5.12 Actionneurs pour Micromanipulateurs

5.12.1 Actionneurs à déformation (Dilatation thermique, SMA Shape Memory Alloys, effet Piézoélectrique)

Principes d'amplification: Guidages à lames, bimorphes incrémentaux (Inch-worm, Stick-Slip, Impact-drive)

Moteurs à ultrasons

Applications: Microscopes à sonde proche (AFM, STM)

Books on Micro-Actuators

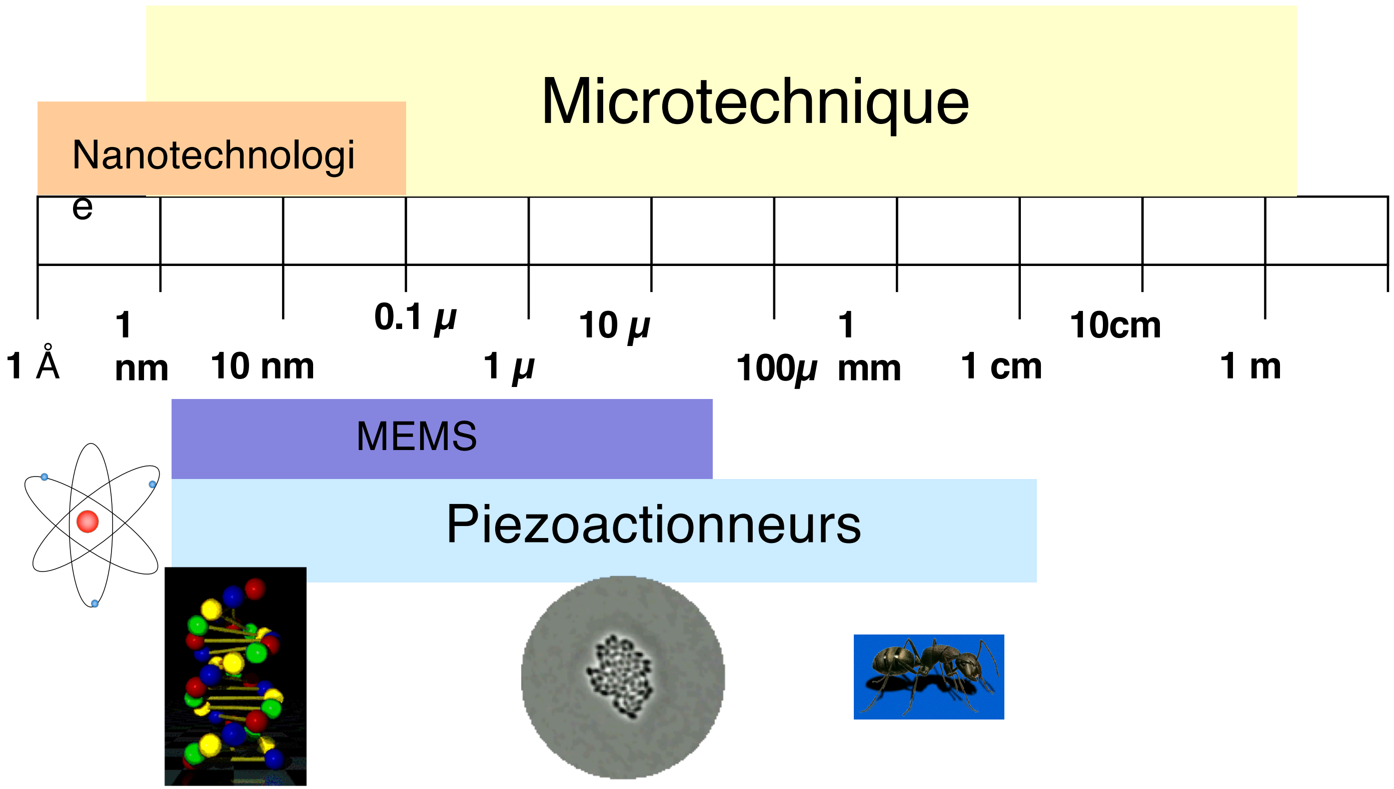
- **Microrobotics** Methods & Applications
  Yves Bellouard, CRC Press, 2010

- **Next-Generation Actuators Leading Breakthroughs**
  Toshiro Higuchi, Koichi Suzumori, Satoshi Tadokoro
  Springer, 2010

- **Micro-actionneurs éléctromagnétiques**
  Orphée Cugat, Hermes-Sciences, Lavoisier, 2002

Préliminaires

Rappel des ordres de grandeur



Typical accuracies in robotics

Conventional (industrial): ***100 - 10 μ***

Precision (micro-assembly): ***10 μ order***
(machine tools)

1/10

High precision : ***10-1μ order***
(micro-robotics)

Ultra-precision ***from μ to nm order***

1/1000

Quelques principes de base pour la haute précision:

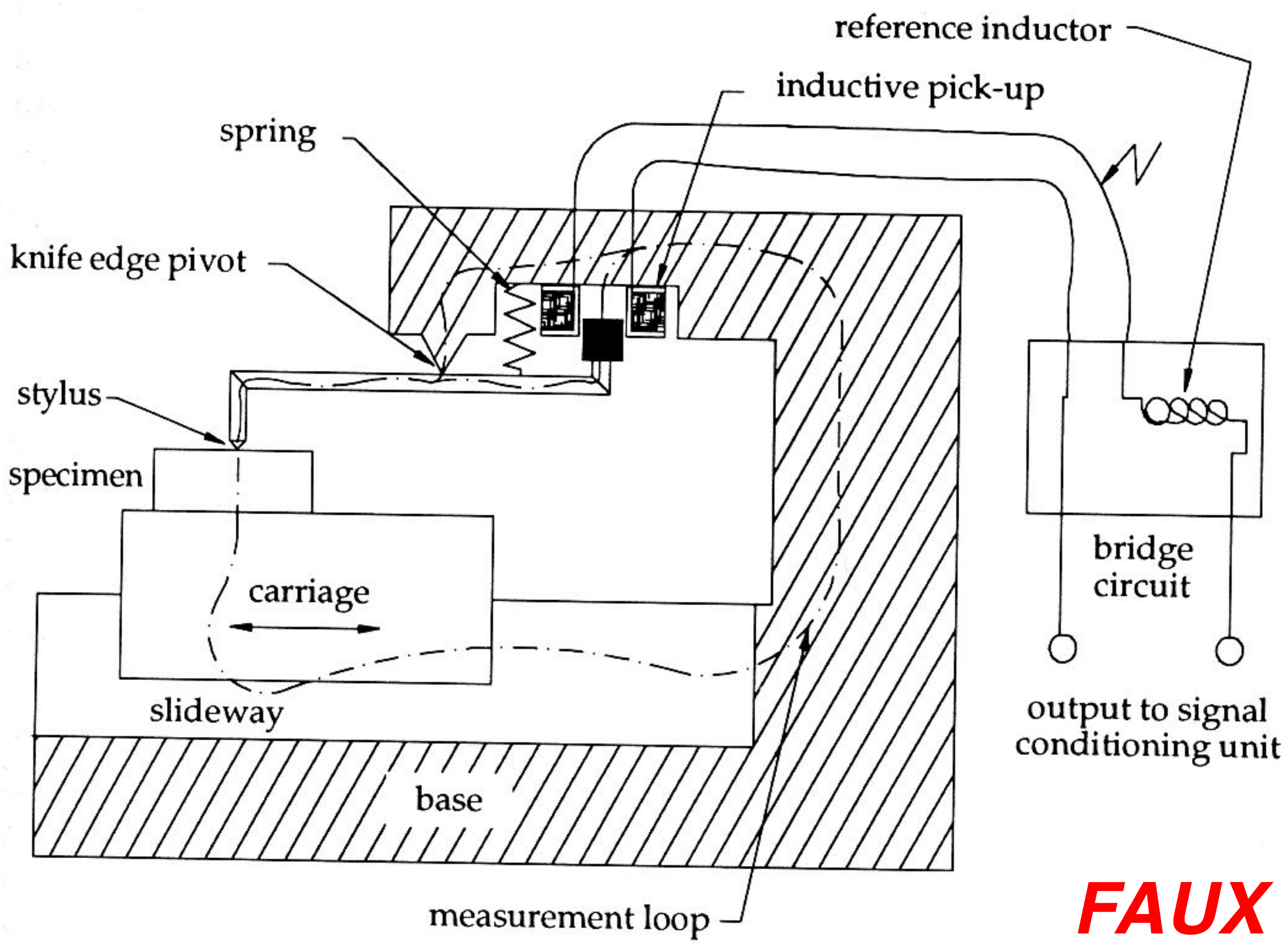
Eviter

- Jeux (Backlash)
- **frottements secs**
- hyperstatismes !
- sources de chaleur, gradients de température

Quelques principes de base pour la haute précision:

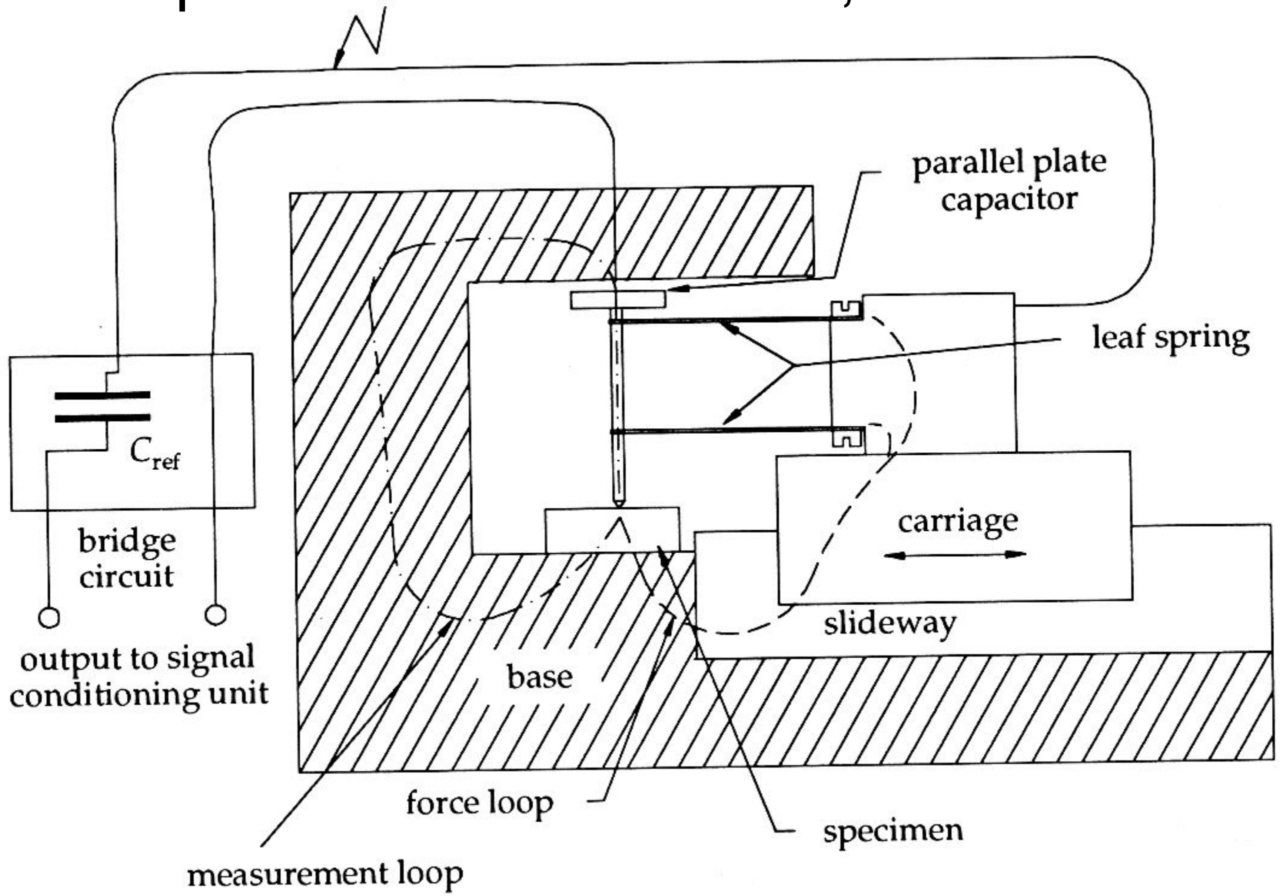
- Minimiser les boucles de forces et boucles de mesures.
- Séparer autant que possible ces deux boucles!
- Respecter le principe d'Abbe (colinéarité sortie-actionneur-mesure)
- Rechercher la symétrie

S.T. Smith,
D.G. Chetwynd
"Ultraprecision
Mechanism Design"



FAUX !

Concept de boucle de mesure, boucle de force



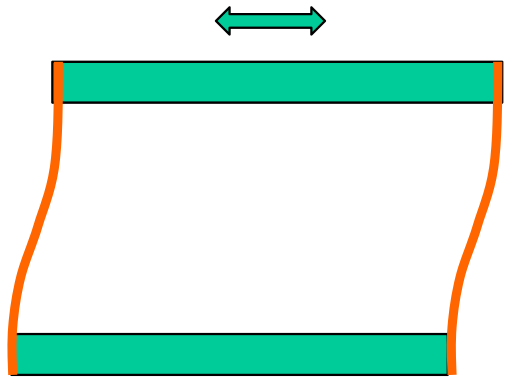
JUSTE!

S.T. Smith, D.G. Chetwynd
"Ultraprecision Mechanism Design"

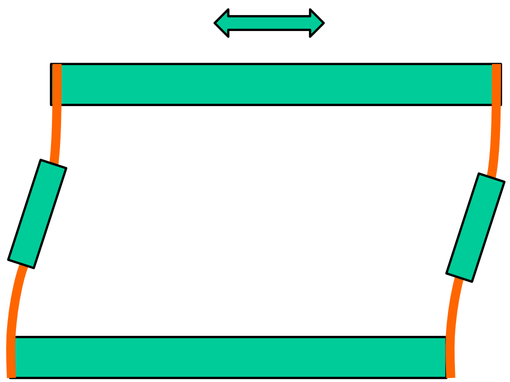
Articulation sans jeux & sans frottements sec:

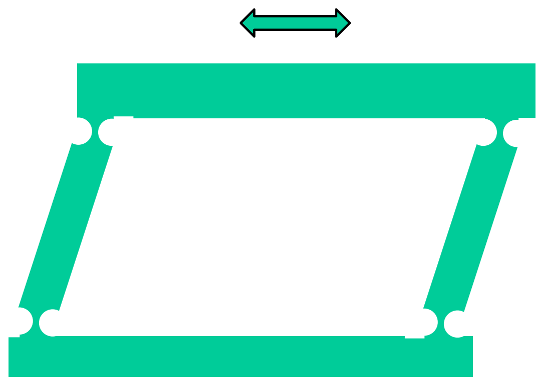
Guidages à lames

Question: Linéaire?



