can be considered as constant. Then $U'_d/U_d=1$

- Zone 3: d<5µm – U_d increases when d decreases. It is possible to approximate that U_d is proportional to $1/d^2$. Under these conditions, the scale factor on U_d is: $U'_d/U_d=(d/d')^2=f^{-2}$

⬇

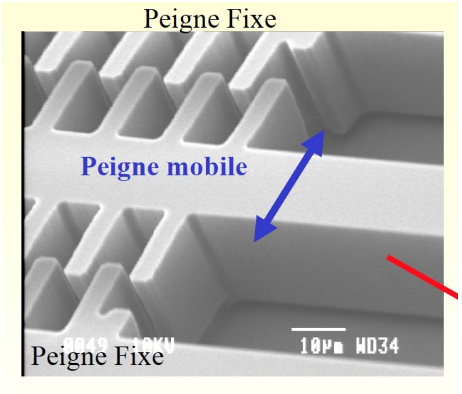
For micro actuators, the distances between electrodes are in zones 2 and 3.

Electrostatic / capacitive actuation

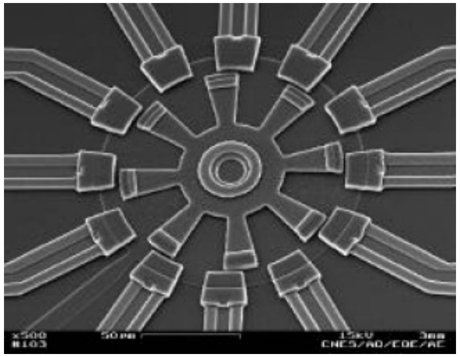
3 kinds of actuator:

- Capacitive plates
- Interdigital combs
- Micromotors

From CNES

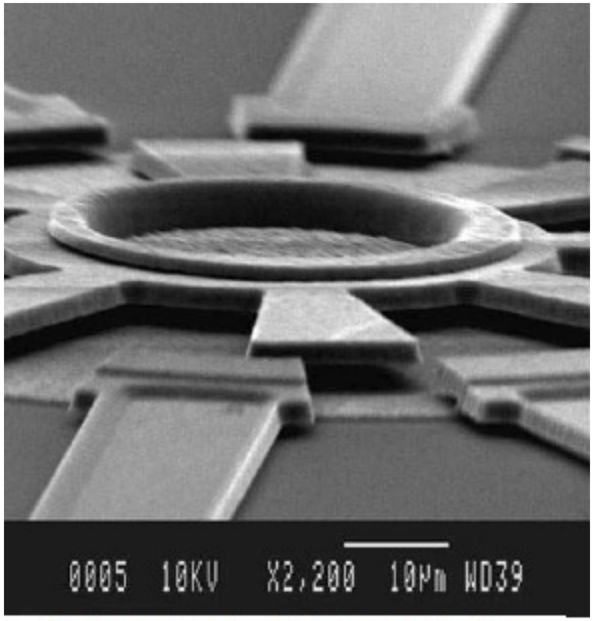


From ESIEE



Electrostatic / capacitive actuation

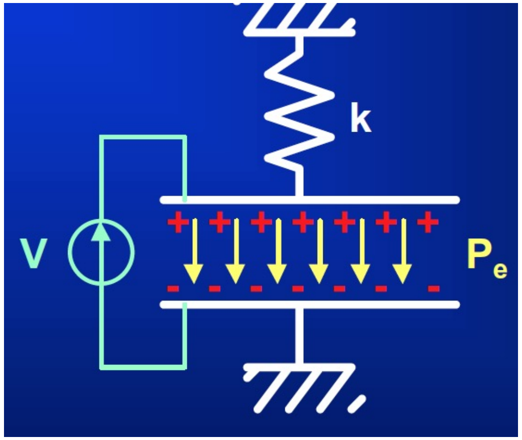
An electrostatic force is created by applying a potential difference between two accumulator plates separated by an insulator. This principle is the basis of highly miniaturized electrostatic actuators (silicon-machined motor with 120 μm diameter rotors). They require high voltages (hundreds of volts) and provide very low torques (from 10^{-12} to 10^{-9} N.m).

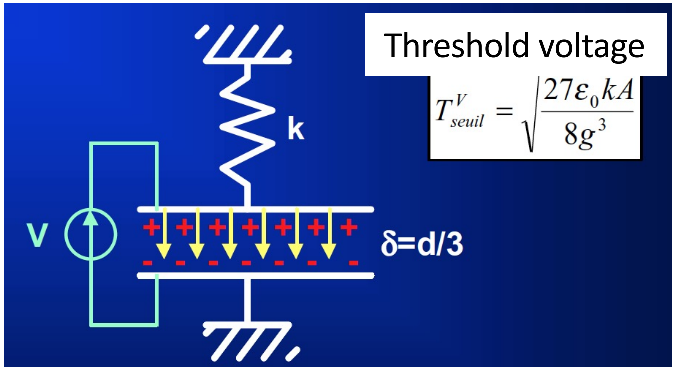


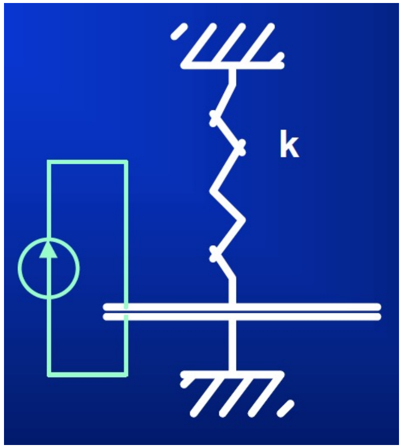
Moteur électrostatique usiné en silicium [CNRS]

Electrostatic / capacitive actuation

Pull-in effect in electrostatic MEMS devices







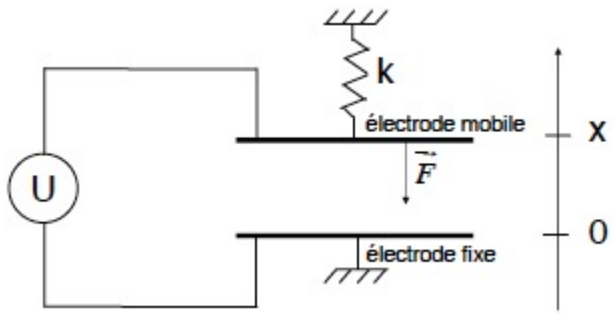
Calculation of the pull-in effect

Electrostatic / capacitive actuation

Calculation of the pull-in effect

$$\vec{F} = -\vec{\nabla} W_e \qquad W_e = \frac{1}{2} C U^2$$

Calculating the actuation force of an electrostatic micro-actuator essentially consists of calculating C and then exploiting these two relationships.



Electrostatic micro-actuator acting on an elastic deformable structure acting on an elastic deformable structure, the resting position at U=0 of the electrode is $x=x_0$
F : force between the two plates
W_e = electrical energy in the capacitor

F_m : force from the actuator
F_r : force (resistant) from spring stiffness k

Calculation of F_m and F_r

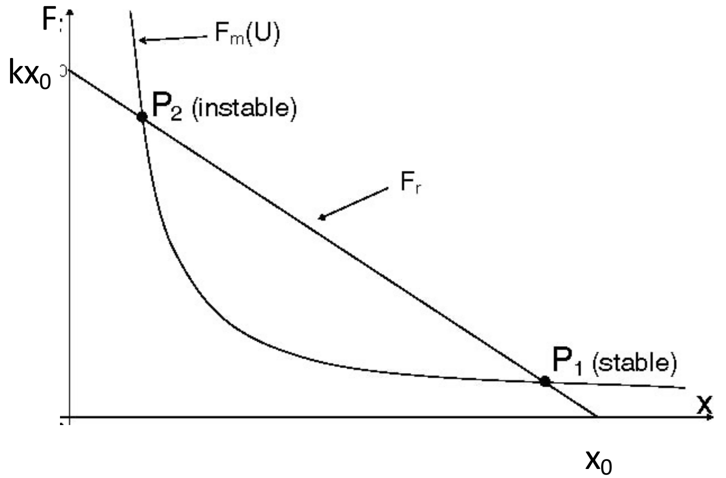
$$F_m = \frac{\varepsilon A}{2\, x^2} U^2$$
$$F_r = k\, (x_0 - x)$$

Pull-in voltage is : $U_l = \sqrt{\dfrac{8 k x_0^3}{27 \varepsilon A}}$

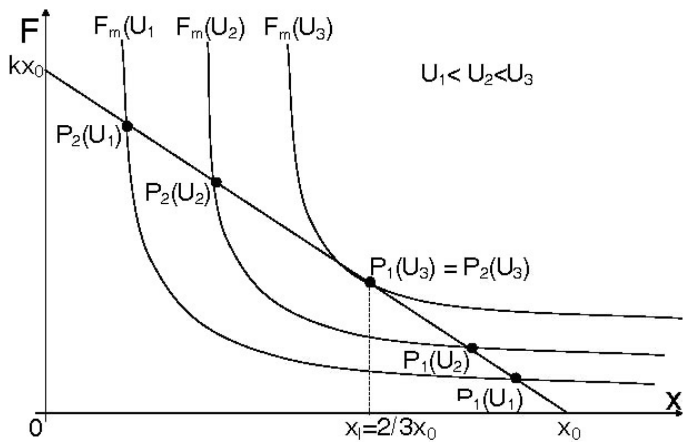
Electrostatic / capacitive actuation

Calculation of the pull-in effect

$$\begin{cases} F_m(x_l) = F_r\,(x_l) \\ \dfrac{dF_m}{dx}(x_l) = \dfrac{dF_r}{dx}(x_l) \end{cases}$$



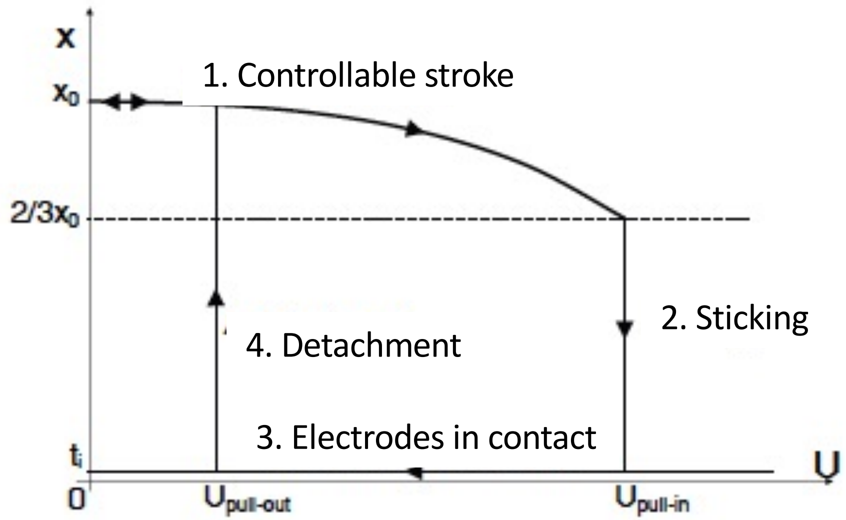
Force plot F_m and F_r at U fixed



Force plot F_m and F_r when U increases

Electrostatic / capacitive actuation

Alternating between pull-in and pull-out (sticking - detachment)



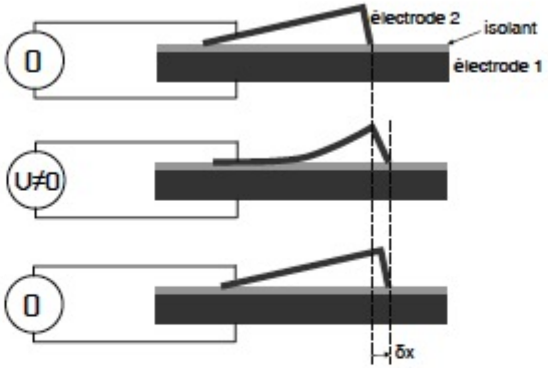
Hysteresis when functionning

$$F_m = \frac{\epsilon A}{2t_i^2} U_{pull-out}^2 = F_r = kx_0$$

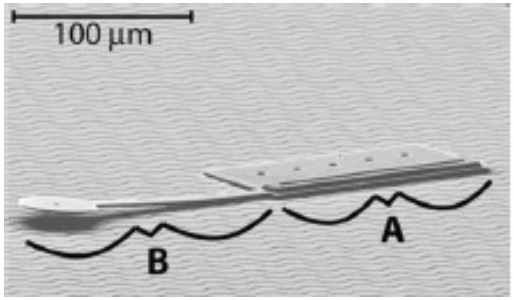
$$U_{pull-out} = \sqrt{\frac{2kx_0 t_i^2}{\epsilon A}} \qquad (< U_{pull-in})$$

Actuation for microrobotics

Use of electrostatic actuator

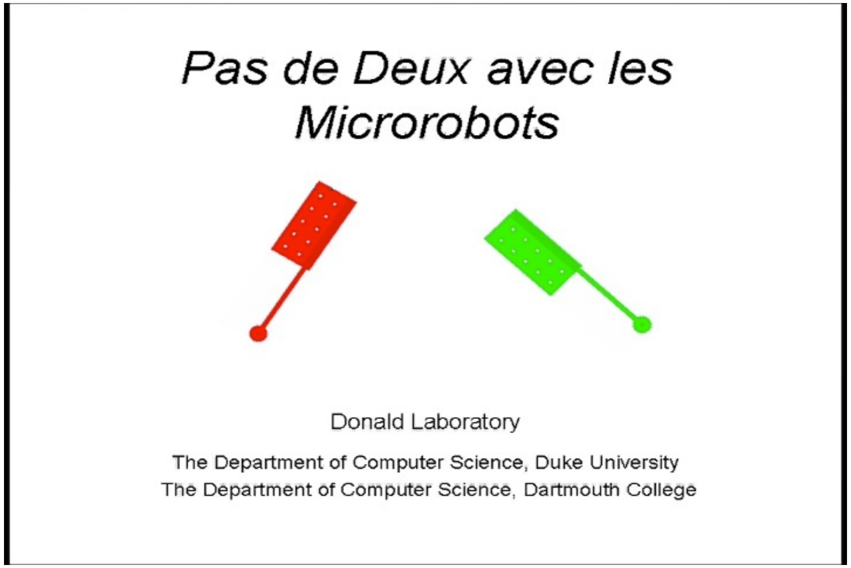


Operating principle of a SDA
(Scratch Drive Actuator)



The steps taken are submicrometric. Typically, for a flexible electrode 60 µm long, 2 µm thick and a foot length of 2 µm, a δx step of about 80 nm is obtained at U = 150 V at 1 kHz.