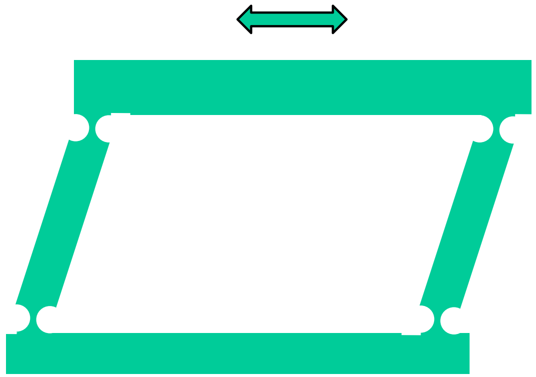
Constat: La partie centrale de la lame travaille peu
=> idée de laisser cette partie rigide





Avantage de tailler le guidage dans la masse:

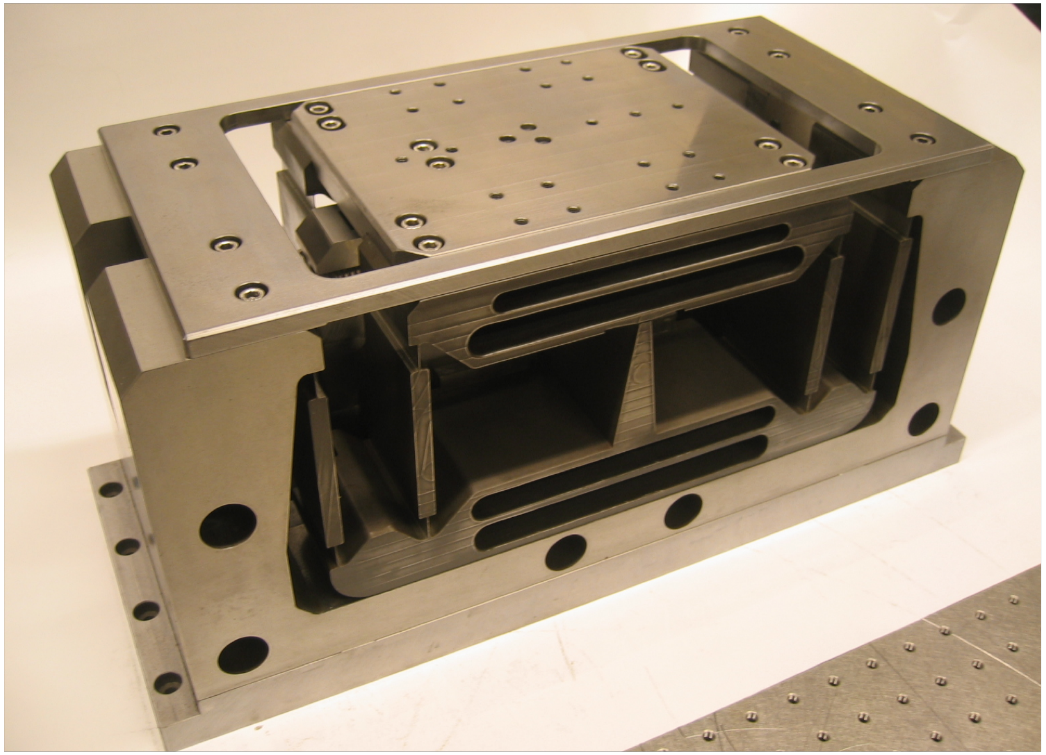
- Pas d'assemblage!



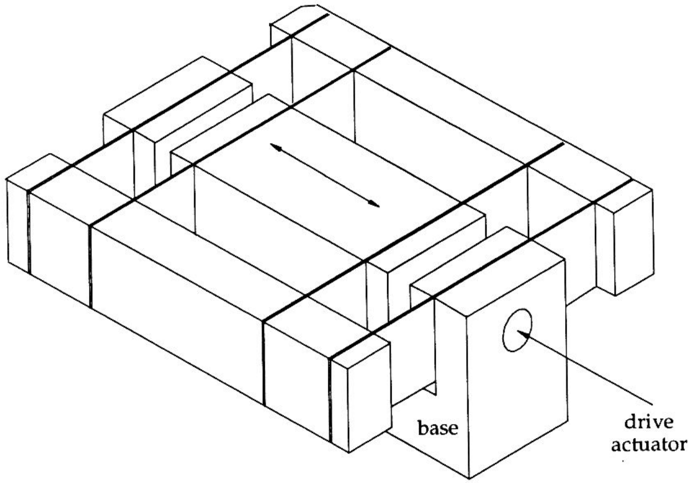
Usinage:
Par électroérosion à fil

Possibilité de faire des guidages parfaitement rectiligne

Linear Displacement:
Compensate parasitic transverse motion



S.T. Smith, D.G. Chetwynd
"Ultraprecision Mechanism Design"
Gordon & Breach 1992

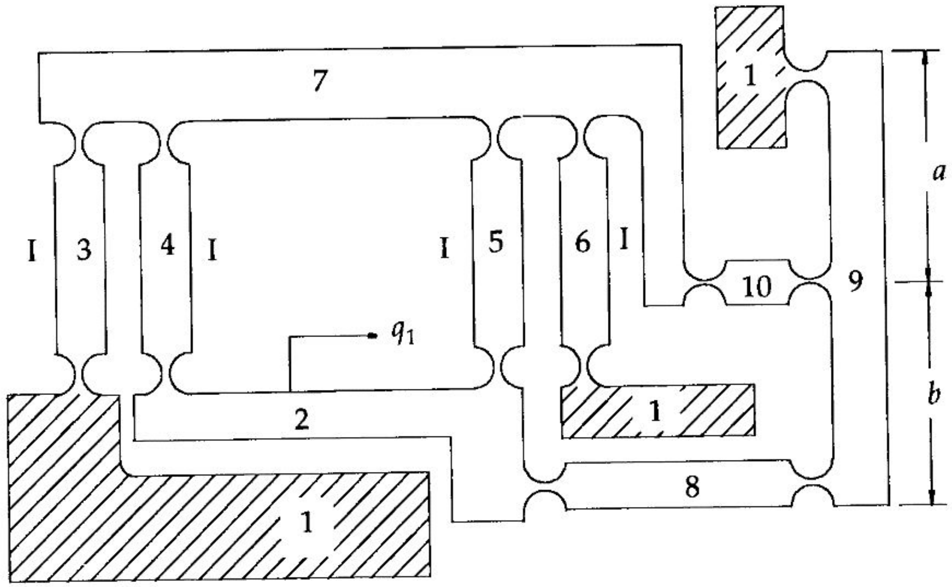


Bon guidage, mais problèmes de dynamique non-contrôlable et non-observable

S.T. Smith, D.G. Chetwynd

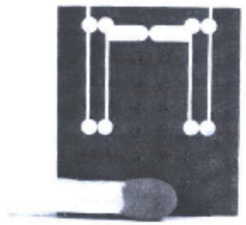
"Ultraprecision Mechanism Design"

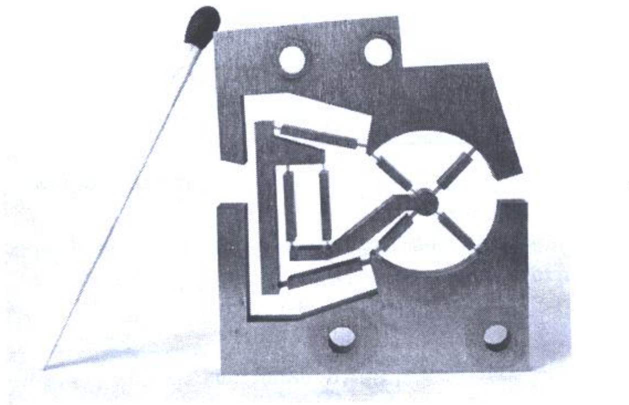
Gordon & Breach 1992



Linear and rotational flexures hinge mechanisms

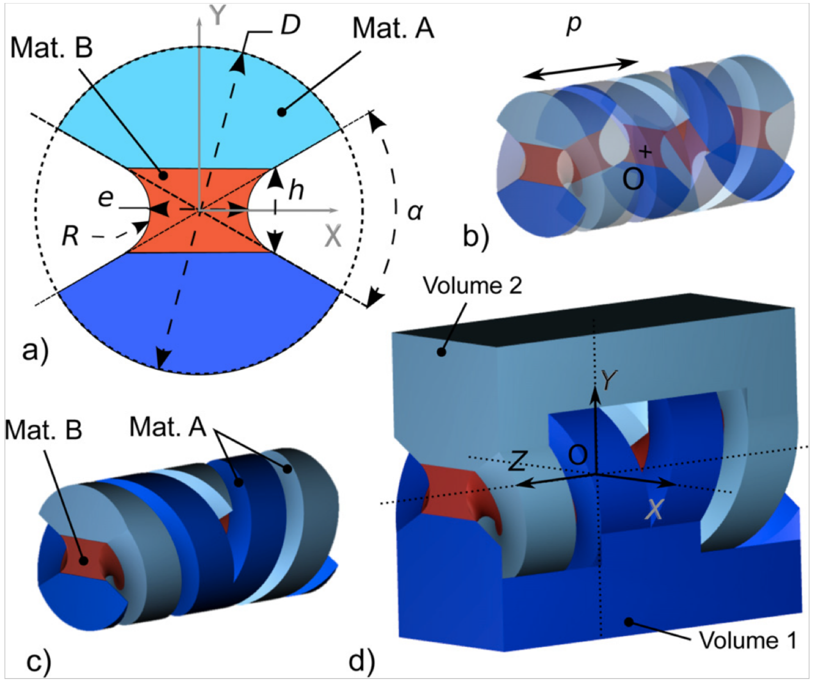
- No dry friction
- No wear
- No backlash

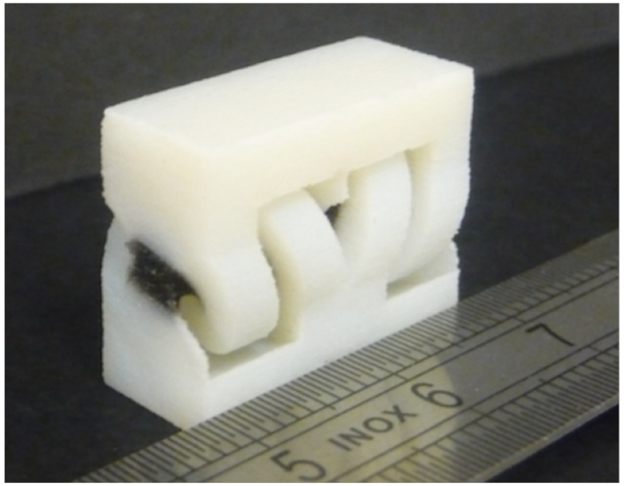




Flexure hinges in Multi-Material Additive Manufacturing

- Multi-Mat.-Ad.Manuf. by PolyjetV® (Stratasys, USA) or AKF® (Arburg, Germany) processes
- manufacturing of functional parts in FDM (Fused Deposition Modeling)



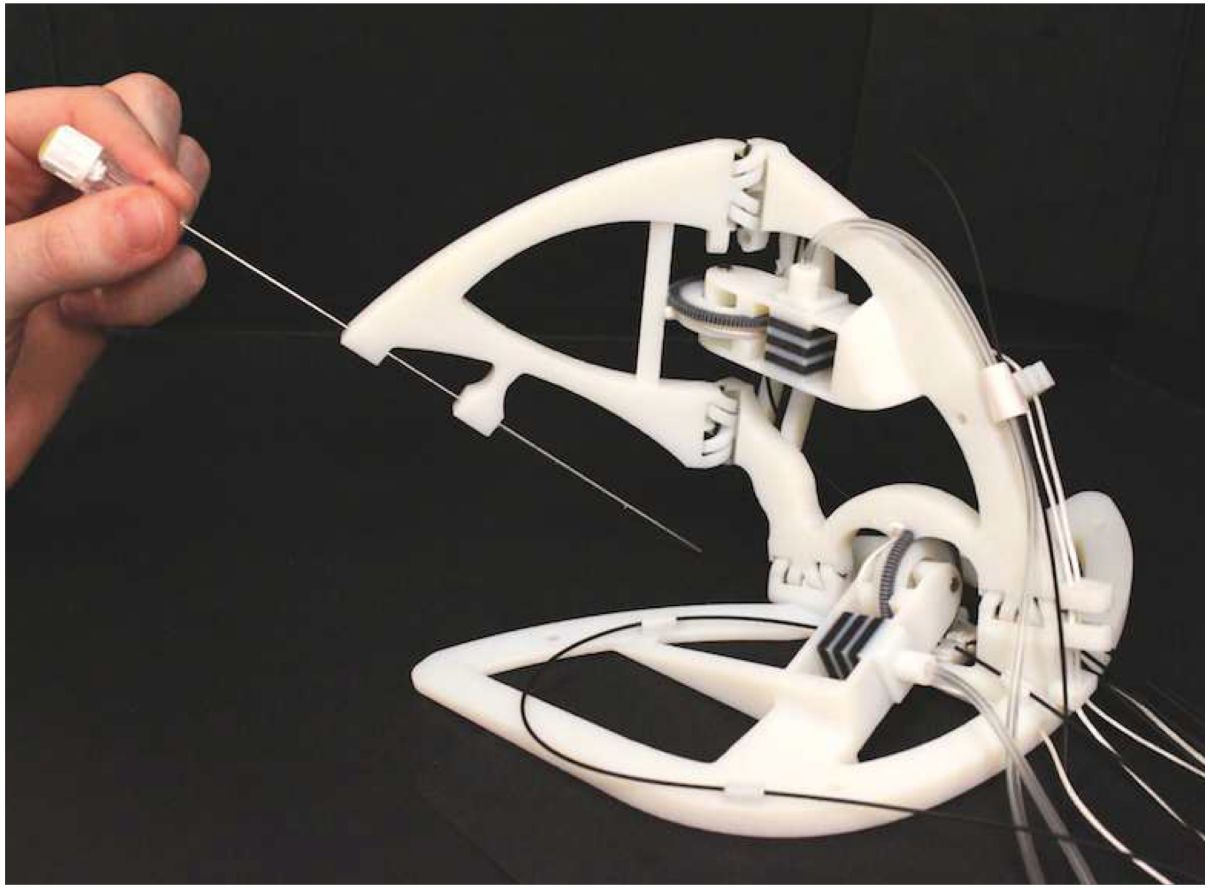


up to ± 30°, 40°, 50° …

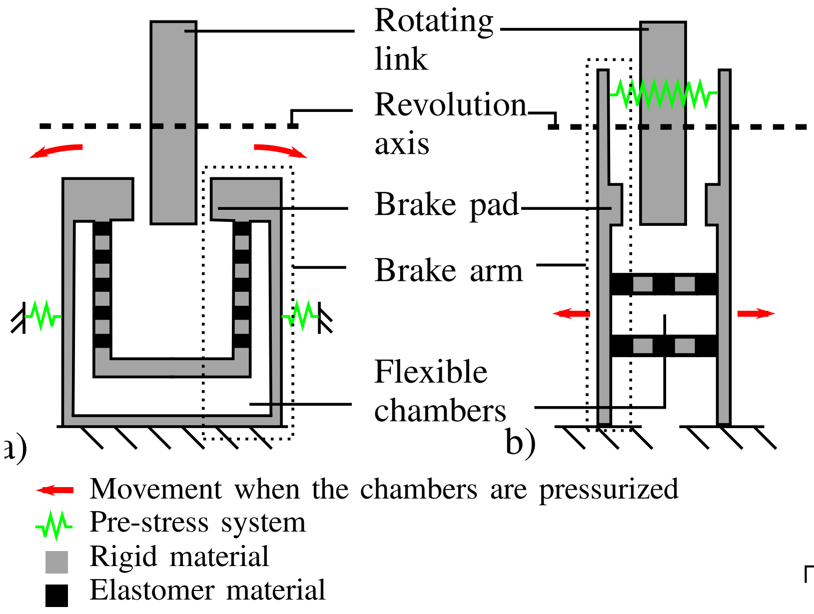
A. Bruys, F. Geiskopf, P. Renaud,
INSA Strasbourg
« Design and Modeling of a Large Amplitude Compliant Revolute Joint: The Helical Shape Compliant Joint »

Trans. ASME **137**, 85003 pp1-8 / Vol. 137, Aug. 2015
DOI: 10.1115/1.4030650

Un robot complet en fabrication aditive

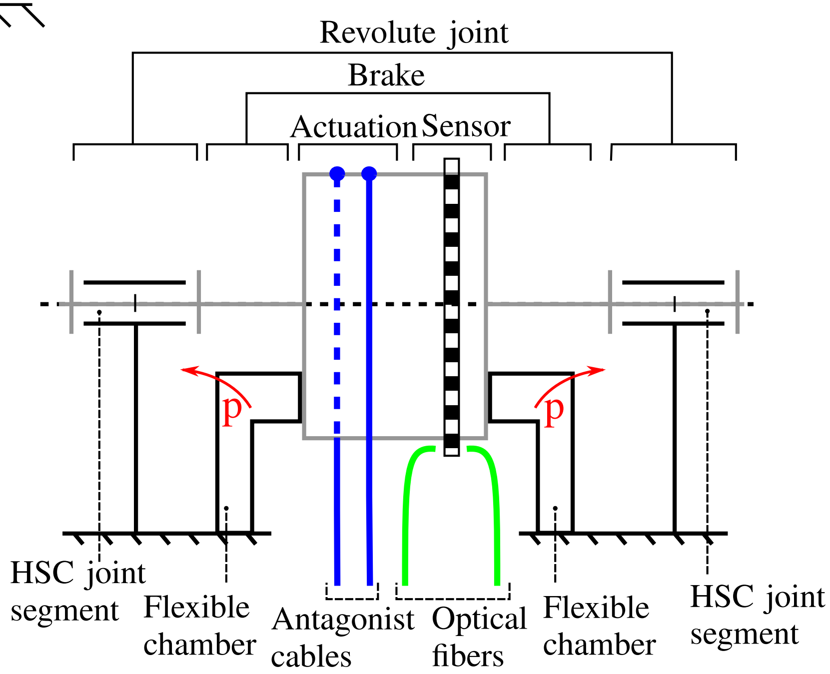


Freins, Capteurs



2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)

Toward Unibody Robotic Structures with Integrated Functions using Multimaterial Additive Manufacturing: Case Study of an MRI-compatible Interventional Device
Arnaud Bruyas, Francois Geiskopf and Pierre Renaud
CNRS, INSA Strasbourg



2 Principes de Micro-Actionneurs

- Moteurs électriques
- Déformation de matériaux

- Eviter des assemblages
- Compatibilité avec technologies de microsystèmes (MEMS, micro-electro-mechanical-systems)

Recherche de principes par **déformation de matériaux**

Les **effets d'échelles** favorisent les forces **électrostatiques** par rapport aux forces magnétiques

Petits moteurs électriques

- Des petits moteurs auront un rendement acceptable qu’avec de hautes vitesses

–> Besoin de réducteurs
(Planétaire = épicycloïde)

A plusieurs étages. Rapport de réduction par ex. 5 à 10 par étage, 3 ou 4 étages pour des rapports de réduction entre 100 et 1000

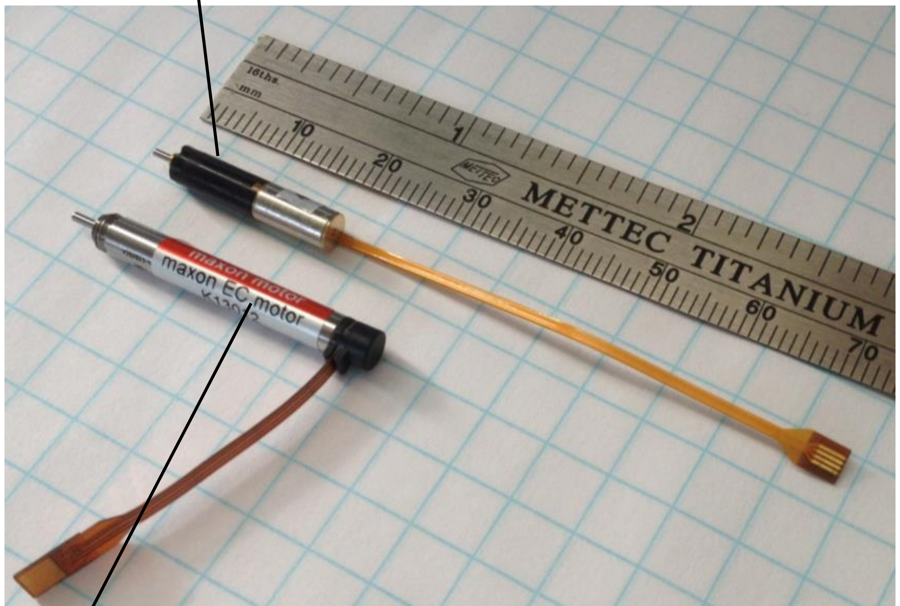
Exemple Minimotor (Groupe Faulhaber)

BLDC
Brushless DC motor
Ø = 3mm, L = 8mm
60'000 rpm
couple
0.02 mNm @ 15'000 rpm
puissance sortie max ~ 40 mW
rendement 17%

Jeu (backlash) 0.03 mm radial
0.15 mm axial

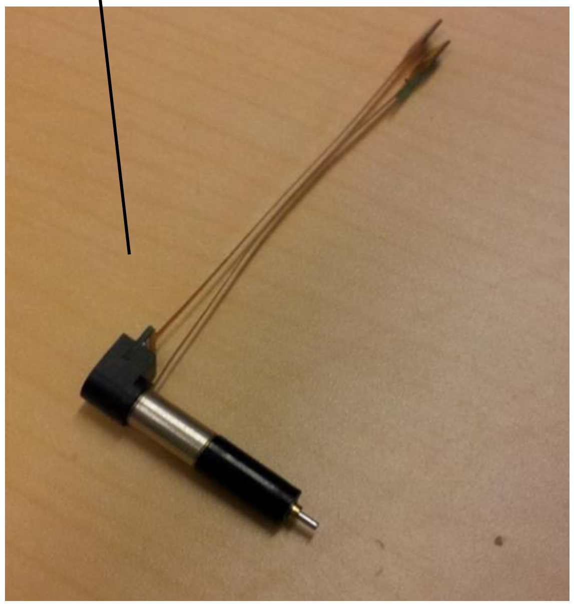
4mm geared motors

Namiki 337:1, no encoder



Maxon 280:1, 0.5W, with encoder

Namiki 337:1, with encoder

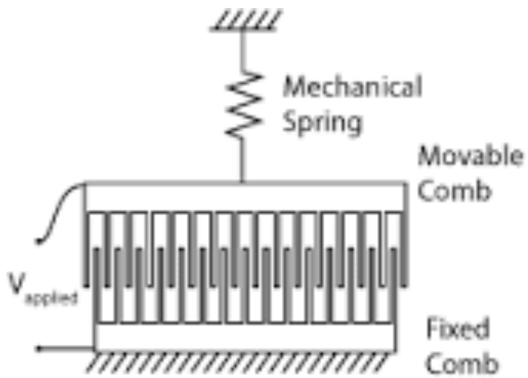


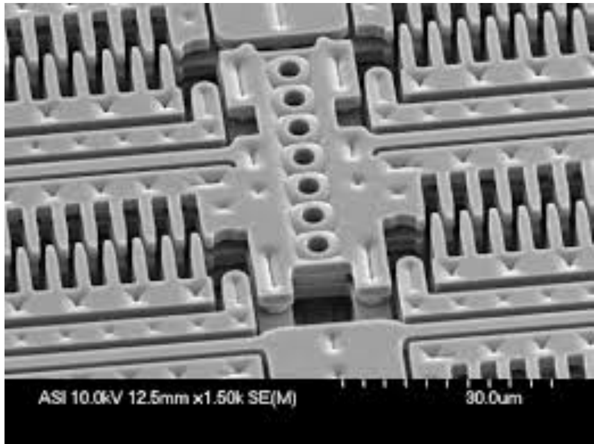
Electrostatic motors, Electrostatic actuators

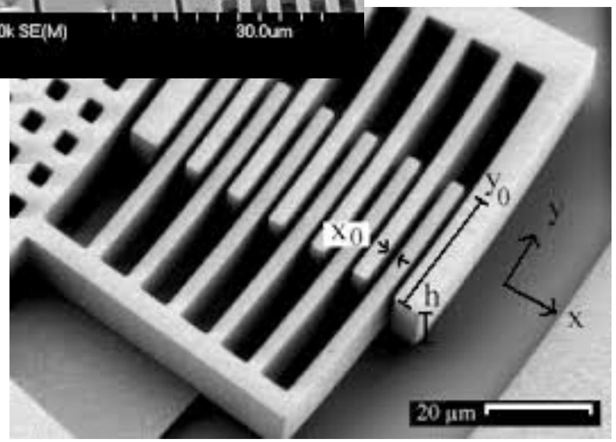
- Standard for MEMS: Comb-drive
- Exotic: Electrostatic high-power actuators
- Electrostatic glass motor

The “standard” MEMS actuator: Comb drive

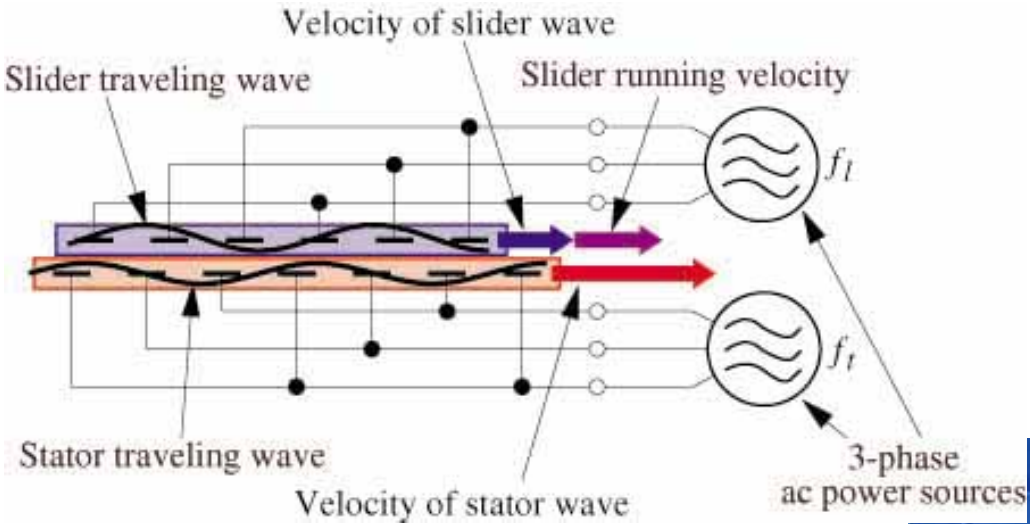
- Compatible with MEMS technologies
- simple structure, good efficiency at MEMS scale

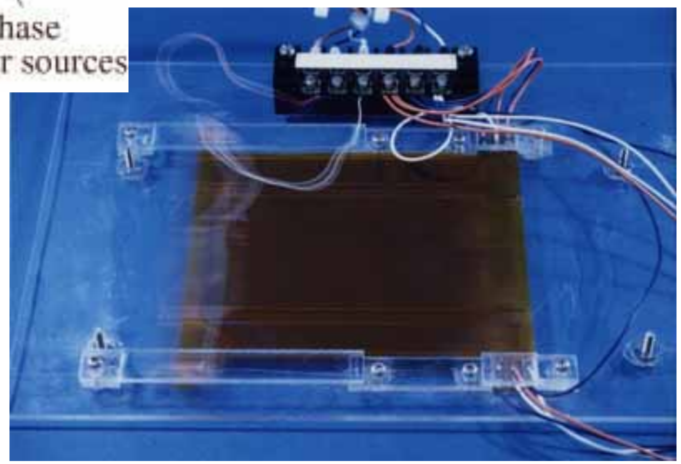






Exotic: Electrostatic high-power actuators





5.12.1. Déformation de matériaux

1. Dilatation thermique
2. Aliages à mémoire de forme (SMA, Shape Memory Alloy)
3. Piezo-électricité
4. Electro– & magnétostriction
5. Polymères électroactifs

1. Dilatation thermique
2. Piezo-électricité
3. Electro– & magnétostriction

}

- *Déformation: très faible*
- *Grandes forces*

1. SMA

- *Déformation: (très) grande*
- *Force: « moyenne »*

2. Polymères électroactifs

- *Déformation petite jusqu'à grande*
- *Forces faibles*

A compact mechanism is intrinsically more accurate than a large system!