Video: Duke University SDA microrobot



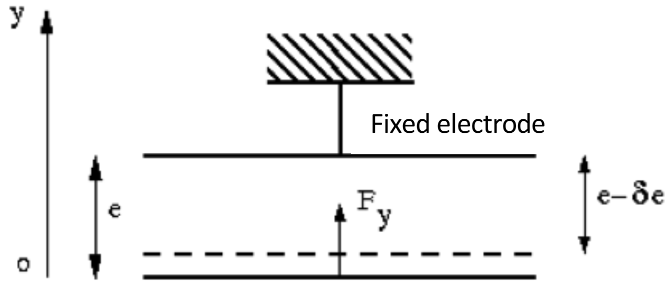
Electrostatic / capacitive actuation

Comb drive

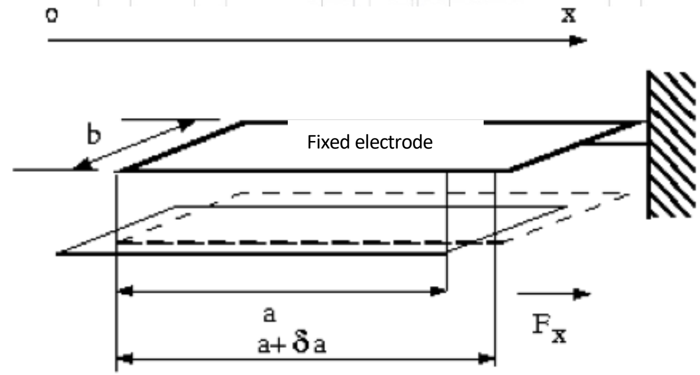
$$\vec{F} = -\vec{\nabla} W_e$$

$$W_e = \frac{1}{2} C U^2$$

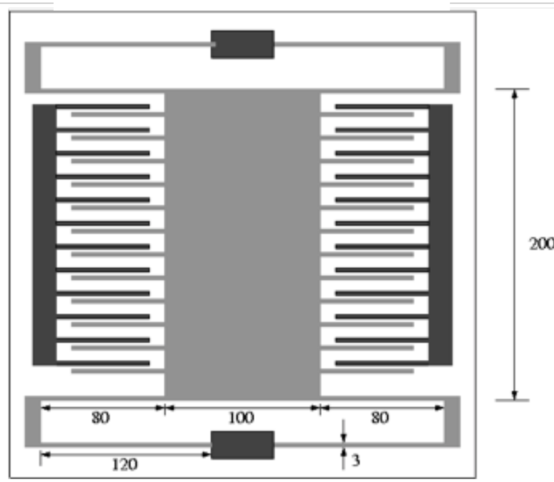
ε *is the dielectric permitivity*

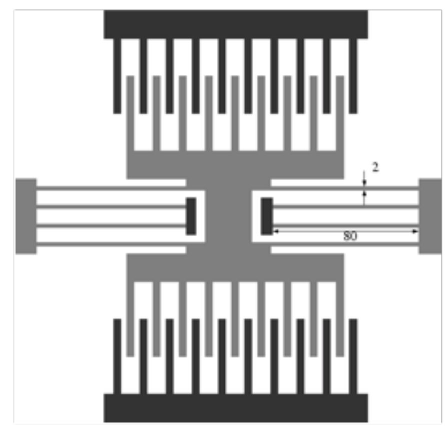


Mobile electrode following y



Mobile electrode following x





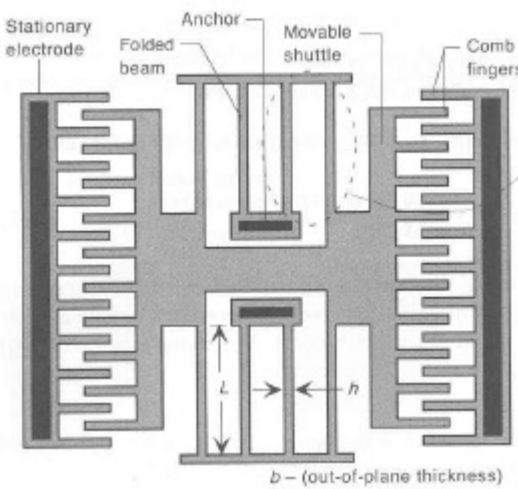
$$C = \varepsilon \frac{A}{y} \qquad F = \frac{\varepsilon A}{2\, y^2} U^2$$

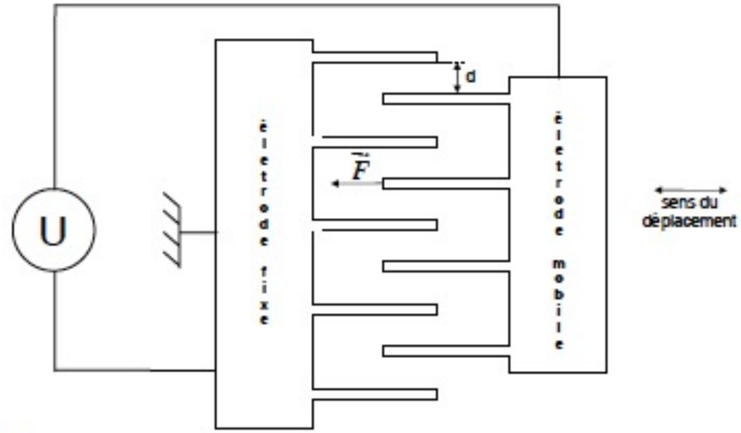
$$C = \frac{\varepsilon\,(a - x)\, b}{y} \qquad F = \frac{\varepsilon\, b}{2\, y^2} U^2$$

The value of F does not depend on x

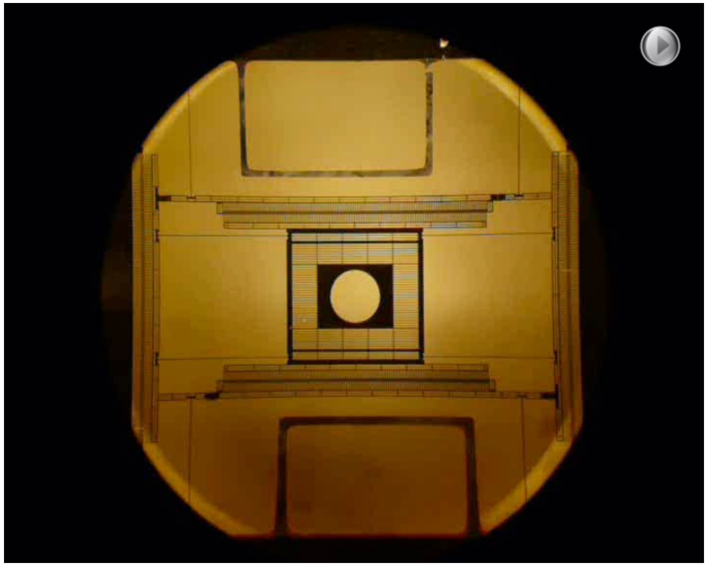
Actuation for microrobotics

Use of electrostatic actuator: comb drive actuation



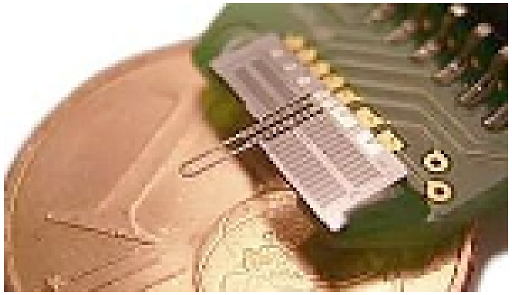


$$F_T = 2NF = N\frac{\epsilon p}{d}U^2$$

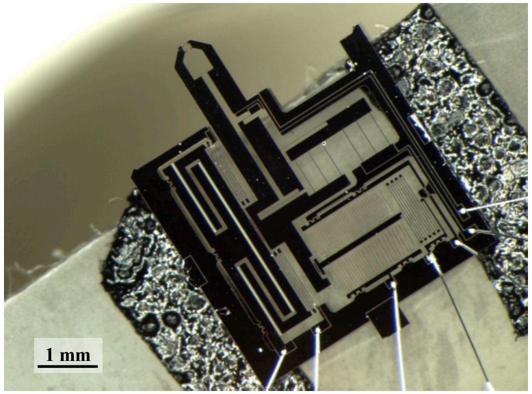


Actuation for microrobotics

Use of electrostatic actuator: comb drive actuation



Micropince de Femto-tools (FT G100)



Nanotweezer du
LIMMS

Microgripper from Femto-tools (FT G100)
Initial gap: 100 µm
Electrostatic actuator
Integrated force sensor
Max. control voltage: 200 V

Issues
Control of gripping force
Unfavourable signal-to-noise ratio
Environmental sensitivity
Goal: filter the noise without penalising the bandwidth of the system, necessary for a firm grip without destroy or damage the micro-objects handled.

Electrothermal Thermal Actuation

and

examples of microrobotics appication

Electrothermal Thermal Actuation

Disadvantages of thermal actuator:

- Its slowness but the scale effect is favourable
- Its efficiency: about 10% due to the convection dissipation of the present thermal energy.

Actuation dynamics:

Considering only convection, the heat equation can be written:

$$mC_v\frac{d\Delta T}{dt}+hS_e\Delta T=P_{in}$$

m : mas of material, C_v thermal mass capacity,
ΔT difference between its temperature and constant ambient temperature
H convection coefficient, P_{in} power injected into the system

P_{in} 1st order control

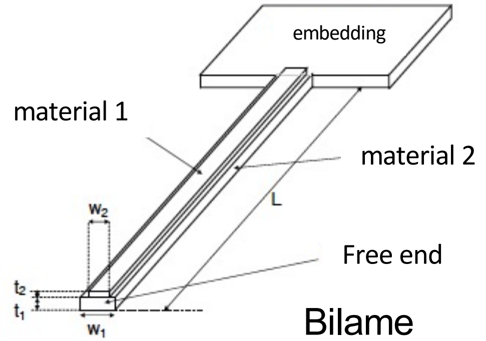
$$\tau=\frac{mC_v}{hS_e}$$

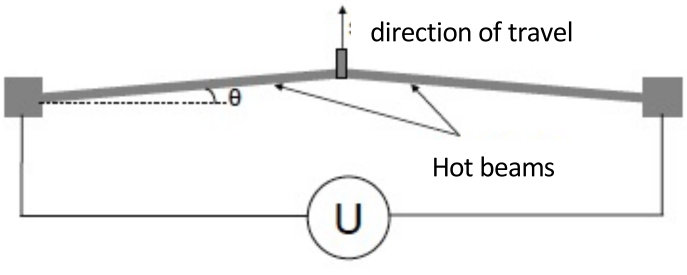
Scaling factor on the time constant

$$\frac{\tau'}{\tau}=\frac{m'C'_v}{h'S'_e}\cdot\frac{hS_e}{mC_v}=\frac{m'}{m}\cdot\frac{C'_v}{C_v}\cdot\frac{S_e}{S'_e}\cdot\frac{h}{h'} \Rightarrow \frac{\tau'}{\tau}=f^2$$

Electrothermal Thermal Actuation

Use of thermal expansion





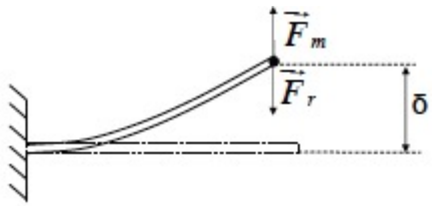
Material	Thermal expansion (10^{-6} K^{-1})	Resistivity (mΩ.cm)	Young modulus (Gpa)
Aluminium	23,5	2,67	70
Nickel	13,3	6,9	199
Copper	17	1,69	129
Chrome	6,5	13,2	279
Gold	14,1	2,2	78
Titanium	8,9	54	120
Silver	19,1	1,63	82,7
Silicon	6,2	23×10^{10}	113

Thermal coefficients of some materials used in microfabrication

Electrothermal Thermal Actuation

Bilame:

– α_1 et α_2 expansion coefficients of bilame materials
- E_1 et E_2 Young modulus of bilame materials
– ΔT temperature difference between bilame and room temperature
- $t=t_1+t_2$ the thickness of the bilame



Curvature for small deformations:

$$k=\frac{6w_1w_2E_1E_2t_1t_2t(\alpha_2-\alpha_1)\Delta T}{(w_1E_1t_1^2)^2+(w_2E_2t_2^2)^2+2w_1w_2E_1E_2t_1t_2(2t_1^2+3t_1t_2+2t_2^2)}$$

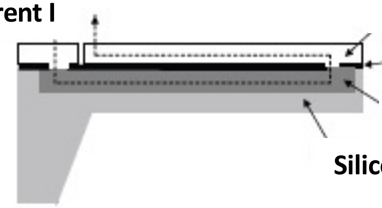
Free deflection of the actuator : $\delta_L=\frac{kL^2}{2}$

Deflection in the case of a resistive force Fr at the end of the bimetal plate : $\delta=\delta_L-\frac{L^3}{3EI}F_r$
(with I quadratic moment and E Young modulus)

Blocking force (δ=0) : $F_B=\frac{3EI}{L^3}\delta_L=\frac{3kEI}{2L}$ with $E=\frac{t_1E_1+t_2E_2}{t}$

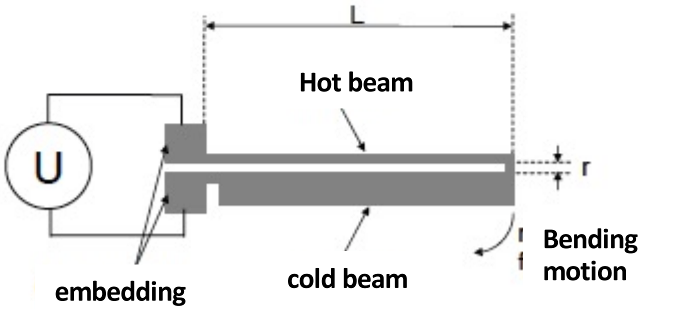
Electrothermal Thermal Actuation

In the majority of cases, an electrothermal actuator is produced by heating the bilame by the direct passage of a current (Joule effect).



Electrothermal Thermal Actuation

Exploitation of the thermal gradient



U-shape actuator

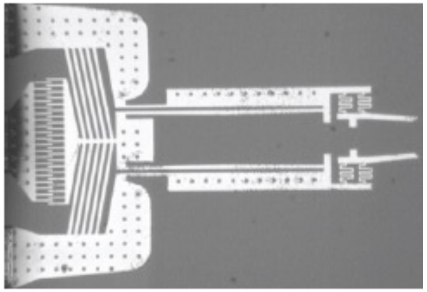
The analytical description is very complex: deformable structure with thermal and mechanical behaviour dependent on their geometry (equations to partial derivatives)

Order of magnitude of free deflection: $\delta_L = d_T \frac{L}{r}$ with d_T direct thermal expansion of the hot beam

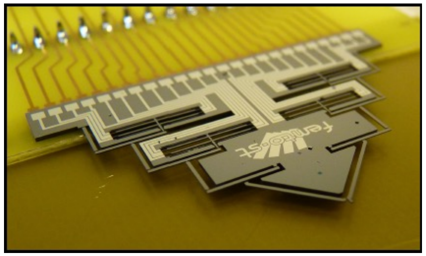
For L=500µm, r=10µm, a hot beam at 100°C → $\delta_L = 6\ \mu\text{m}$ For polysilicon (d_T=2,4 10^{-6} K^{-1})

Actuation for microrobotics

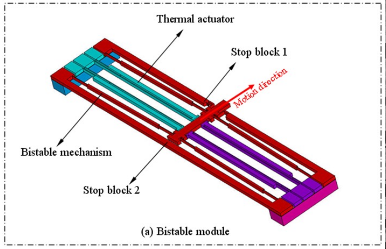
Examples :

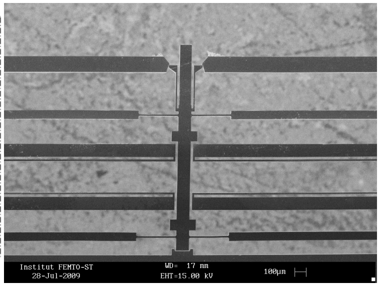


microgripper



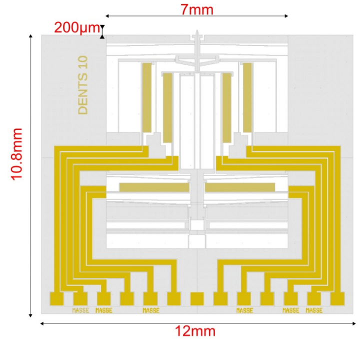
Dimibot – first generation



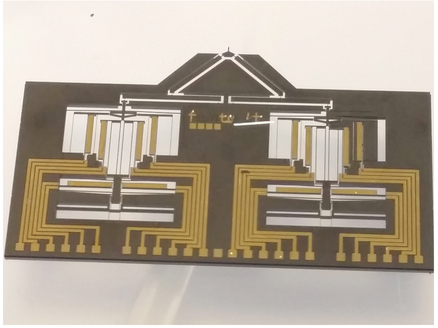


Bistable module of a digital microrobot

Dimibot – second generation



The multistable module



Lay out of the new digital microrobot

Piezoelectric Actuation

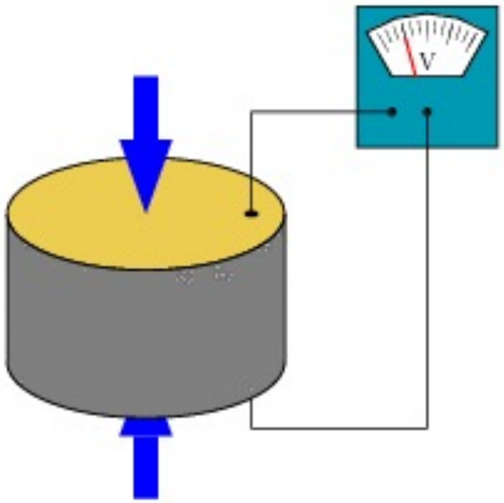
and

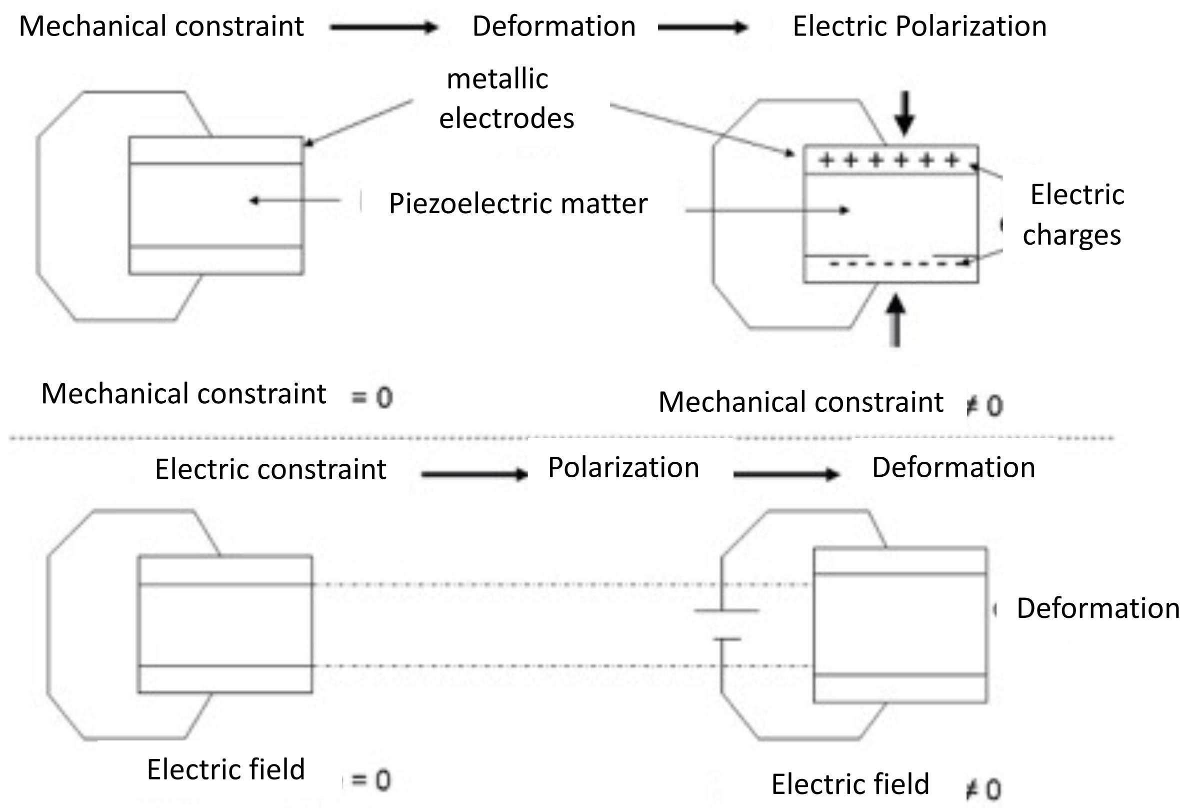
examples of microrobotics appication

Piezoelectric Actuation

Piezoelectric effect (discovered by Pierre and Jacques Curie on crystals in 1880):

- Direct and converse effect:





Piezoelectric Actuation

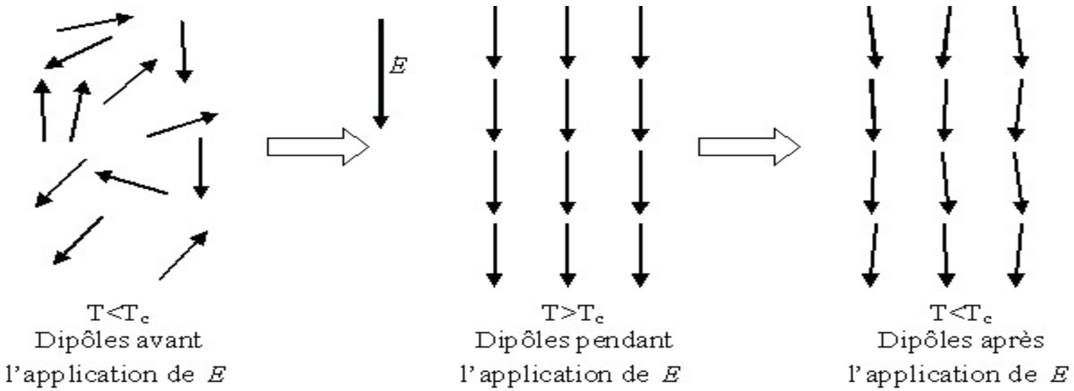
Piezoelectric materials:

- The best known: quartz (SiO_2) is naturally piezoelectric
  ceramic
  certain polymers such as polyvinylidene fluoride (PVF2)
- The family of piezoelectric ceramics forms an important group. They are polycrystalline ferroelectric materials with a tetragonal/rhomboedral structure, close to the cubic structure. These are mixtures of lead oxide, the most common of which is PZT (Plomb, Zirconium and Titanium). These materials, unlike quartz, **must be polarized** to present a piezoelectric effect. It will be much higher. A PZT bar subjected to an electric field will have a deformation several hundred times greater than that of a quartz bar of the same size and subject to the same field.

Example of sensors and actuators:

printhead for inkjet printers, tension control in the textile industry, blood pressure measurement, valve actuators, hardness and strain gauges, motorization for small movements and precise positioning.

Polarization process of piezoelectric ceramics:



T_c: Curie temperature

Piezoelectric Actuation

Mechanical deformation of a piezoelectric material:

E: electric field applied

T: stress resulting from external forces

$$S = d \,.\, E + s \,.\, T$$

d: piezo coefficient of deformation

s: elastic compliance (inverse of Young's modulus)

Electric displacement (from dielectric properties):

E: electric field applied

T: pressure (external forces)

$$D = \varepsilon \,.\, E + d \,.\, T$$

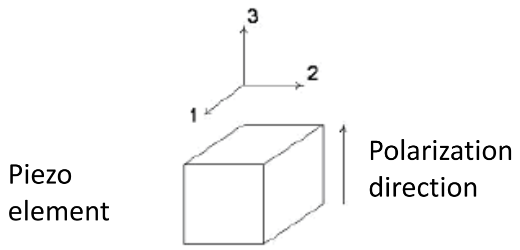
ε: dielectric permitivity

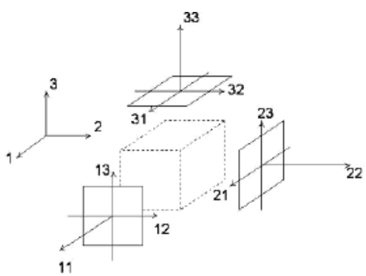
d: Electric field strength (V/m) is the intensity of an electric field exerting a force of 1 Newton on a body charged with a quantity of electricity of 1 Coulomb.

$$\Rightarrow \quad \begin{pmatrix} S \\ D \end{pmatrix} = \begin{pmatrix} s & d \\ d & \epsilon \end{pmatrix} = \begin{pmatrix} T \\ E \end{pmatrix}$$

d is therefore what defines the piezoelectric character of a material, and in particular the *strength* of the electromechanical coupling within it: the larger this is, the stronger the coupling.