A compact design offers also a higher thermal stability:

Thermal expansion: $\Delta l = \alpha * l * \Delta\theta$

***eg. a 40 mm rod in steel will expand* 480 nm *per* degree C**

The material must be chosen carefully:

materials	$\alpha\ 10^{-6}\ K^{-1}$
steel	12
aluminium	24
*Invar**	1.5
*Polymers***	60 to 200

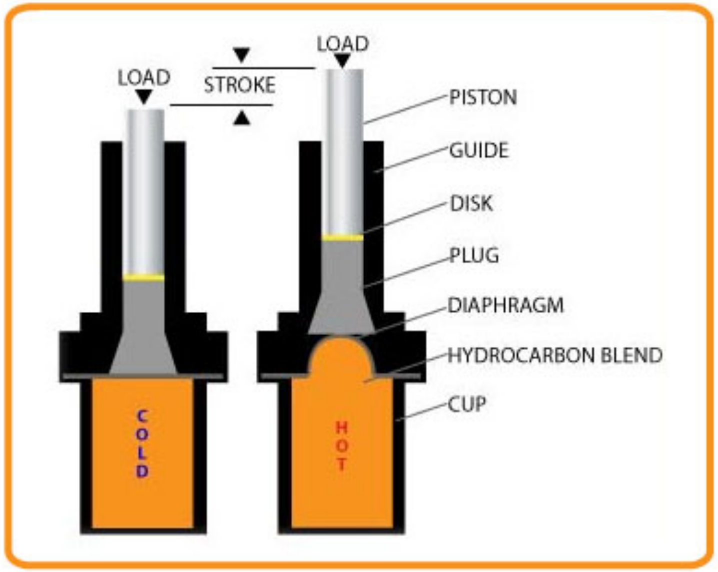
materials	$\alpha\ 10^{-6}\ K^{-1}$
glass	9
silicon	2.8 to 7.3
zerodur (Li Alumino-silicate glass)	0.02 to 0.1

**** Fe-Ni36%, prix Nobel suisse 1920 Charles Edouard Guillaume***
***** PVC, POM, PMMA …***

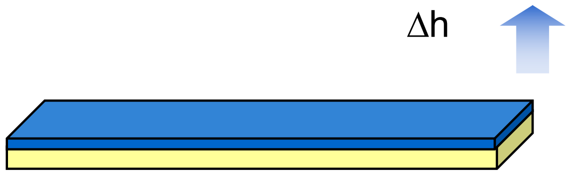
Actionneurs thermique

Utilisation directe
ou
Amplification par bilame
(principe bimorphe)

Thermal bimorph, bilayer



Exemples
•Thermostat (fer à repasser, raclette)
•Thermomètre
•Choke automatique
•Balancier et pendule
de montre et d'horloge



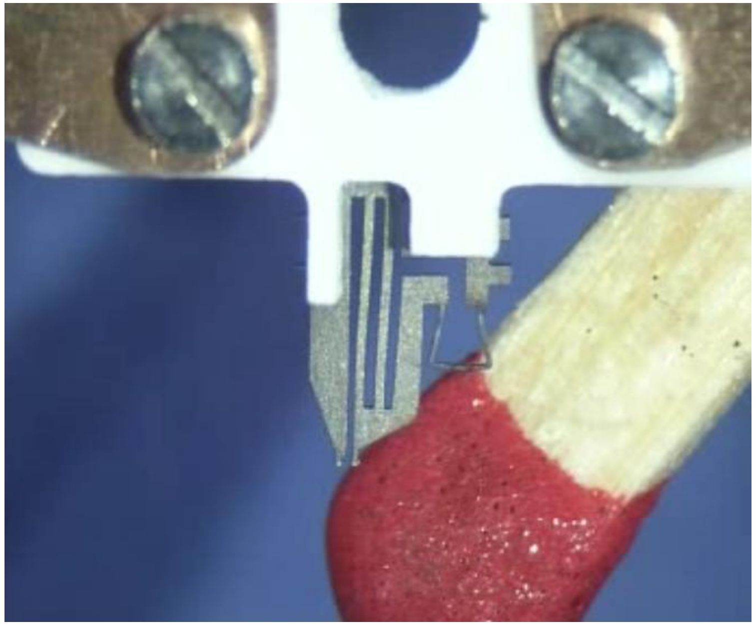
Deux métaux à coef. de dilatation différents.

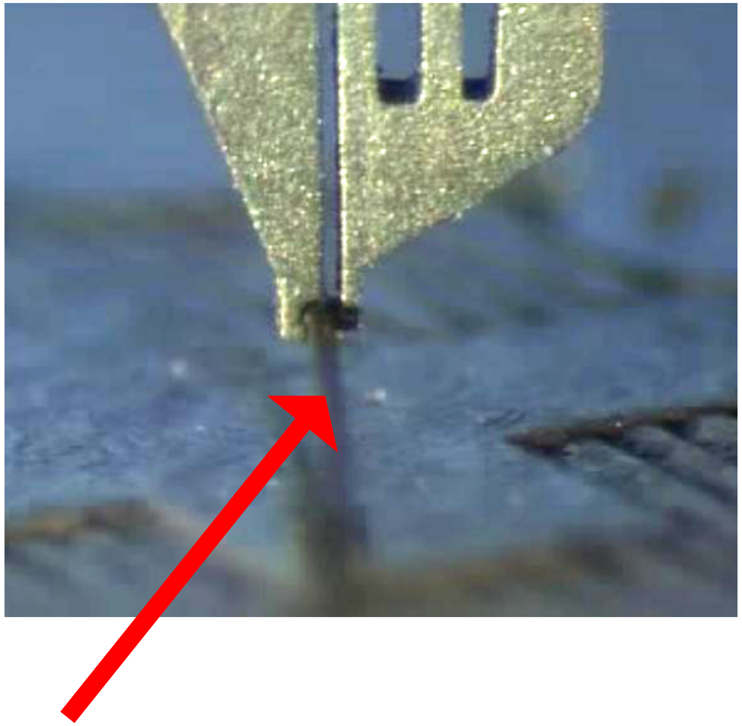
Shape Memory Alloys (SMA)

(Alliages à mémoire de forme AMF)

- Ni-Ti alloys
- Change from Austenite to Martensite structure
  at small temperature differences (around room temp.)
- Large deformation
- Hyper Elasticity
- Many applications

SMA microgripper





Human hair

Eléctrostricicion

- Peu utilisés
- Proche des Piézoélectrique (infra)
- ~ 0,01%. @ 100V
- Usinage plus facile que Piézocéramiques

Magnétostriction

- Déformation induite par champ magnétique
- Pas de contacts électriques
- Coûteux (terres rares)
- Hystérèse, dérive (drift)
- Exemple: Terfenol $1{,}6\ \mu/\mathrm{cm}$.

Piezoelectric Actuators

Piezo-électricité

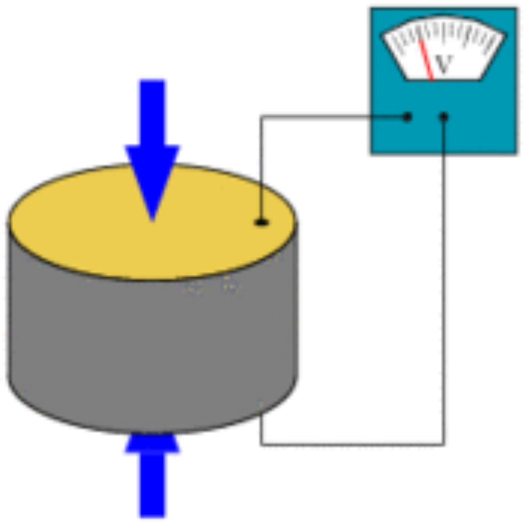
πιέζειν piezein = presser

Jacques et Pierre Curie, 1880

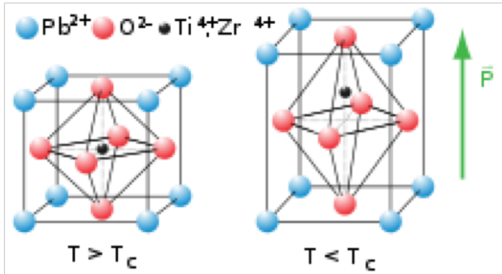
Quartz, minéraux

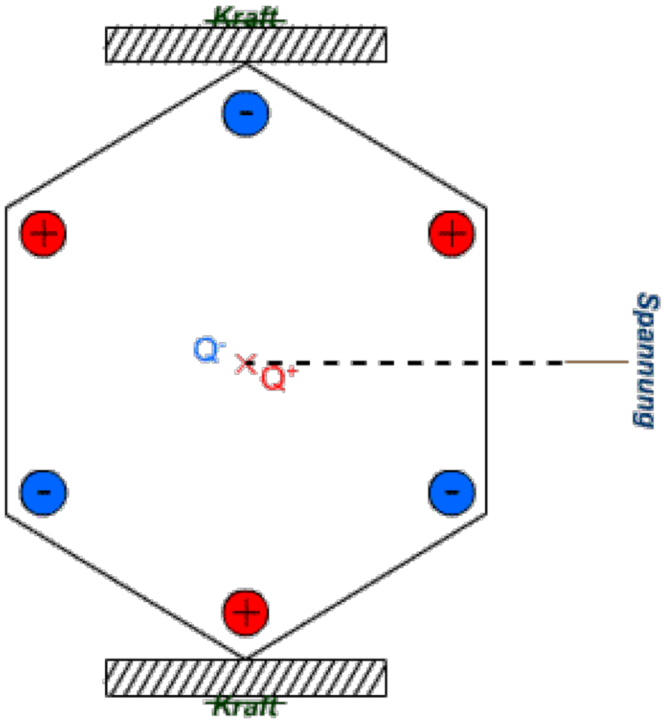
Après 1945
PZT
Plomb-Zirconium-Titanate
et beaucoup d'autres

(compatibles MEMS,
pour filtres etc)



Piezoelectric Actuators: Basics





Tenseur piezoélectrique:

E = champ électrique D = Polarisation
S = Déformation (strains) T = Contraintes (stresses)

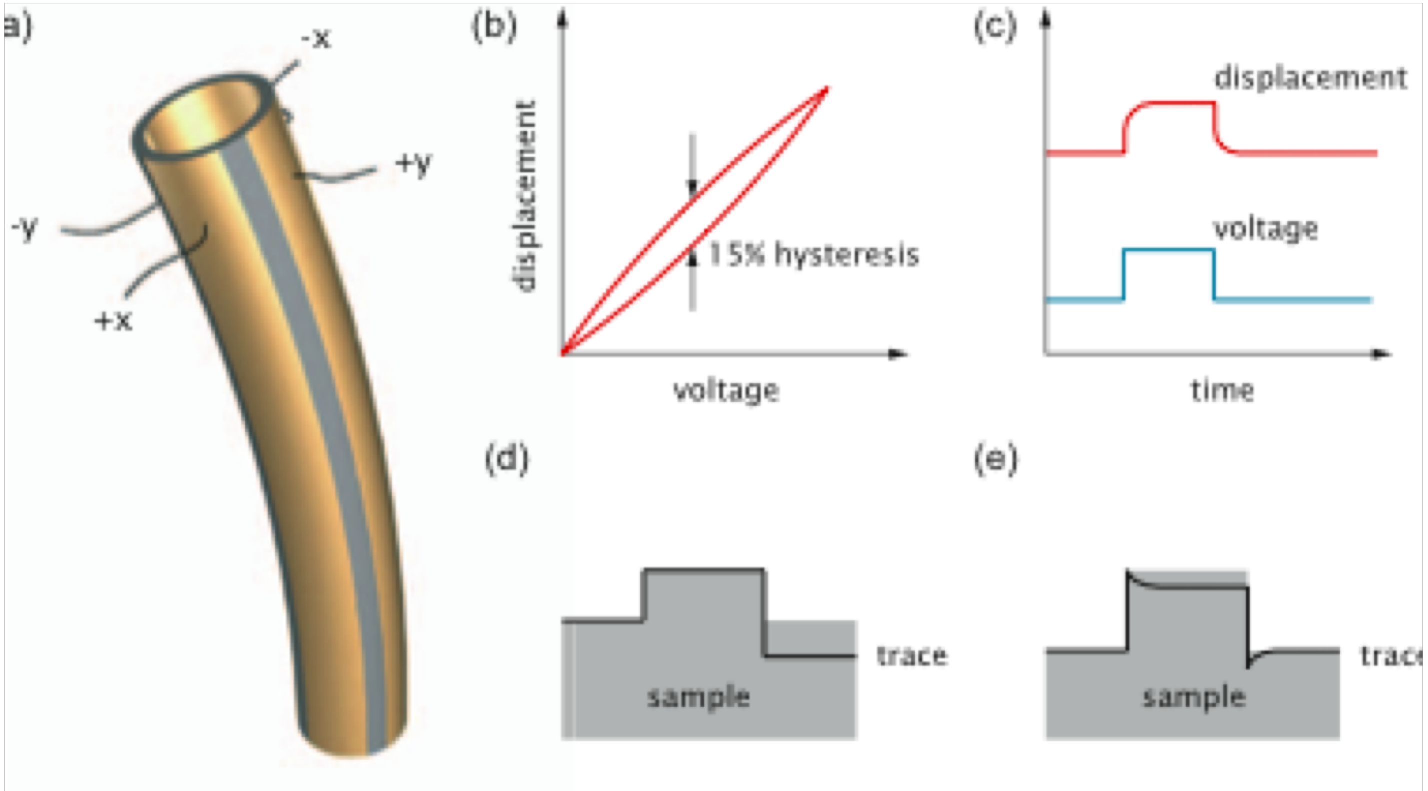
	T_1	T_2	T_3	T_4	T_5	T_6	E_1	E_2	E_3
D_1	0	0	0	0	d_{15}	0	ε_{11}	0	0
D_2	0	0	0	d_{15}	0	0	0	ε_{11}	0
D_3	d_{31}	d_{31}	d_{33}	0	0	0	0	0	ε_{33}
S_1	s_{11}	s_{12}	s_{13}	0	0	0	0	0	d_{31}
S_2	s_{12}	s_{11}	s_{13}	0	0	0	0	0	d_{31}
S_3	s_{13}	s_{13}	s_{33}	0	0	0	0	0	d_{33}
S_4	0	0	0	s_{44}	0	0	0	d_{15}	0
S_5	0	0	0	0	s_{44}	0	d_{15}	0	0
S_6	0	0	0	0	0	$2(s_{11}-s_{12})$	0	0	0

Céramique: résistance à la compression
mauvais en traction
–> pré-contrainte

Déformation en - cisaillement ou en
- traction/compression

(Matrice des coefficients piézo-électrique, pas traitée dans ce cours!)