Piezoelectric Actuation





$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\ s_{21} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\ s_{31} & s_{32} & s_{33} & s_{34} & s_{35} & s_{36} \\ s_{41} & s_{42} & s_{43} & s_{44} & s_{45} & s_{46} \\ s_{51} & s_{52} & s_{53} & s_{54} & s_{55} & s_{56} \\ s_{61} & s_{62} & s_{63} & s_{64} & s_{65} & s_{66} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{pmatrix} + \begin{pmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ d_{41} & d_{42} & d_{43} \\ d_{51} & d_{52} & d_{53} \\ d_{61} & d_{62} & d_{63} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix}$$

$$\begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{pmatrix} + \begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix}$$

- **Short circuit case:** $S = s\,T$ and $D = d\,T$

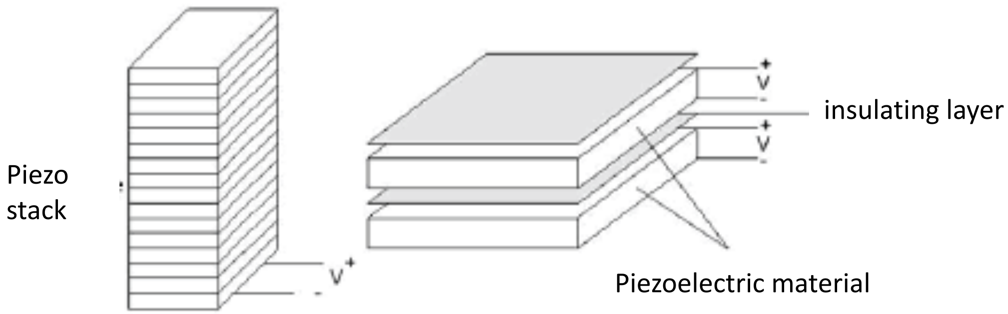
- **Open circuit case:** $0 = d\,T + \varepsilon\,E$, then $E = -\varepsilon^{-1} d T$,
  $S = s\,T + d^T E$, then $S = (s - d^T \varepsilon^{-1} d) T$

$$\mathbf{S} = \mathbf{s^E} \cdot \mathbf{T} + \mathbf{d^T} \cdot \mathbf{E}$$
$$\mathbf{D} = \mathbf{d} \cdot \mathbf{T} + \boldsymbol{\varepsilon}^{\mathbf{T}} \cdot \mathbf{E}$$

With $s^E = s$ and $s^D = s - d^T \varepsilon^{-1} d$

Piezoelectric Actuation

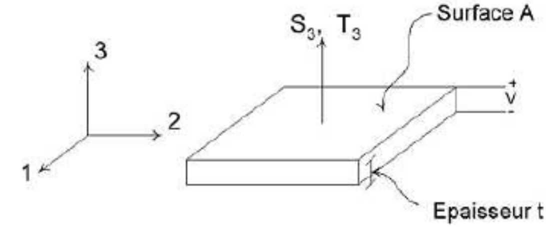
Piezoelectrique stack



Assumptions:

- All deformations other than S_3 can be ignored
- All stresses except T_3 can be ignored
- The electric field is only in direction 3
- The only non-zero charge density is D_3

for one layer



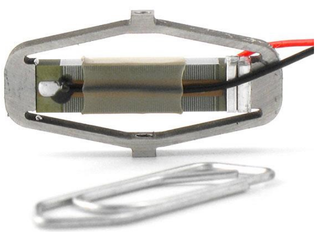
$$S_3 = s_{33}^{E} T_3 + d_{33} E_3$$

$$D_3 = d_{33} T_3 + \epsilon_{33}^{T} E_3$$

Total displacement of the actuator (sum of the displacement of each of the n layers in series)

$$X = \frac{s_{33}^{E} L}{A} F + \frac{d_{33} L}{t} V$$

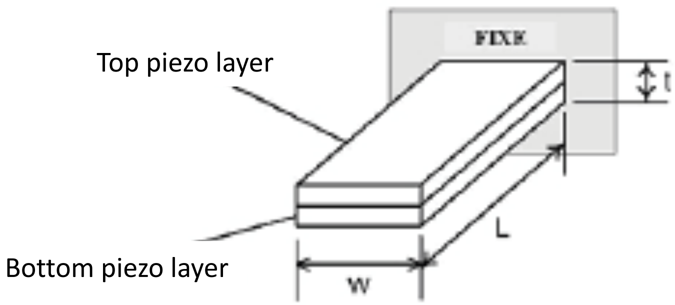
Based on this equation, plot the static linear characteristic of a piezoelectric stack actuator for 3 tension $V_1 < V_2 < V_3$



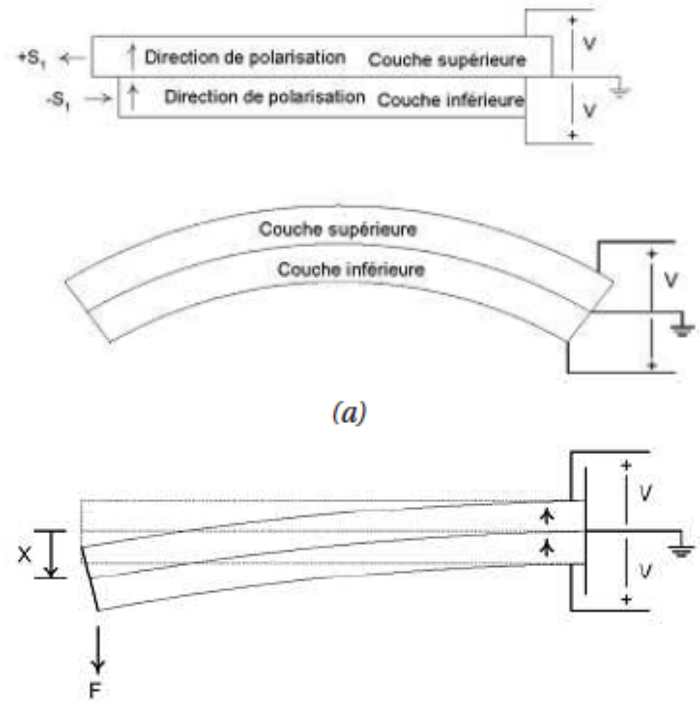
Piezo actuator APA 60S from Cedrat Technologies

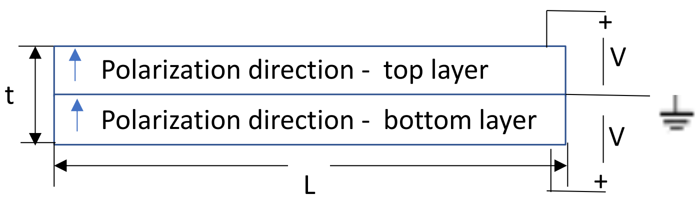
Piezoelectric Actuation

Bimorph (bender actuator)



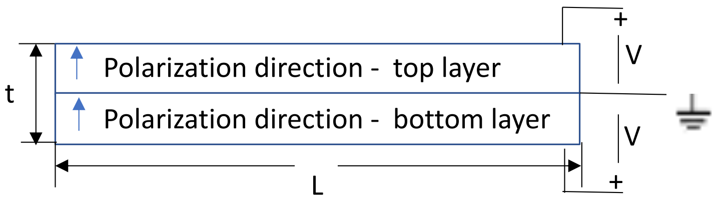
Operating principle



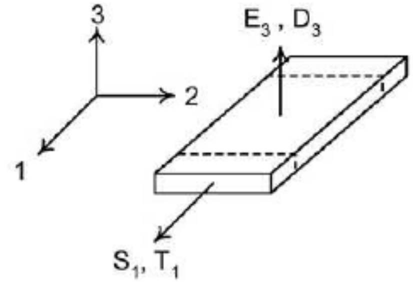


Piezoelectric Actuation

Bimorph (bender actuator)



Assumptions:
- All deformations except S_1 can be ignored
- All stresses except T_1 can be ignored
- The electric field is only in direction 3
- The only non-zero charge density is D_3



$$S_1 = s_{11}^E T_1 + d_{13} E_3$$

$$D_3 = d_{31} T_1 + \epsilon_{33}^T E_3$$

Total flexion generated by the bimorph:

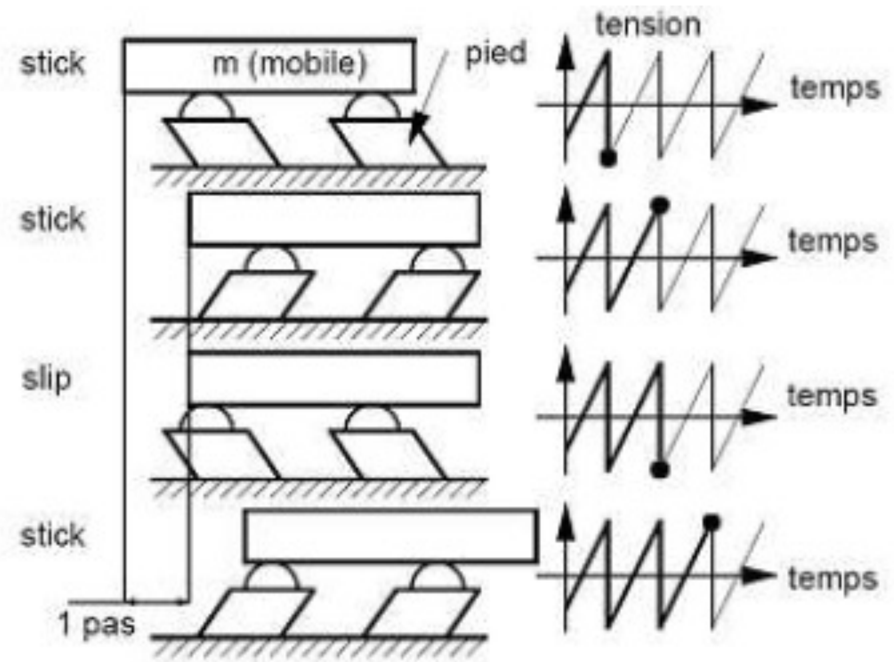
$$\delta = 4\frac{s_{11}^E L^3}{wt^3}F + 3\frac{d_{13}L^2}{t^2}V$$

Based on this equation, calculate the free travel δ_L and the blocking force F_B

Piezoelectric Actuation

Use of piezo actuators: stick slip actuators

2 modes : stepping mode and scanning mode

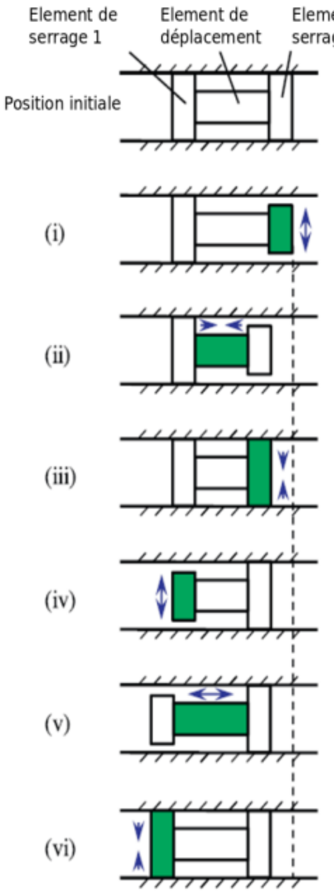


Operating principle in stepping mode

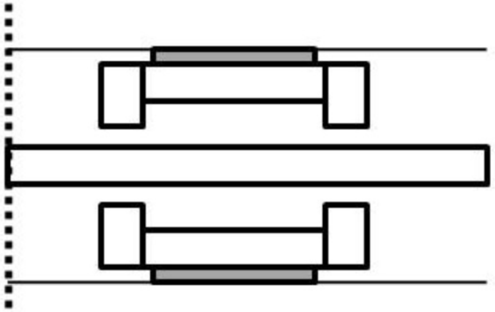
Characteristics of stick-slip actuators:
- a resolution of a few nanometers (<5nm) for travels of the order of a centimeter at velocities of several millimeters per second (2-5mm/s)
- a high rigidity (6.5 N/μm) guaranteeing an excellent tolerance of strong perturbations
- a great simplicity achieved through the combination of guiding and driving functions

Piezoelectric Actuation

Use of piezo actuators: Inch worm motors



We can also use the same principle to push a part



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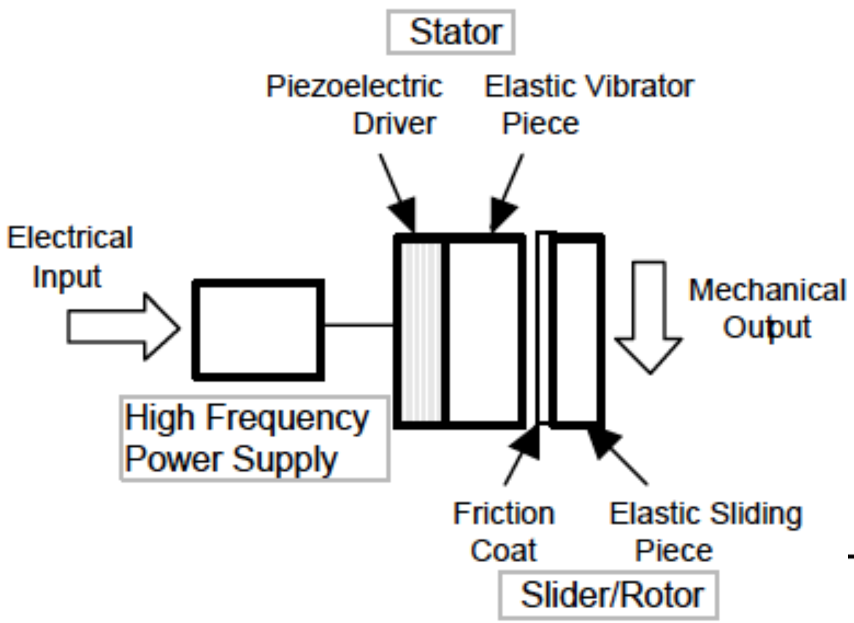
Piezoelectric Actuation