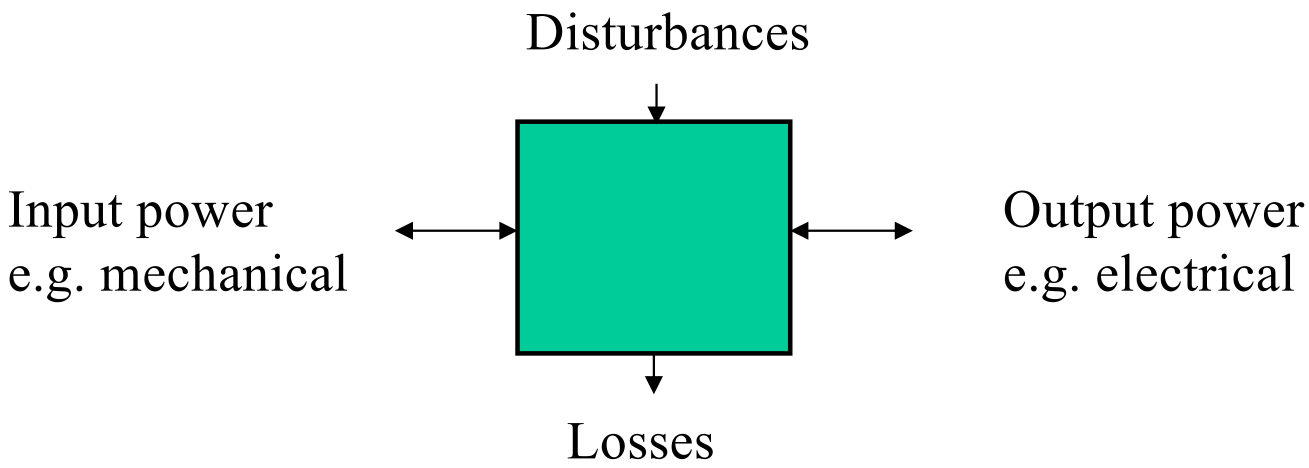
Hysterèse et fluage du piezo



g. 2.12. (a) A piezo tube scanner [18] (b) hysteresis, (c) creep, and their respective influences

L'effet piézoélectrique fonctionne dans les **deux** sens

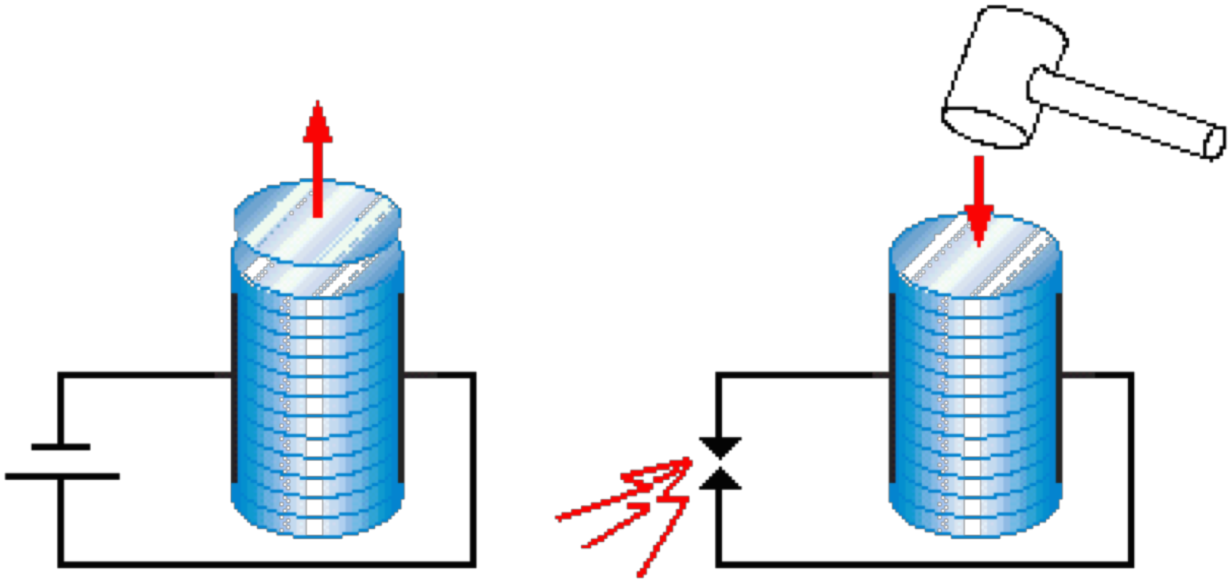
él. –> méc. **&** **méc. –> él.**



Il s'agit d'un TRANSDUCTEUR

Travaille en actionneur ou en capteur

Piezoelectric actuators :



Piezo as an **actuator**:
charge -> strain -> stress

Piezo as a **sensor**:
stress -> strain -> charge

Piezoelectric materials

- quartz (weak)
- salt (very weak)

polycrystaline ferroelectric ceramics:

- $BaTiO_3$,
- Lead Zirconate Titanate (PZT)

Basic mechanism:
Stress –> strain –> charge

- Also charge –> strain (actuator)
- complex geometry
  (polarisation direction, strain tensor, shear…)
- small displacements, high forces, high voltages
  (μm to tens of μm for cm size PZT, 100s of Volt)
- nonlinearity, hysteresis
- Ceramics –> brittle –> prestress

Mécanisme piezo-électrique

Le point de vue « transducteur » révèle:

La déformation est proportionelle non à la **tension**, mais à la **charge**

(Capteurs e.g. Kistler: « **Charge amplifier** »)

Dans le **schema électrique**, l'élément piézo est représenté par une **capacité**

Déformation faible: 0.015% @ 100V

Ex. PZT   Longueur 10 mm
Déformation de 1.5µm (!)

Donc l'application de piezo sera très souvent intégré avec un principe **d'AMPLIFICATION** du **mouvement**

Principes d'amplification de mouvmt.

Stack (empilement)
Bimorphe
« Genouillère »

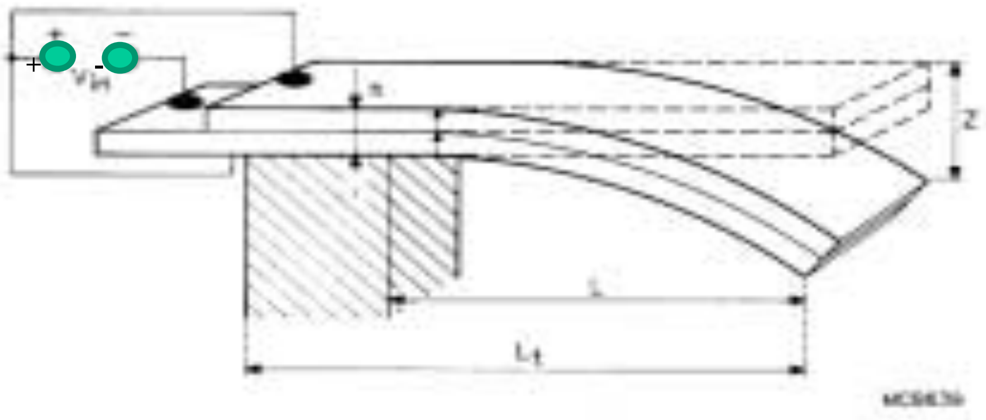
Stick-Slip
Impact-drive
Inch-Worm

} *Techniques « pas à pas », déplacement en principe infini*

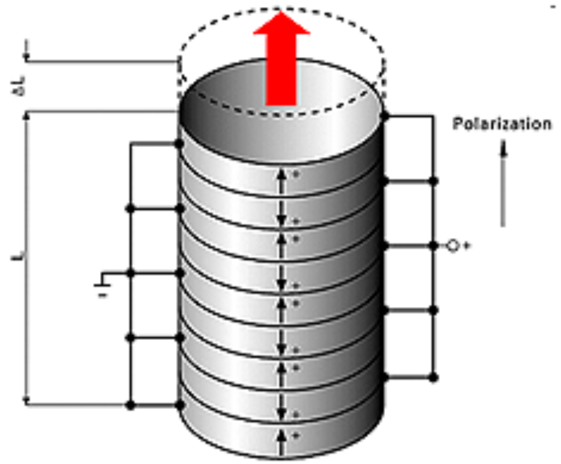
Levier

Principe bimorphe

- Bimétal thermique classique (régulateur « rechaud raclette »)
- S'applique à tous les actionneurs à faible déformation
- Deux piézos en différentiel ou piézo et matériau neutre



Principe de la « pile » piezo multi-couche « stack »

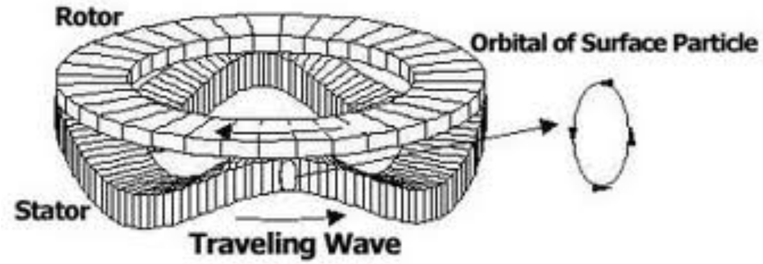


Empiler des couches, épaisseurs entre 0.2 et 1 mm, connectées électriquement en parallèle

déformations de l'ordre de **0.1%** à 100V (**10 µm @ 10 mm**).
relativement coûteux (**~80 CHFr pour un actionneur de 10*5*5 mm3**)

Moteurs Ultrasoniques

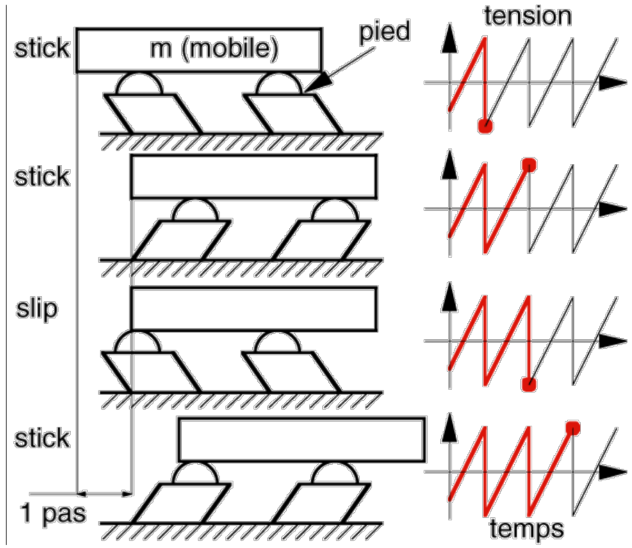
(Piezoelectric motors)



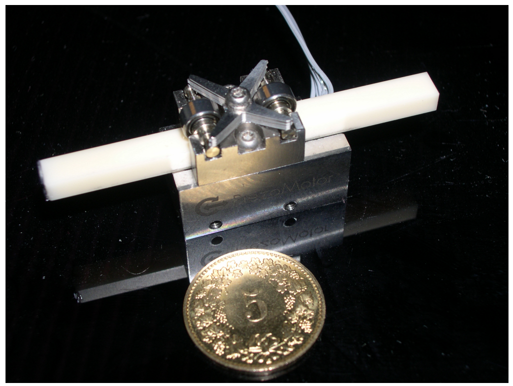
- Disques en contact
- Onde stationnaire sur le stator, induite par piezo-électicité
- Fréquences typiquement de l’ordre de 20 à 60 kHz
- Couple puissant
- Positionnement précis
- Application typique: Auto-focus de caméras
- Beaucoup de variante, de producteurs
- Vidéos: Principe ondes stationnaires, Noliac

Stik-Slip principle

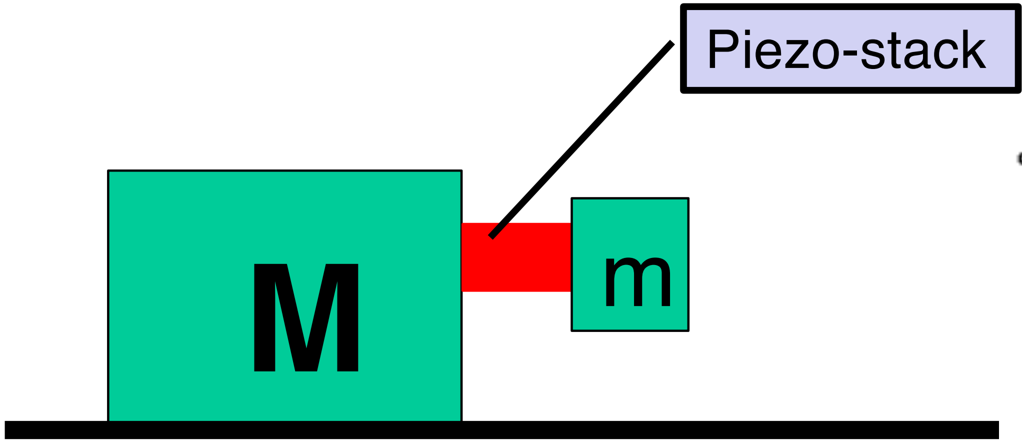
Combines high resolution with long motion range