Use of piezo actuators: ultrasonic motors



Fundamental construction of an ultrasonic motor

Merits

1. Low speed and high torque -- Direct drive
2. Quick response, wide velocity range, hard brake and no backlash -- Excellent controllability -- Fine position resolution
3. High power / weight ratio and high efficiency
4. Quiet drive
5. Compact size and light weight
6. Simple structure and easy production process
7. Negligible effect from external magnetic or radioactive fields, and also no generation of these fields

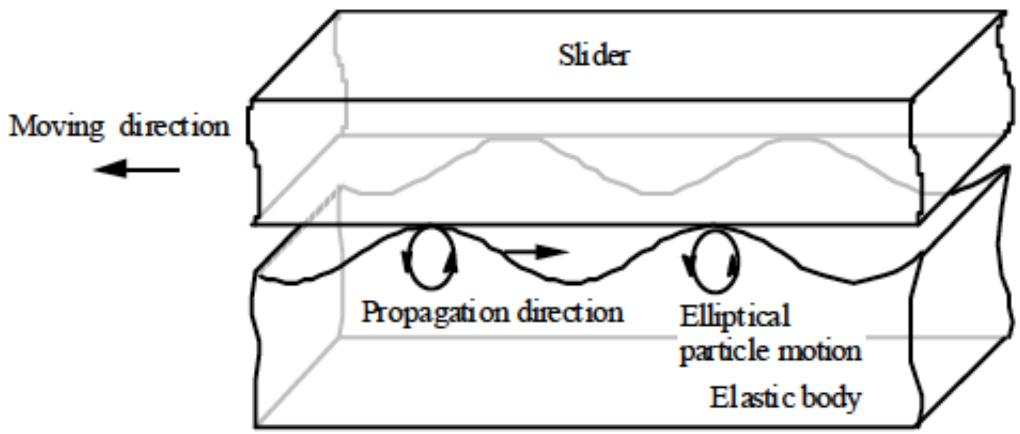
Demerits

8. Necessity for a high frequency power supply
9. Less durability due to frictional drive
10. Drooping torque vs. speed characteristics

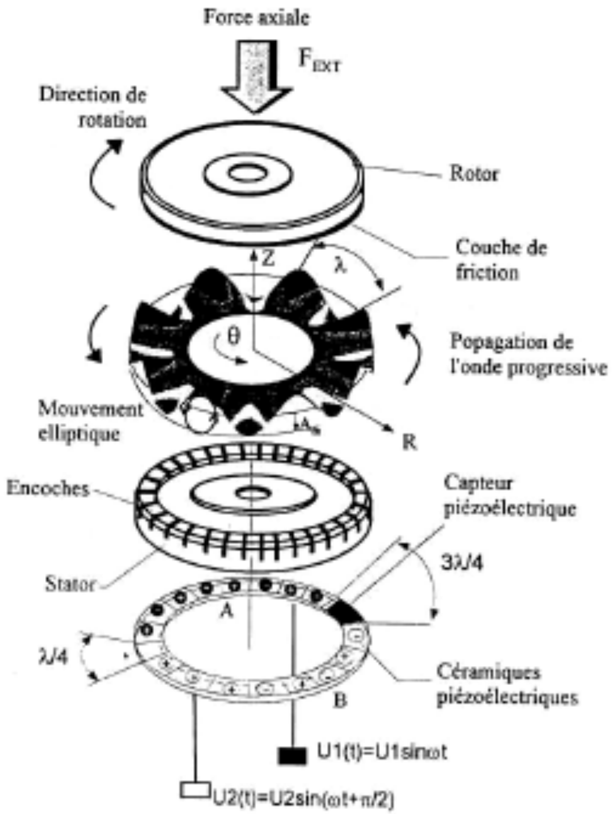
(from K. Uchino, Penn State university)

Piezoelectric Actuation

Use of piezo actuators: ultrasonic motors



Example of the propagating wave type motor



1 - Introduction – scale effect

2 - Scale effect on robotics and control

3 – Actuation for microrobotics

- Overview of actuation
- Electrostatic / capacitive actuation
- Electrothermal Thermal Actuation
- Piezoelectric Actuation

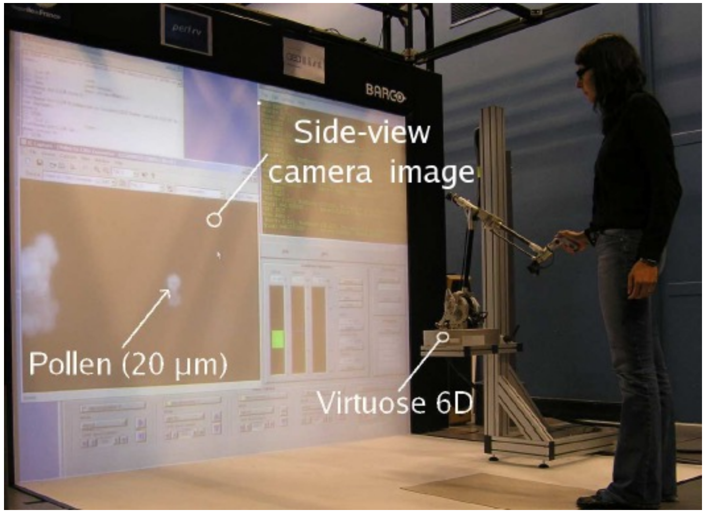
4 – Sensing

5 - Microrobot architecture : 2D – 3D

Sensing objectives

Goal: to obtain a representation of the micromonde

Depending on needs, perception can be:
- simple (some data about the working scene)
- complex (3D representation, virtual reality, augmented reality...)



We need sensing:
- Because of the uncertainties
- To detect micro-objects ad their state
- To determine position and orientation of the objects
- To verify quality of links
- To control a task realization
- To determine the shape of micro-nano objects
- To close the loop for control
- …

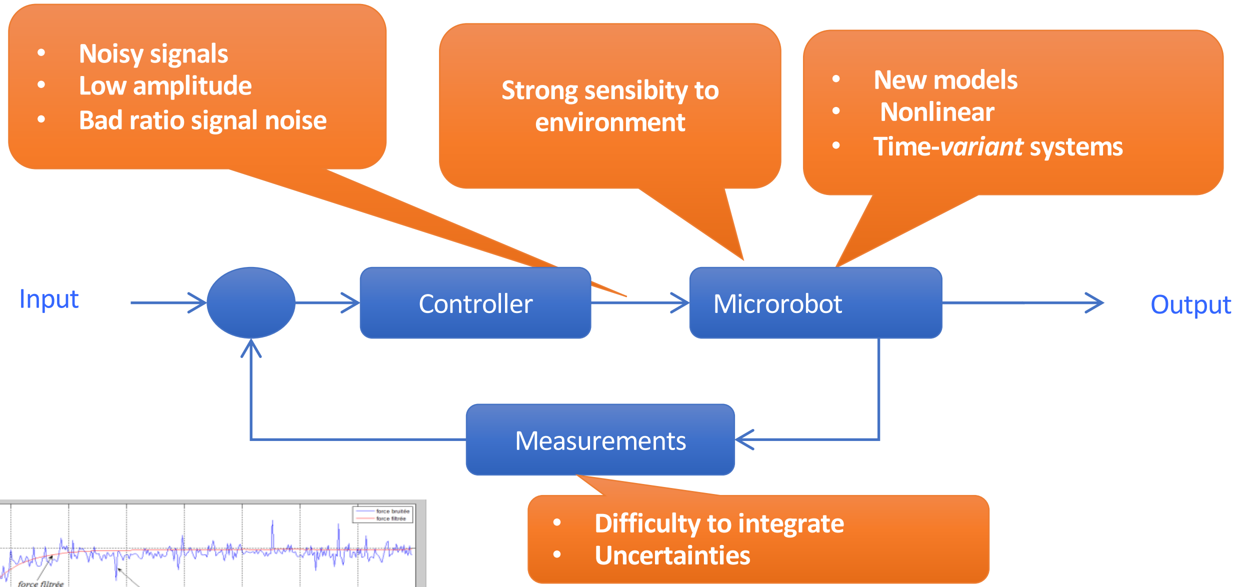
What we want to measure?

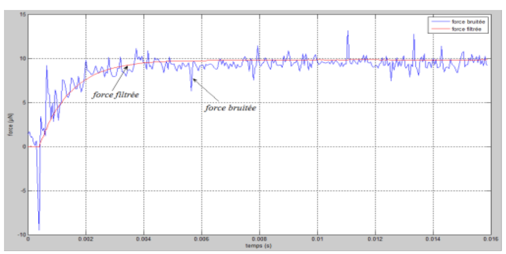
- The position and orientation of micro-objects
- The size of micro-objects
- External appearance of micro-objects
- The position of the end organs of the micromanipulators
- Forces exerted on micro-objects
- Trajectories, speeds, accelerations
- The quality of a bond (example: quality of a bond...)
- In some cases, it is useful to measure the quantities characterizing the working environment because these quantities strongly influence work in the micromonde.
- Temperature,
- Pressure,
- Humidity content,
- Mechanical vibrations produced by surrounding devices.

What are the problems to measure?

- The influence of the environment is great (Temperature, Pressure, humidity, vibrations,...)
- the signal-to-noise ratio is unfavourable
- Every physical measurement is tainted by a noise called "measurement noise".
- This noise has various origins (conditioning and amplification circuits, principle of "translation" of the physical quantity into an electrical quantity...)
- the amplitudes (position and force) are very small:
- displacement of a few micrometers with a resolution of a few nm
- some nN to some mN
- accessibility is very poor
- Need to be as close as possible to fingertips

What are the problems to measure?

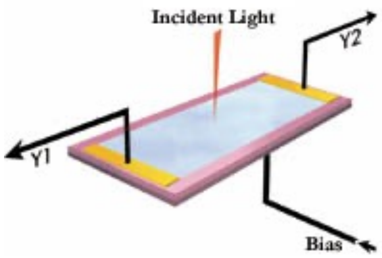




Position measurement

Problems:
- The aim is to measure very small displacements in the order of a few µm with a resolution of a few nm (example: moving the fingers of a microgripper or a micro-object...)
- The S/N ratio is very unfavourable.
- The working space is often difficult to access due to its small dimensions.

Solutions:
- Infrared reflection sensors
- Optical triangulation
- Capacitive measurement
- Linear Variable Differential Transformer (LVDT) sensors

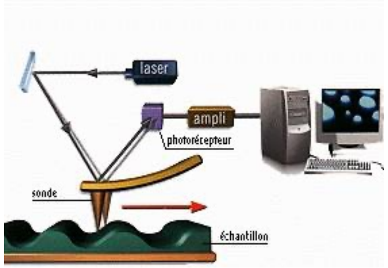


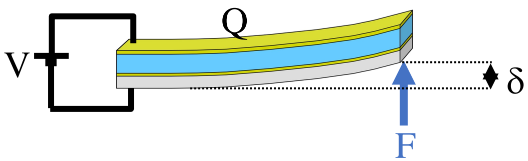
Force measurement

Problems:
- The intensity of the forces at play in the micromonde is very low (from a few nN to a few mN)
- Knowledge of the forces of interaction between the terminal organs and the micro-objects handled is essential to avoid damaging or destroying the micro-objects handled.
- Useful to ensure the quality of a connection between two parts (example: bonding)

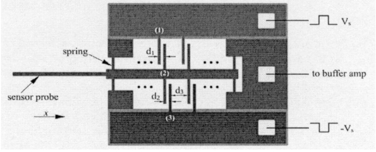
Solutions:
- Measurement by strain gages
- Reflection measurement on a deformable beam
- Measurement by deformation of a complicated structure
- Measurement by relative displacement of elements : capacitive measurement
- Estimation (observation) of interaction forces