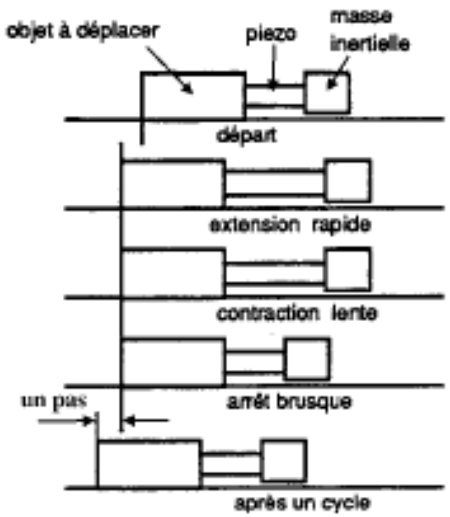


- Haute résolution (nm)
  Longues courses (cm)
- Simplicité (mécanique, électrique)
- Vitesses (nm/s – mm/s)
- Force (1-2 N)



Impact-Drive:





Series of impacts for incremental motion
low precision per step, low power

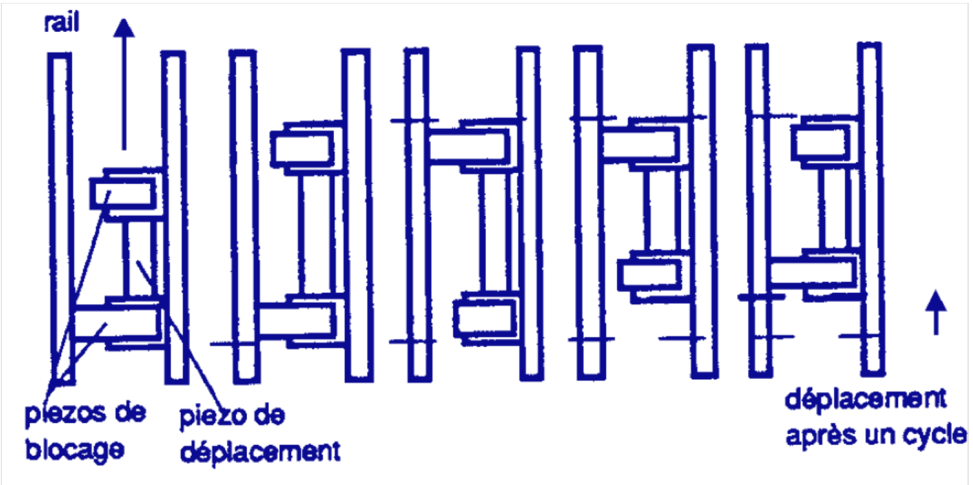
Adhesion and robustness can be improved
e.g. by permanent magnets.

Inch-worm

inspiré du mode de déplacement d'un ver (worm)

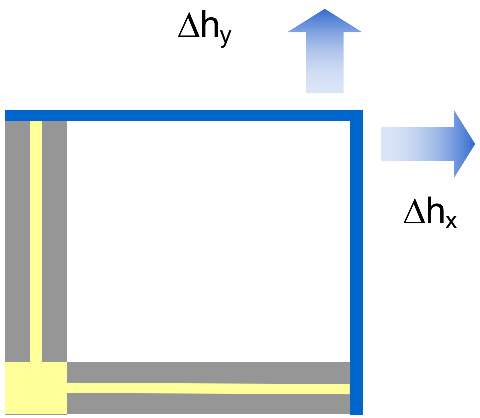
1.Une des extrémités est **bloquée**, le système **s'allonge**. L'autre extrémité est à son tour bloquée.

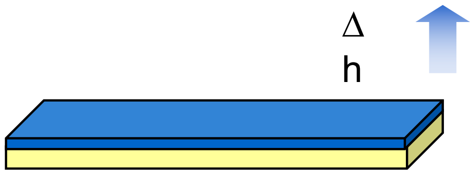
2.La première est alors **débloquée** et le système **se contracte**.



- \+ **force d'entraînement élevée**.
- \+ **excellente résolution**
- – **Exige usinage très précis ➔ Cher!**

Principe « bimorphe »





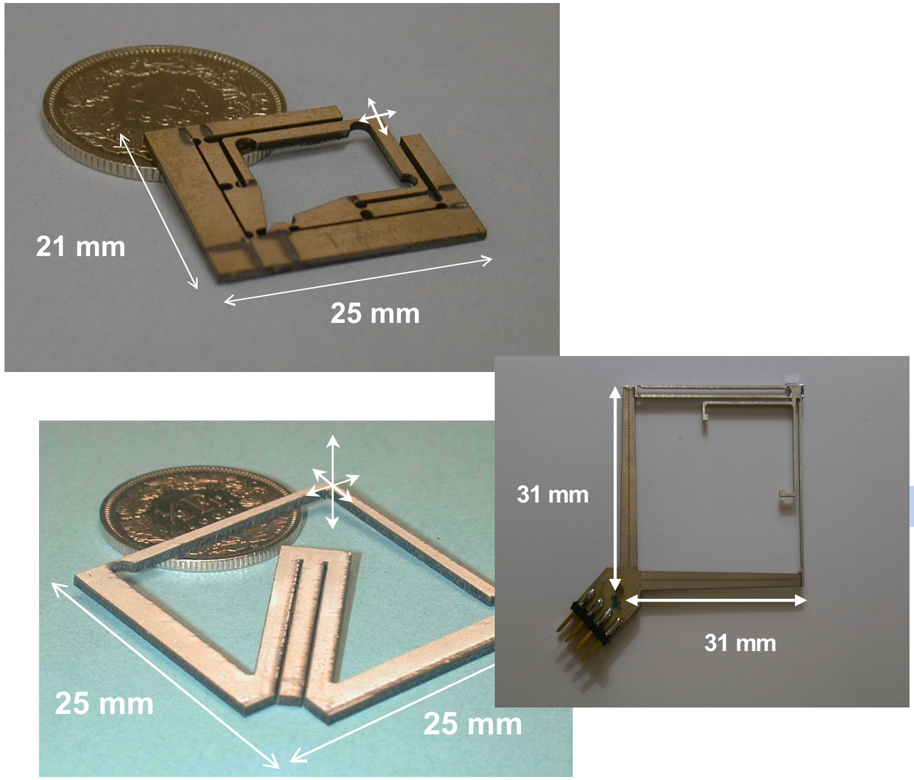
Piézocéramique

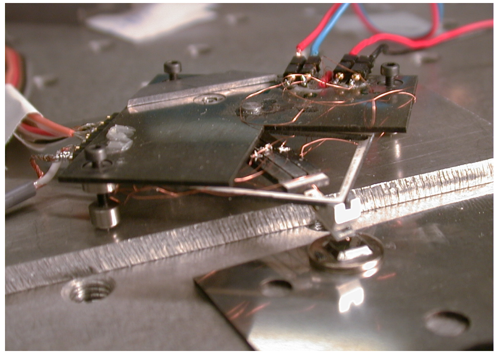
Piézo avec Electrode

Matériau non PZT

(Ashwin Lal, LSRO)

Exemples





AFM complet

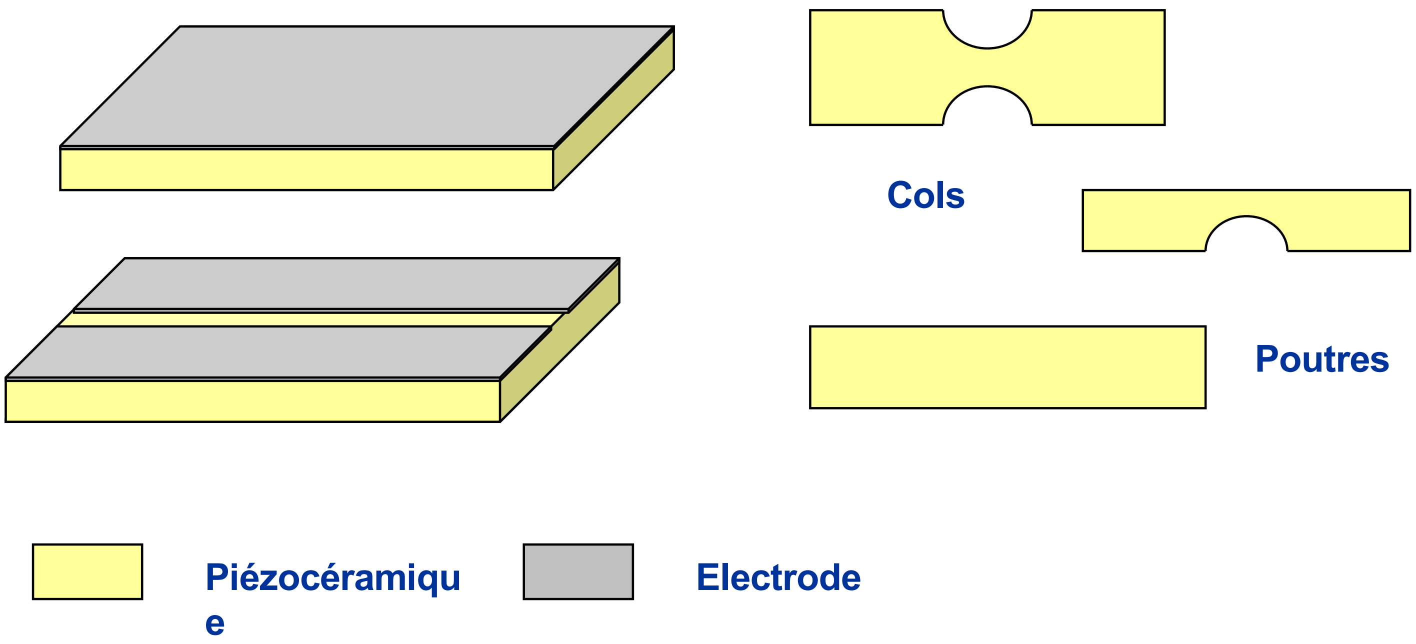
(Ashwin Lal, LSRO)

Effet « genouillère »

Deux parties différentes dans une même structure

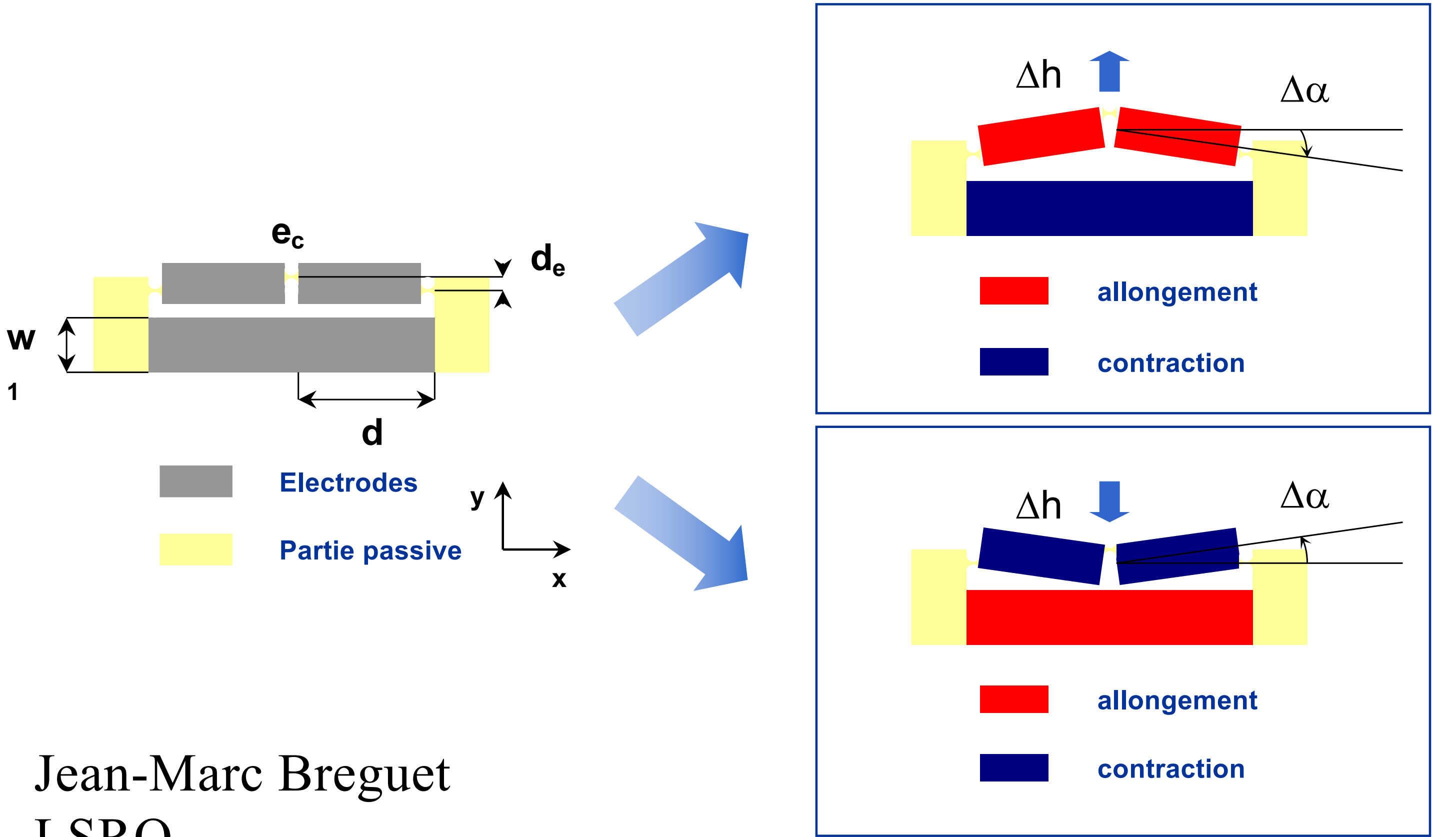
(Thèse Ricardo Perez, LSRO)

Parties actives ***Parties passives***



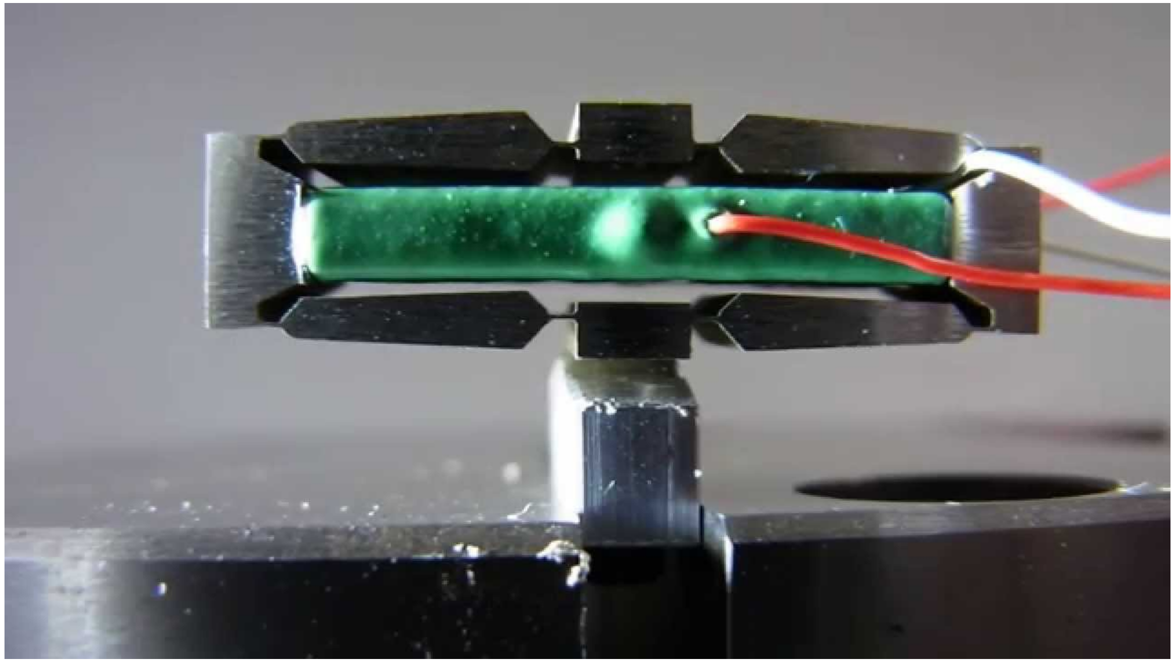
Amplification par effet « genouillère »

(offset d_e des cous élastiques)



Jean-Marc Breguet
LSRO

Quelques exemples…



Quelques exemples…

Example de PiezoMotor (Groupe Faulhaber)

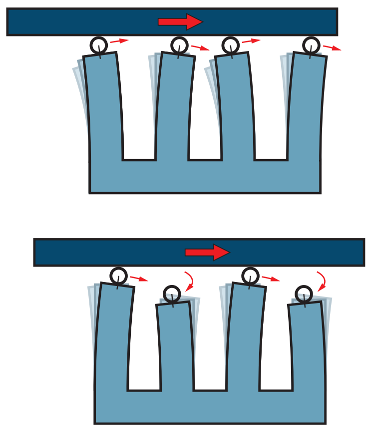
PiezoMotor — Piezo LEGS® Linear 6N

Drive rods 30 – 100 mm

- **Direct drive - backlash free**
- **Nanometer resolution**
- **Simple drive electronics**
- **No power draw in hold position**
- **Quick response and high speed**

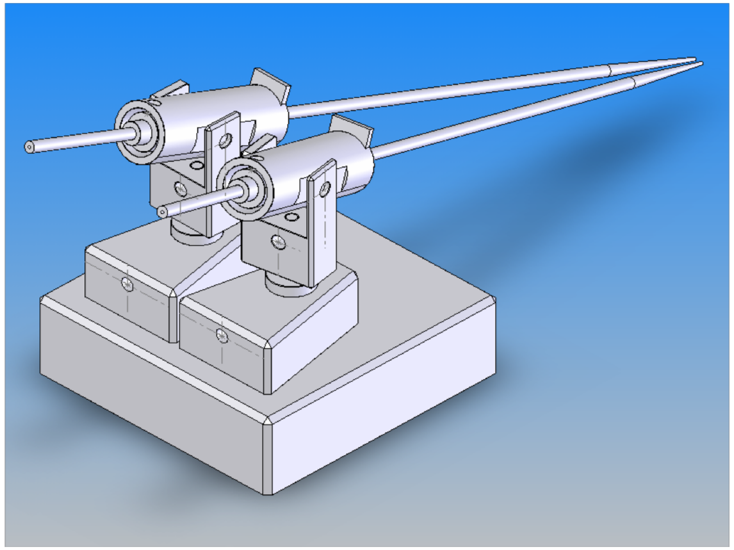
Standard version, stainless steel
Non-magnetic version

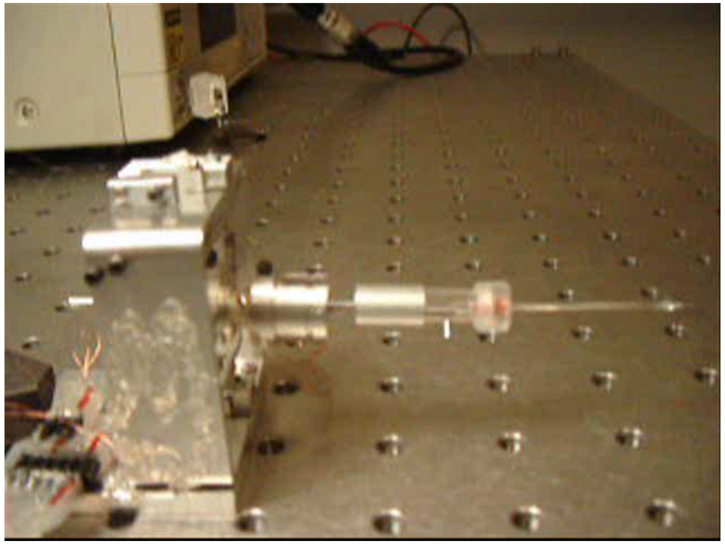
Vacuum version, non-magnetic



In analog bending mode or with higher resolution D/A converter it is possible to position in the sub nanometer region.

Piezotube – Impact drive: 3 DoF Micromanipulator



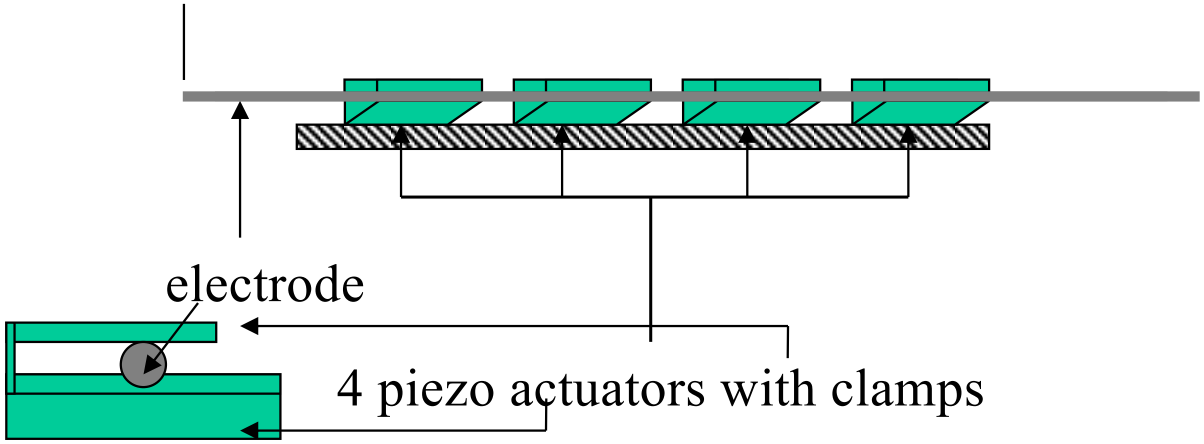


- 3DoF
- Several cm^3 workspace
- Nanometer resolution
- Low production cost
- Extremely simple

prototype

Walking mechanism (Electrode-feeder) patented by AGIE

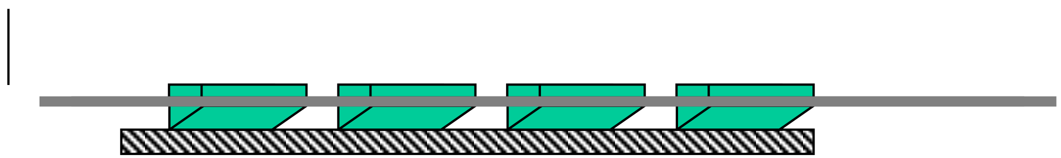
Working principle



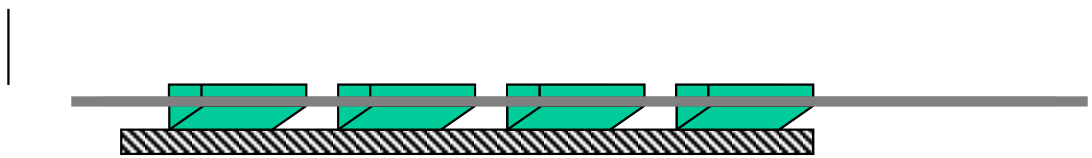
Front view

Walking mechanism (Electrode-feeder) patented by AGIE

Working principle



Electrode-feeder breveté par AGIE

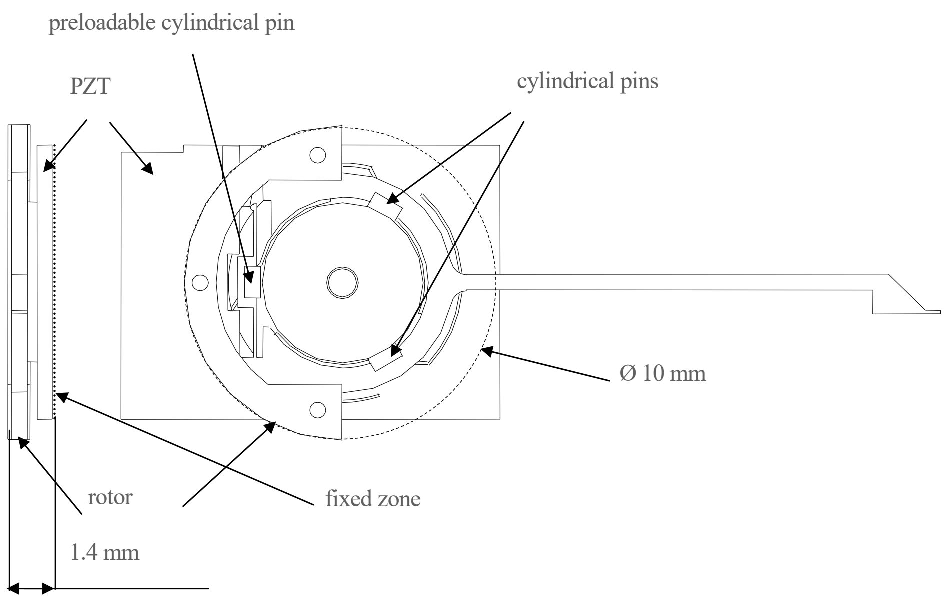


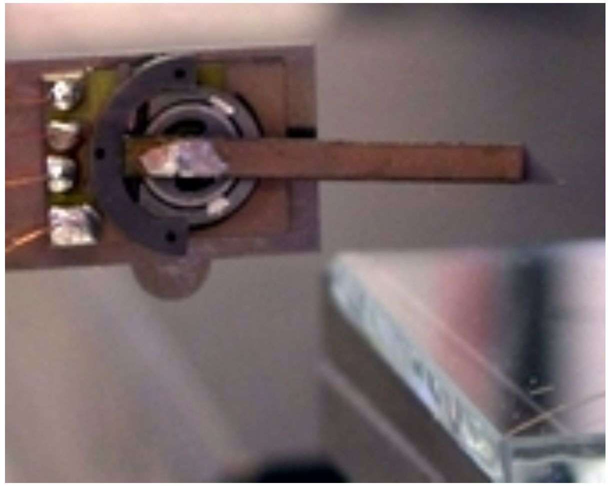
Walking mechanism (Electrode-feeder) patented by AGIE

piezotube_longrange.wmv

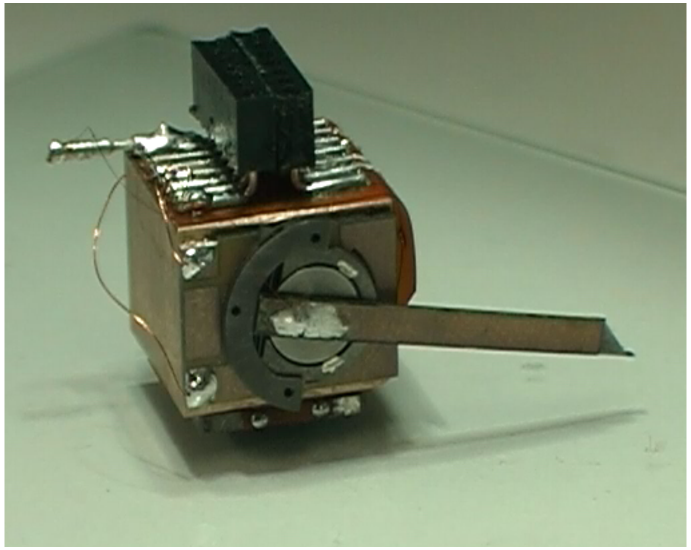
- Velocity: 1 mm/s
- Resolution: 50 nm
- Force: 500 mN
- Electrode diameter: 50 to 1500 µm
- Dimension: 30 x Ø12 mm