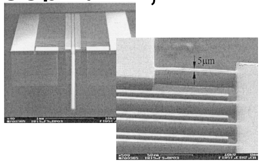
…

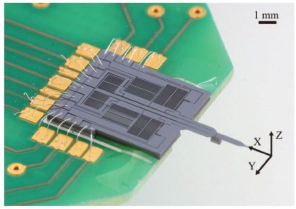




[Sun05] r: +/-1mN, s: 1,35µN/mV,







Comparison between force sensing techniques

Force sensing technique	Advantages	Disadvantages
Thermal sensing	• Small size • Simple structure • Low fabrication cost	• Slow response and dynamic behavior
Electrostatic Sensing	• Rapid response • High sensitivity achievable	• Big size for comb to provide sufficient capacitance • Complex fabrication process
Piezoelectric Sensing	• Good dynamic behavior • High resolution • Good linearity	• Relative poor DC response due to electric leakage across the material • Complex material growth and process flow • Piezoelectric material cannot sustain high temperature operations
Piezoelectric self-sensing	• Low cost • No integration needed • Same structure is used as actuator and sensor	• Long term charge leakage • Temperature influence • Need of nonlinear compensation of the hysteresis and the creep of the material • Need of a supplementary relatively complex electronic circuit
Piezoresistive Sensing	• Small size • High sensitivity achievable • High resonant frequency • Very good resolution can be reached • Flexibility (gauges can be integrated on many different structures) • Simple fabrication process	• Requires doping of silicon to achieve high performance piezoresistors • Only allowing front-facing surfaces • Sensitive to environmental temperature changes

Research orientation for sensing

What to measure: position (in the working area and in the gripper) and force (grip and contact)

Criteria: resolution, sensitivity, number of ddl, size of the sensitive area (so that it is as close as possible to the information to be captured) and integration in microrobotic systems

Range	… nN to a few hundred mN
Sensitivity / resolution	… sensitivity and resolution (<µN to mN) very variable depending on the technology
Number of dof	Ex: 1 to 2 dof on capacitive sensor, 3 to 6 dof on piezoresistive membrane
Size (sensitive area)	… a few tens μm^2 to a few mm^2
Integration	a multi dof on gripper is rare
Vision	mosaicing, sight reconstruction, fast vision, integration (in biorobotic)

- Choice of guided technologies according to the perception objective (compromise!)
- Lack of sensors with suitable range, accuracy, bandwith, number of DOF and size
- Development of microtechnologies for better integration (integration of capture-on-chip means)
- Use of self sensing

1 - Introduction – scale effect

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3 - Actuation for microrobotics

Overview of the actuation

Electrostatic / capacitive actuation

Electrothermal Thermal Actuation

Piezoelectric Actuation

4 - Sensing

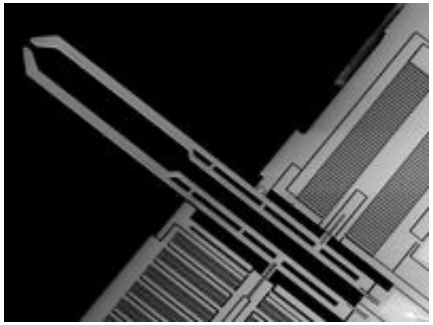
5 - Microrobot architecture : 2D – 3D

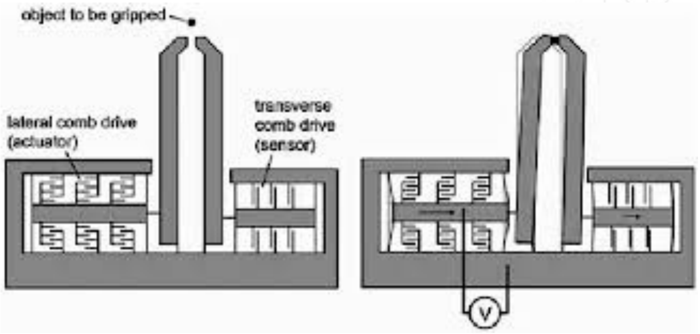
Microrobot architecture: MEMS based approach

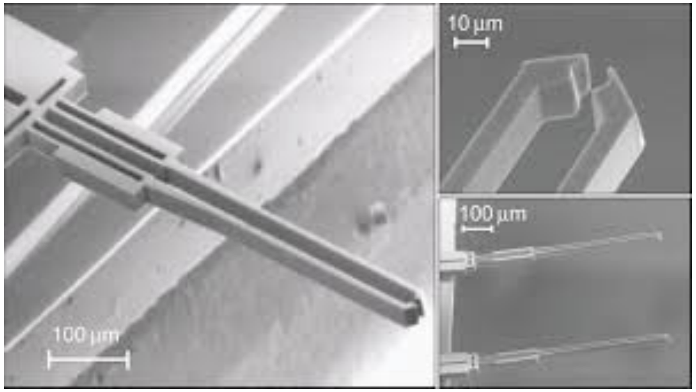
2D architecture:

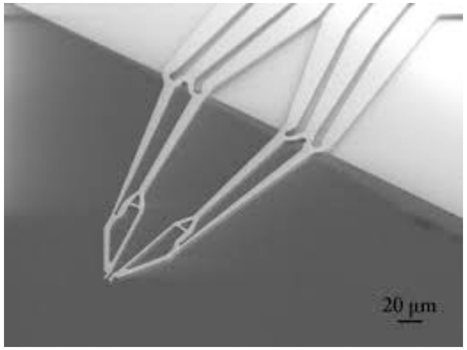
- **Microgrippers**
- **Digital microrobots**
- **XY tables**

femtotools

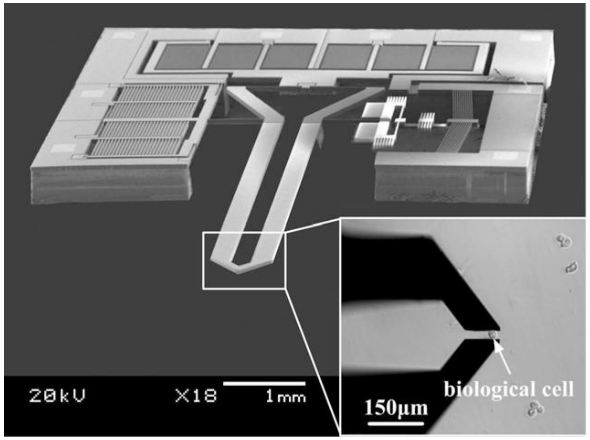








DTU



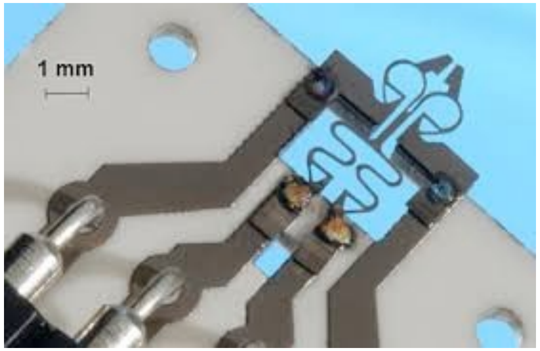
Univ Toronto

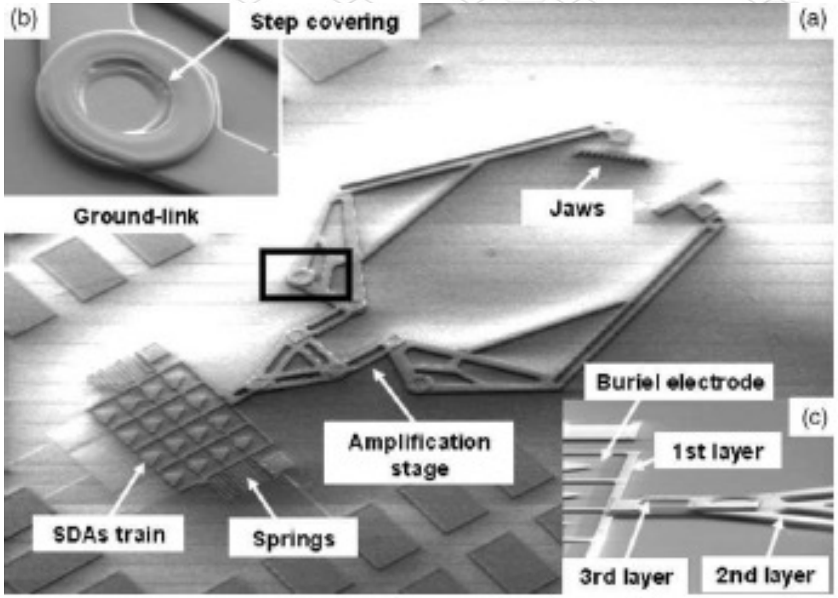
Microrobot architecture: MEMS based approach

2D architecture:

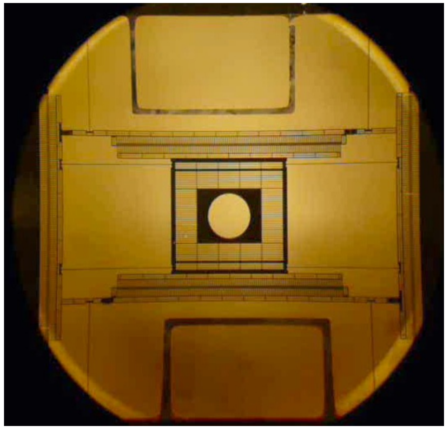
- **Micrograppers**
- **Digital microrobots**
- **XY tables**

KIT - IMT



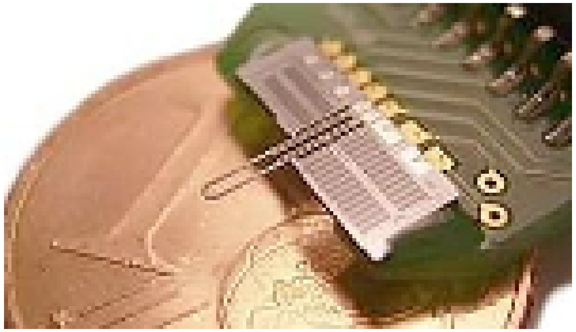


SDA-driven micro-gripper [MIL 04]



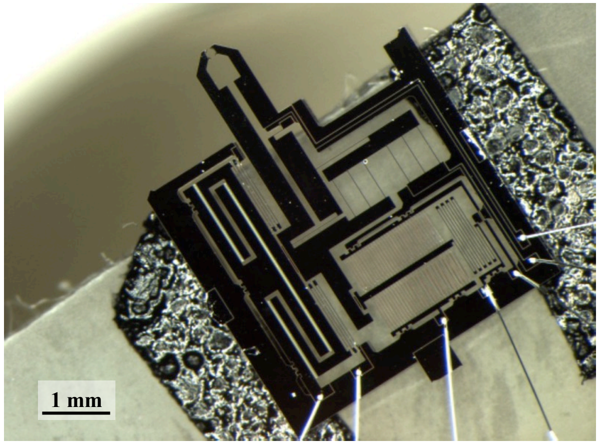
FEMTO-ST (movie)

Microrobot architecture: MEMS based approach



Micropince de Femto-tools (FT G100)

Microgripper from Femto-tools (FT G100)
Initial gap: 100 µm
Electrostatic actuator
Integrated force sensor
Max. control voltage: 200 V

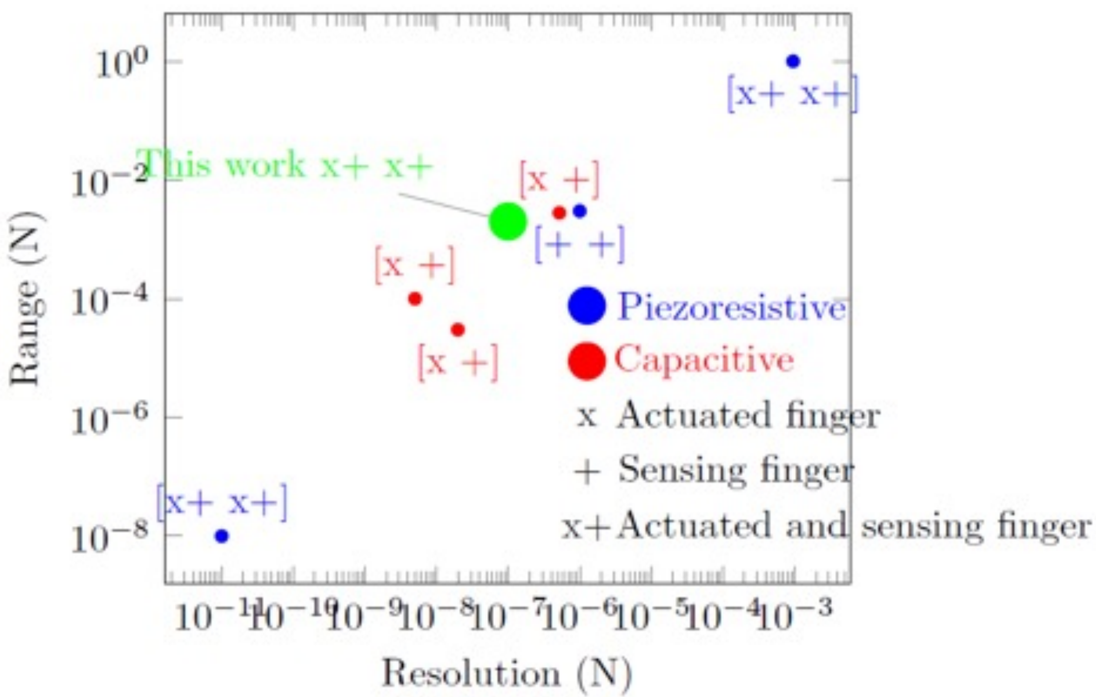


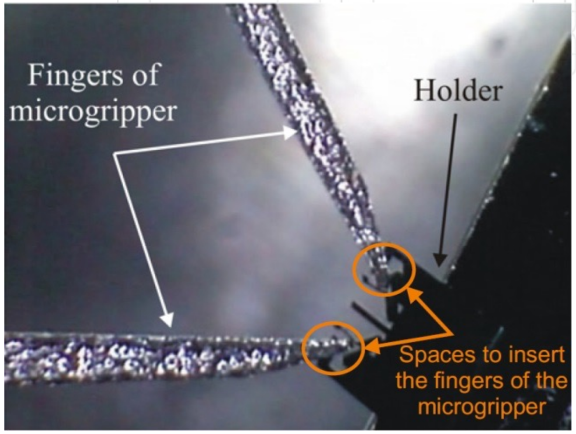
Nanotweezer du LIMMS

Issues
Control of gripping force
Unfavourable signal-to-noise ratio
Environmental sensitivity
Goal: filter the noise without penalising the bandwidth of the system, necessary for a firm grip without destroy or damage the micro-objects handled.

Microrobot architecture: MEMS based approach

Microgripper with instrumented finger





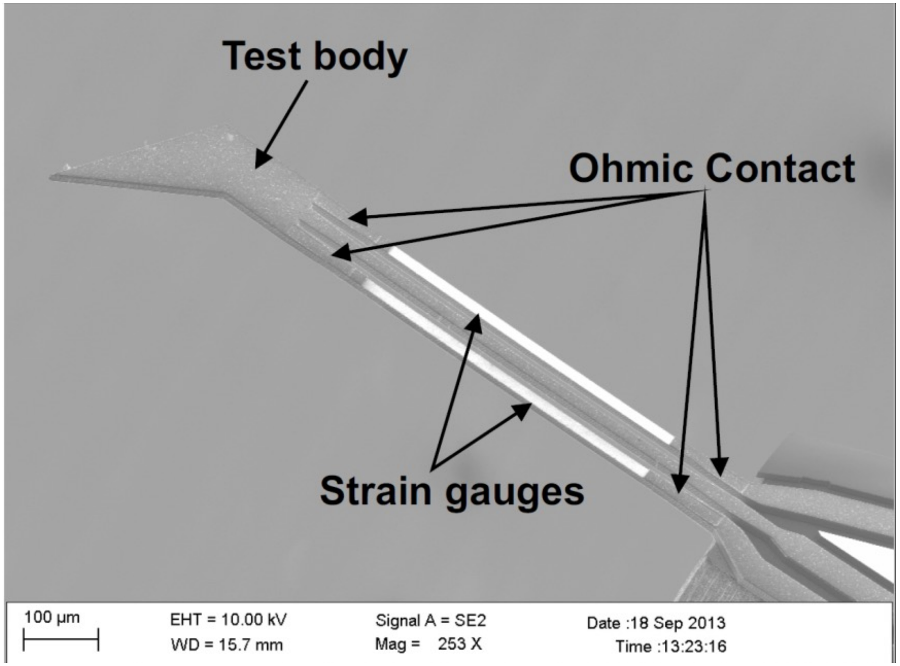
Sensor specifications

- Size: smaller than 1000µm x 100µm x 20µm
- Resolution: hundreds of nN
- Sensing range: several mN
- Bandwidth: large bandwidth bigger than the actuator's
- Simple microfabrication process

Microrobot architecture: MEMS based approach

Microgripper with instrumented finger: sensor fabrication results

SEM image of force sensor



Fabrication errors

Parameter	Design	Error (%)
Length (µm)	700	0,4
Width (µm)	20	0,25
Thickness (µm)	12	2

Performance errors

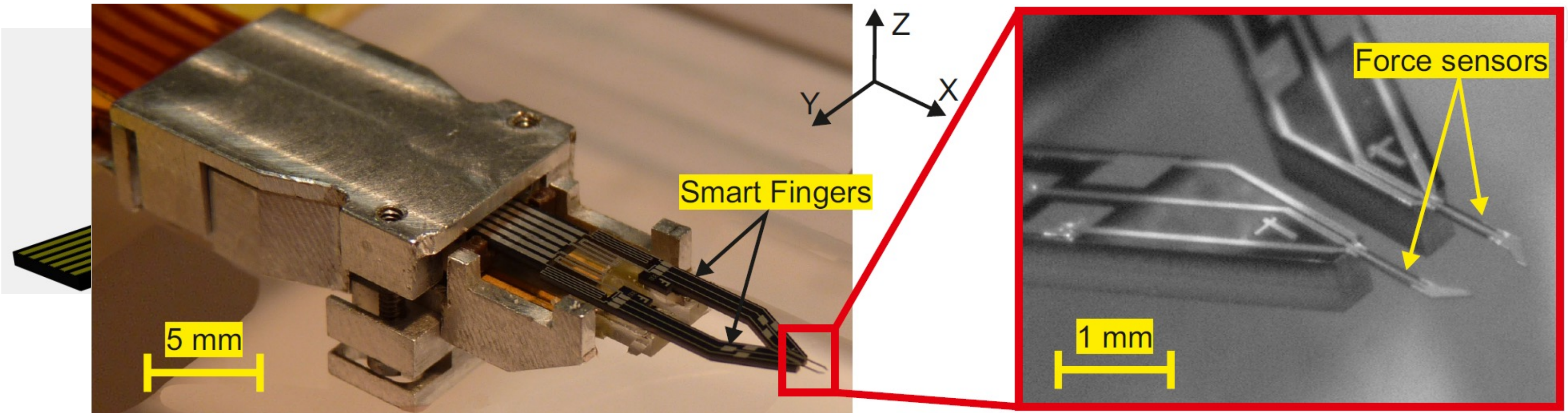
Parameter	Design	Error (%)
Stiffness (N/m)	125	4
Gauge Resistance (kΩ)	3	5

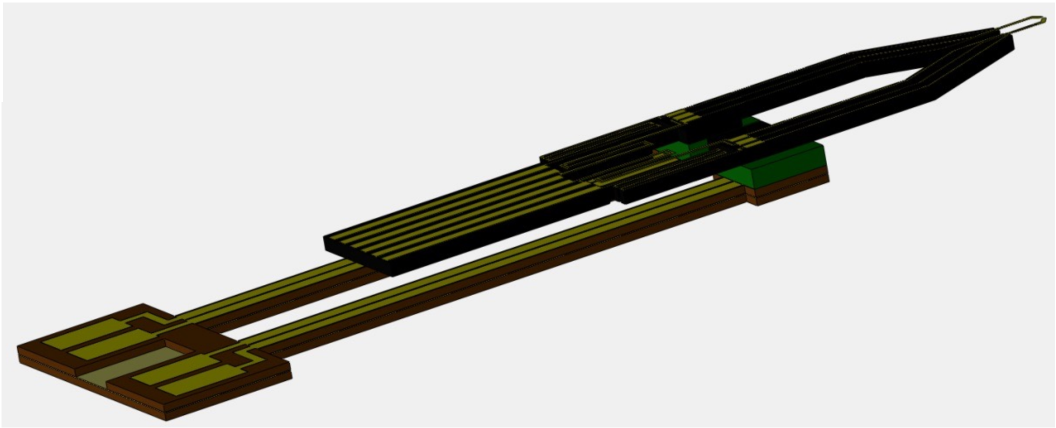
Conclusions on the force sensor performances:

- Small fabrication errors -> small performances errors
- Simple and mastered fabrication process

Microrobot architecture: MEMS based approach

Microgripper with instrumented finger: two smart finger integration





TSFM actuation performances
- Displacement resolution: nm range
- Displacement range: 100 µm
- Dynamics of the actuator: 1 kHz

TSFM sensing performances
- Sensor resolution: 100 nN
- Sensor range: 2 mN
- Dynamics of the sensor: 8.52 kHz
- SNR: 50 dB

Microrobot architecture: MEMS based approach

Finger grasping

Size of objects handled — … from 100 μm à 100 nm

Integration of means of perception — ... position and force, on-board sensors, microfabricated sensors, control of active materials

Integration of control means — ... "Embeddable" control laws

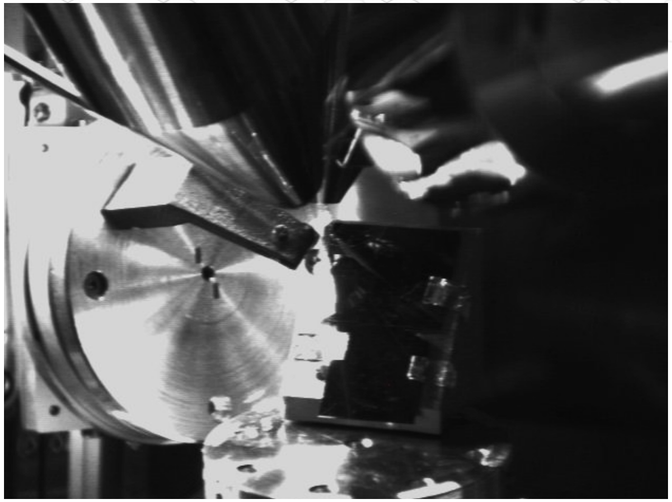
Reliability of release — ... repeatable release, functionality

Gripping environments — ... air, vacuum, liquid

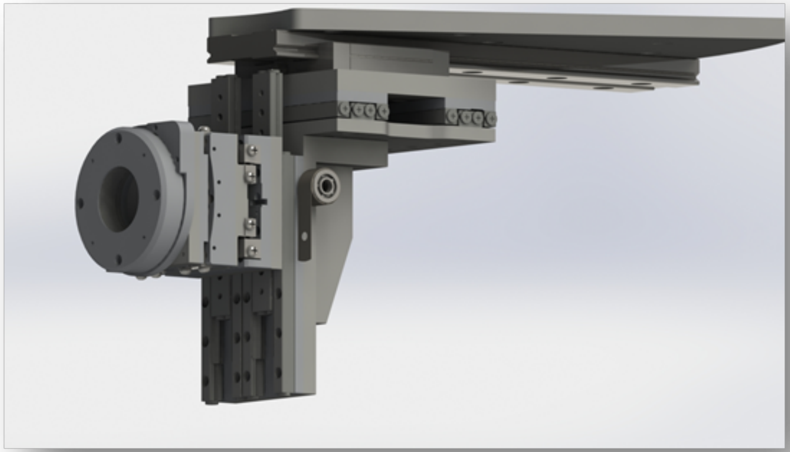
→

- interaction modelling
- interaction control
- purchase
- environmental friendly take/release strategy

Microrobot architecture: 3D architecture



First approach: based on miniaturisation

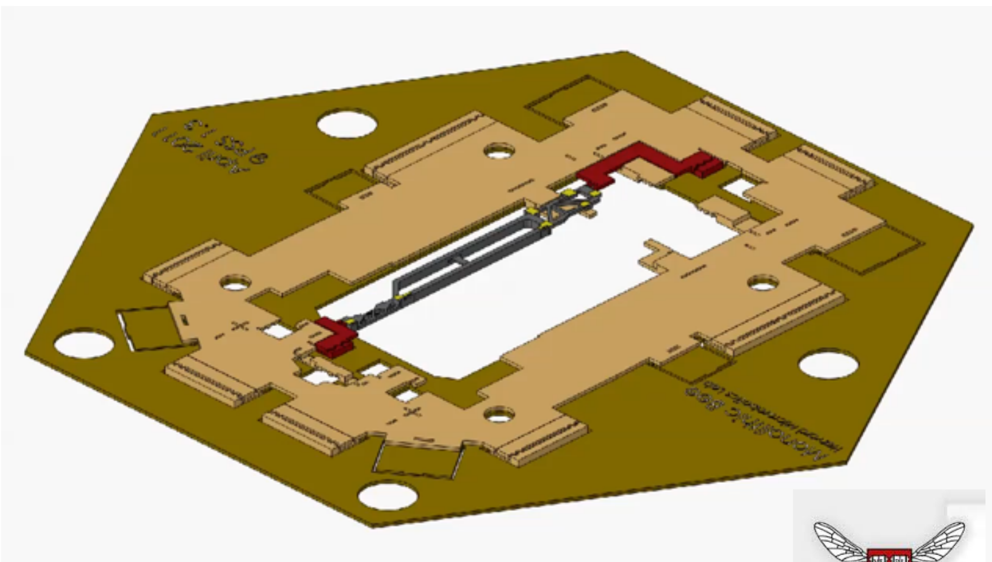


Microrobot architecture: 3D architecture

- fabrication vs microfabrication

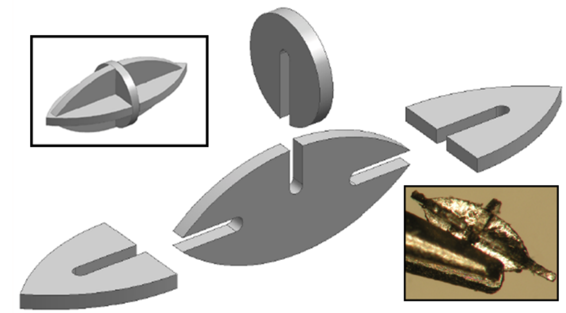
microfabrication inspired from microelectronics : 2D objects

→ Require to propose new design including the fabrication constraints



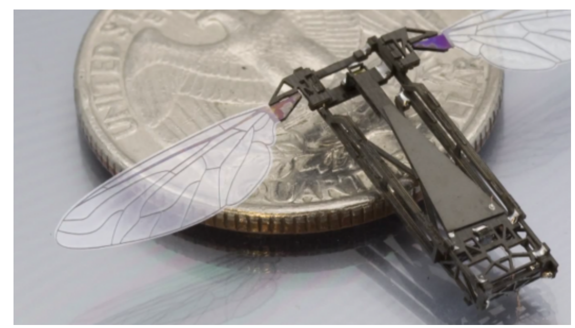
Origami principle

HARVARD MICROROBOTICS LABORATORY



IRIS Institute of Robotics and Intelligent Systems

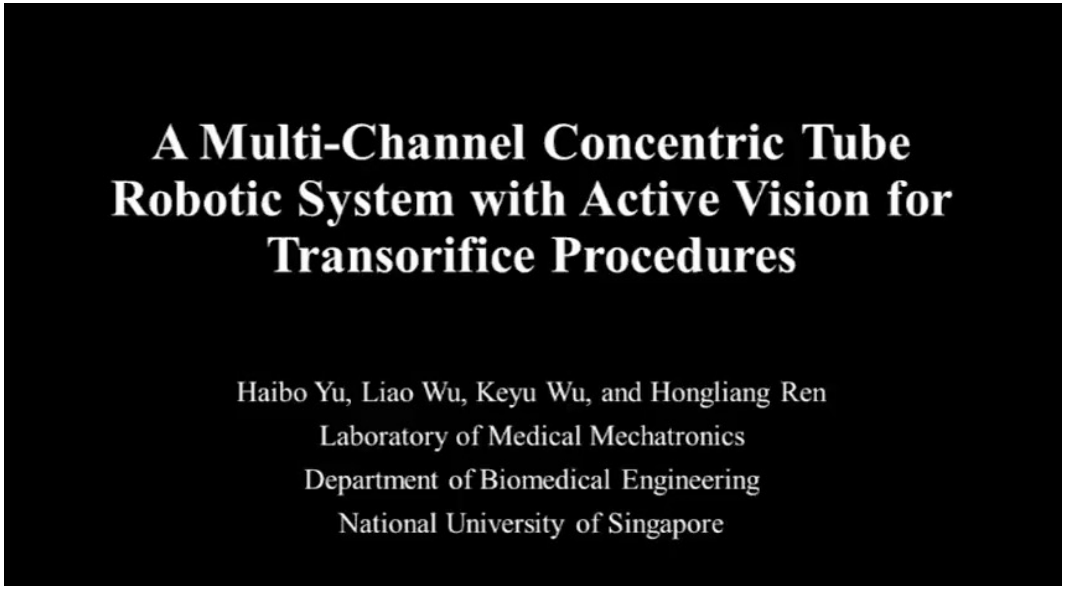
3D microassembly

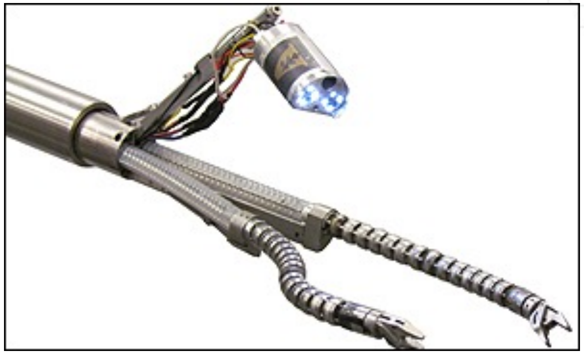


https://youtu.be/f0CluQiwLRg

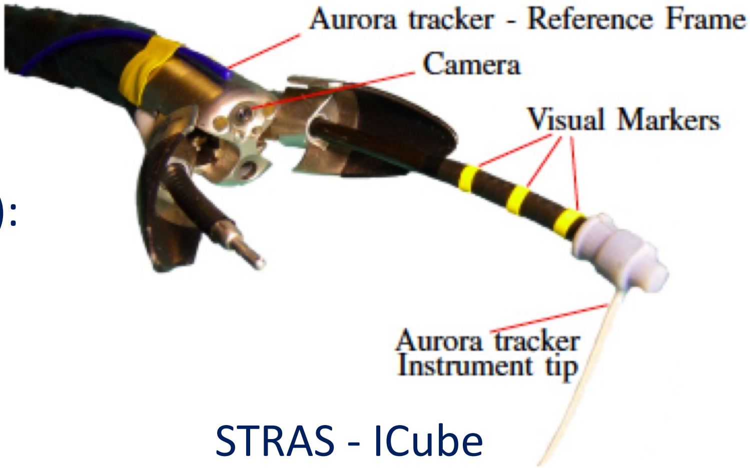
Microrobot architecture: 3D architecture

Continuous robots: towards a dexterous manipulation based on collaborative continuous robots





IREP- Vanderbilt



STRAS - ICube

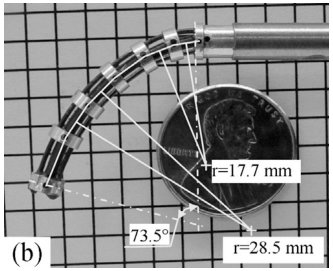
Collaborations of continuous robots (medical domain):
- Laser surgery of the vocal cords
- Middle ear surgery
- Submucosal endoscopic surgery
- Etc.

Microrobot architecture: 3D architecture

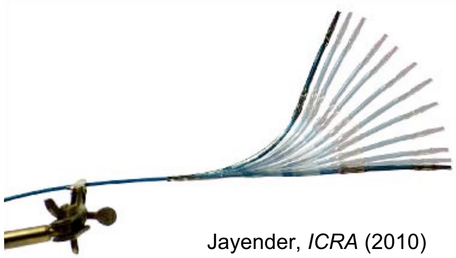
- Flexible body and connections
- Continuous Structures

Camarillo, *IEEE Tracs. on Rob.* (2008)

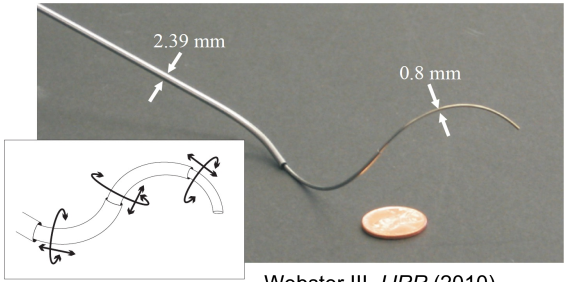
Cianchetti, *Soft Robotics.* (2014)



Simaan, *MICCAI* (2004)



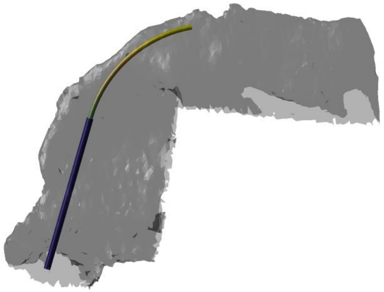
Jayender, *ICRA* (2010)



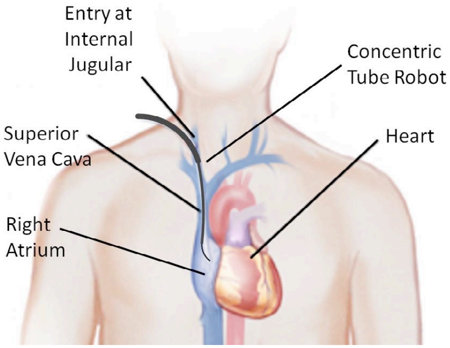
Webster III, *IJRR* (2010)

Dupont, *Hamlyn Symp. on Med. Rob.* (2012)

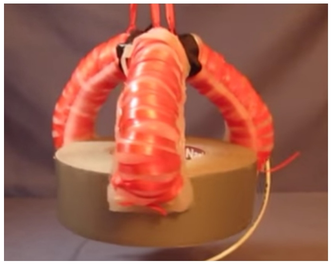
http://research.vuse.vanderbilt.edu/MEDLab/research_files/cannula.htm



Girerd, *ARK* (2016)

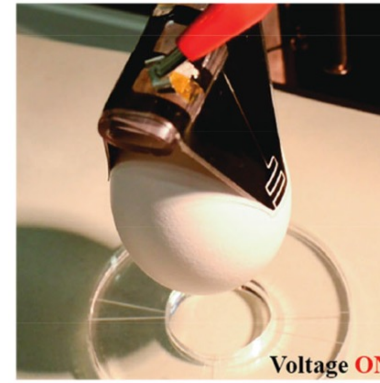


Microrobot architecture: 3D architecture

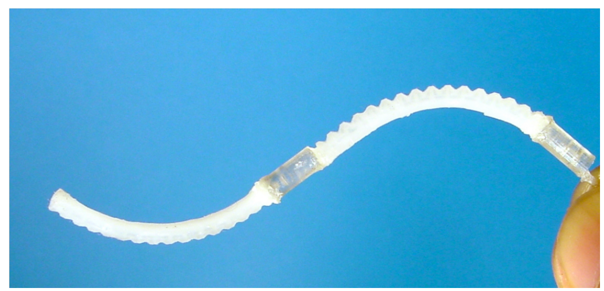


DIY

SOFT ROBOTICS



Shintake 2015



Ikuta 2003

Soft robotics: Technologies and systems pushing the boundaries of robot abilities
C. Laschi, B. Mazollai, M. Cianchetti, Soft Robotics

Microrobot architecture: 3D architecture

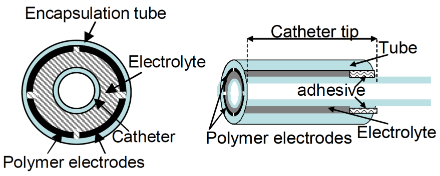
Support arms - continuous robots

Actuation technique comparison

Material	SMA	Piezo	EAP
Biocompatibility	+	-	+
Size	+	+	+
Deformation	+/-	-	+
Required power	-	-	+
Dynamics	-	+	-

- Electronic EAP: high voltages and stretchable electrodes
- Ionic EAP: very low voltages (+/- 2V for Polypyrrole)

Schematic description of Polypyrrole-based actuation



CAD design of the concentric tube robot with embedded actuator (CTR-EA)

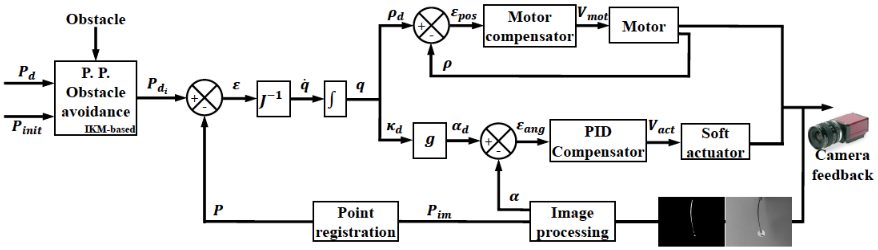
$Ø_{out} = 2,4$ mm
$Ø_{in} = 0,8$ mm
$\ell = 45$ mm

Microrobot architecture: 3D architecture

Support arms - continuous robots

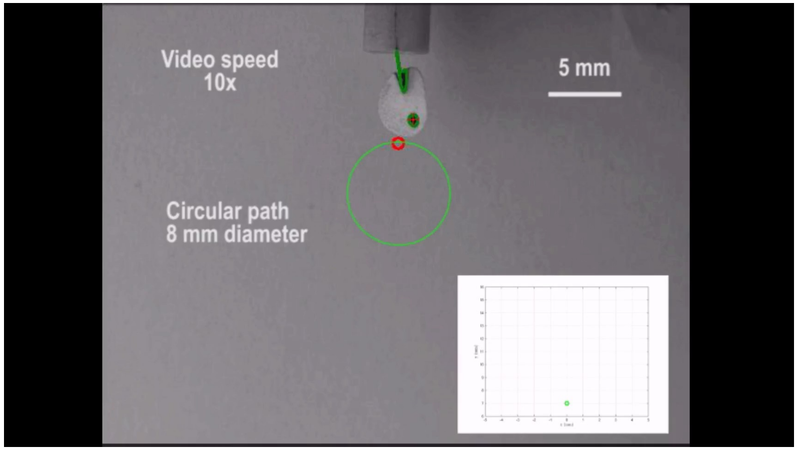
- Closed-loop control of Soft Robot (2 DoF)

Chikhaoui et al., IEEE/*RSJ IROS 2016*



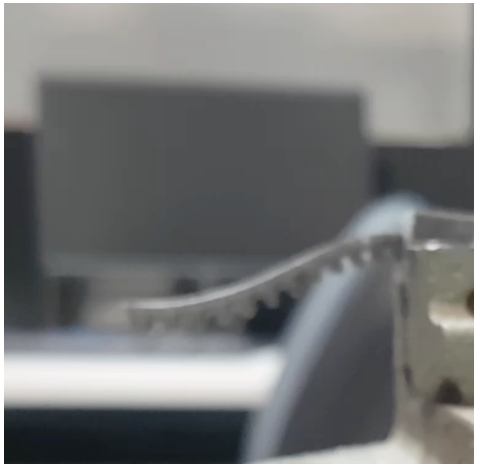
Modeling
Path following
Obstacle avoidance

Tri-layer Polypyrrole based Telescopic Soft Robot



Microrobot architecture: 3D architecture

Manufacture of parts by 3D
multi-material printing



Towards a future generation of microrobots and microgrippers

MIT and Harvard's Wyss Institute

https://youtu.be/_tKI8BUHFLo