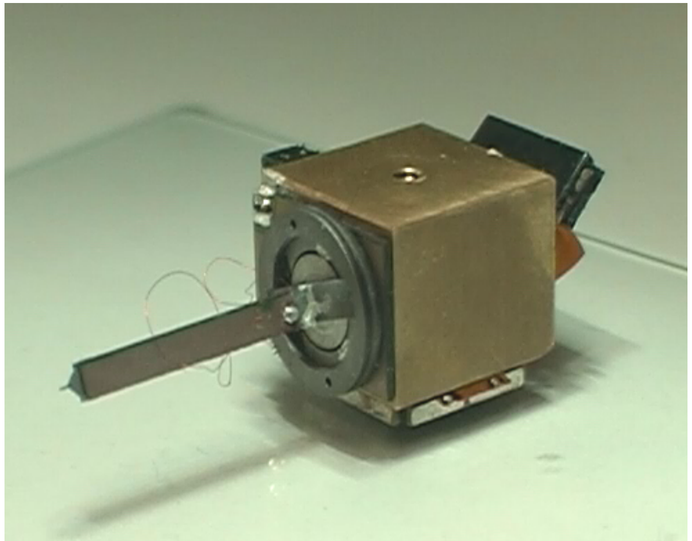
Actionneur rotatif (stick-slip) avec micro-pince intégrée (piezo monomorphe)

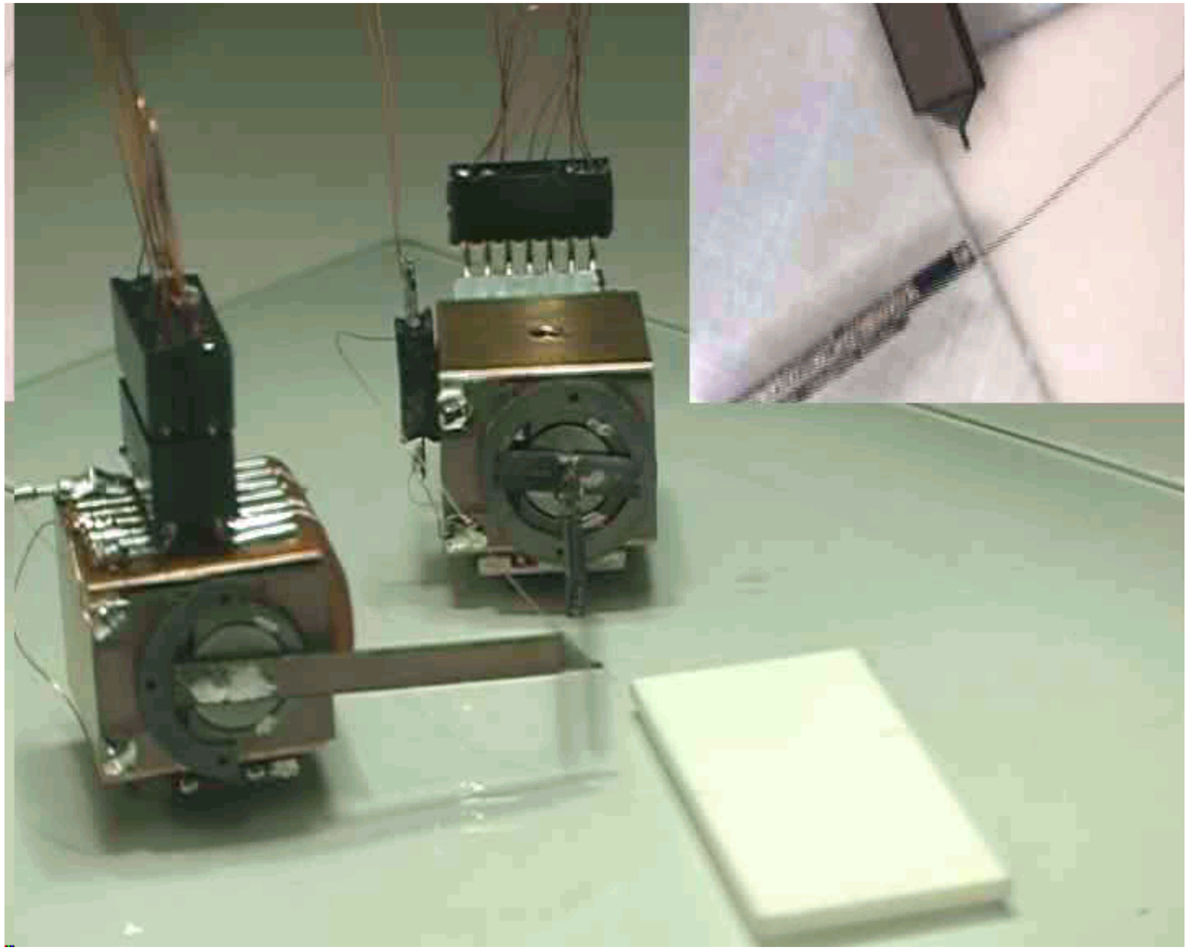




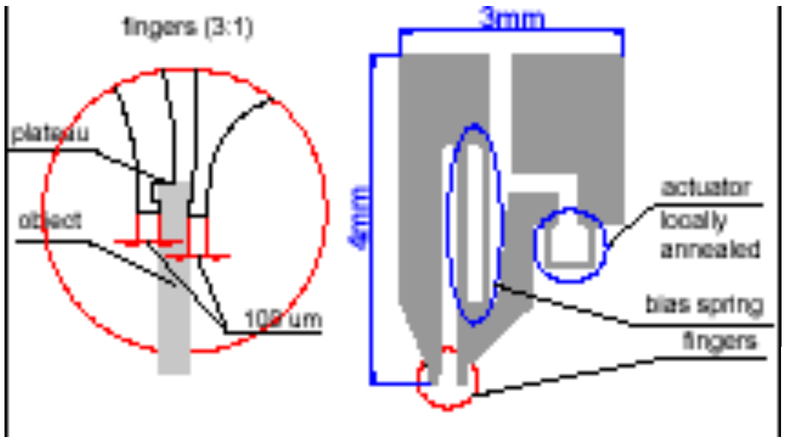
Microrobots 1 cm^3

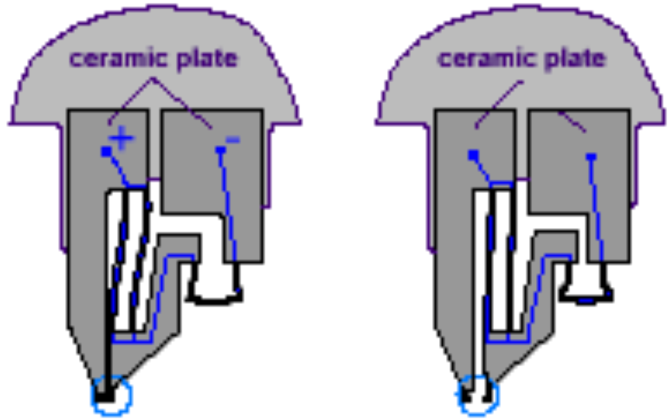






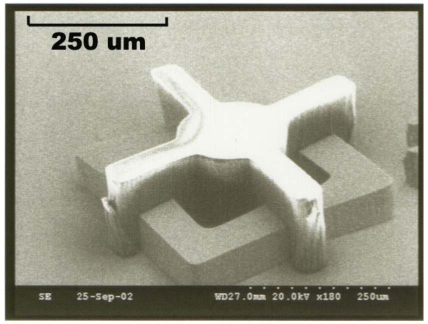
Gripper design

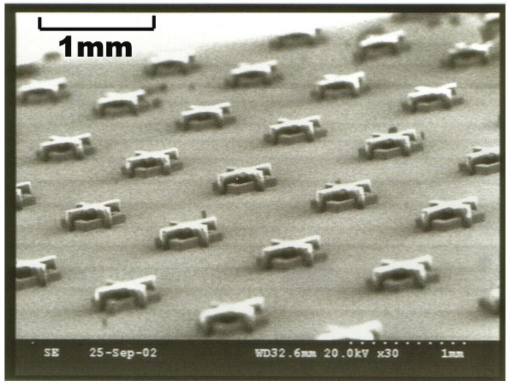


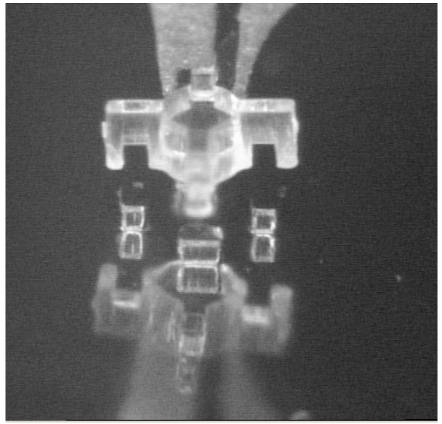


Application example of Shape Memory Alloys (SMA)

(Thèse EPFL Yves Bellouard)







Automated assembly of microparts for tissue engineering

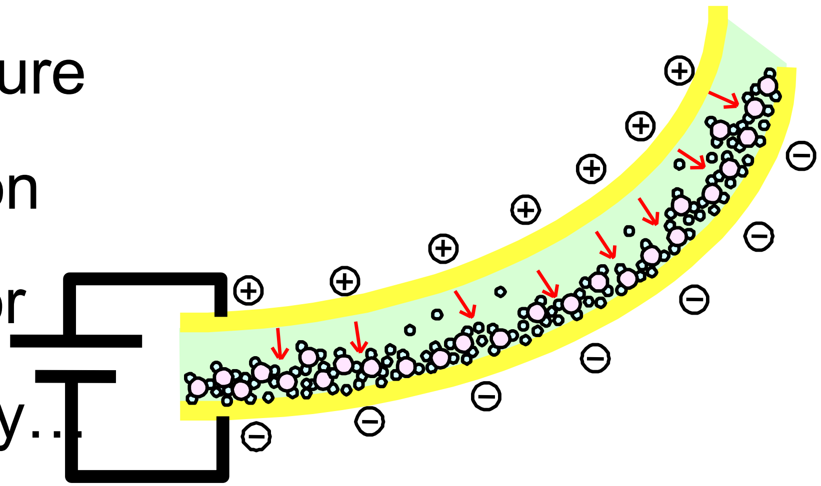
“Unconventional” actuators for grippers

- Gripping by capillary force
- by electrostatic force (e.g.for contact-free handling)
- by freezing liquid
- by thermoplastic glue
- by air flow (for contact-free handling)

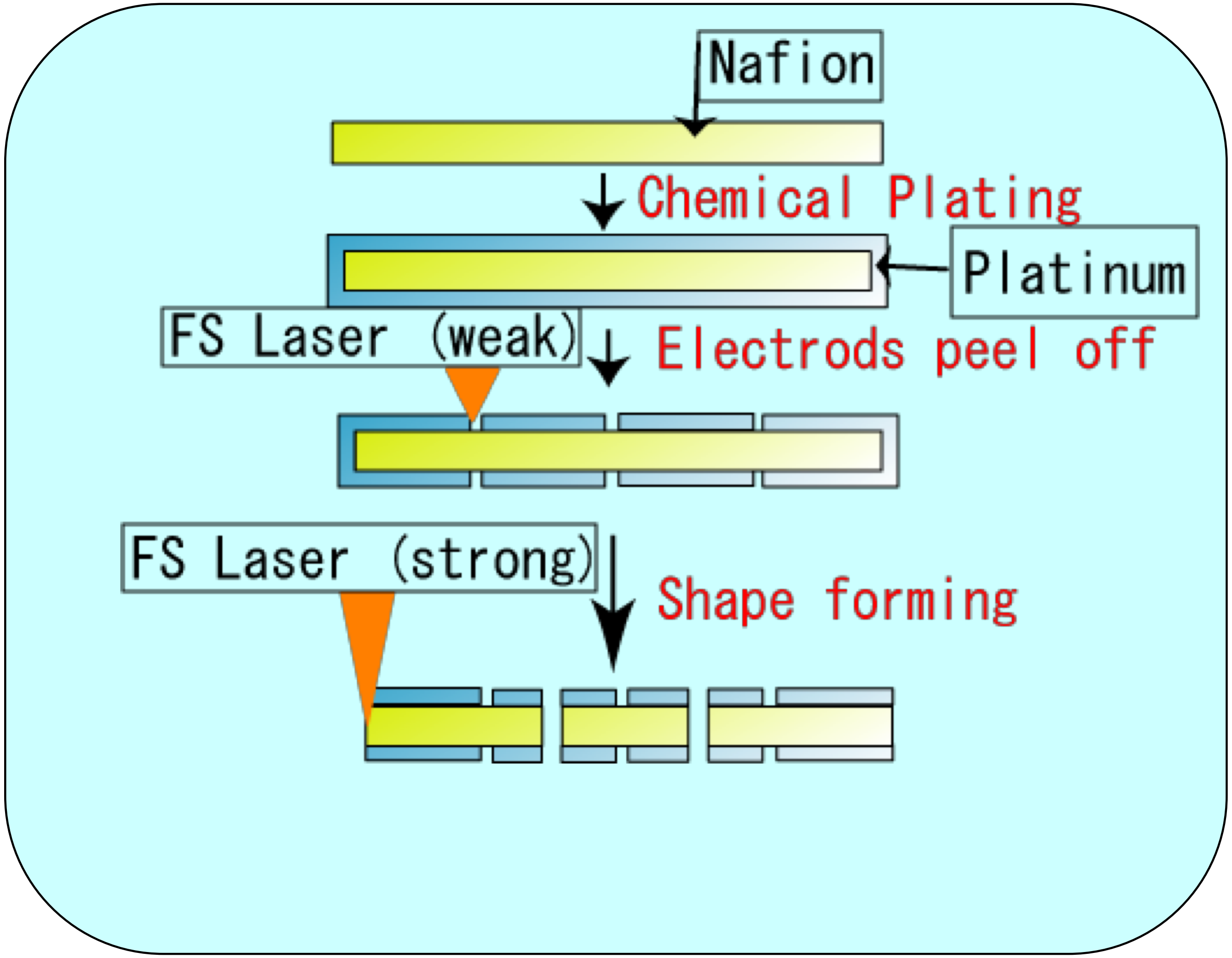
Ionic Polymer-Metal Composite IPMC
Electroactive polymer

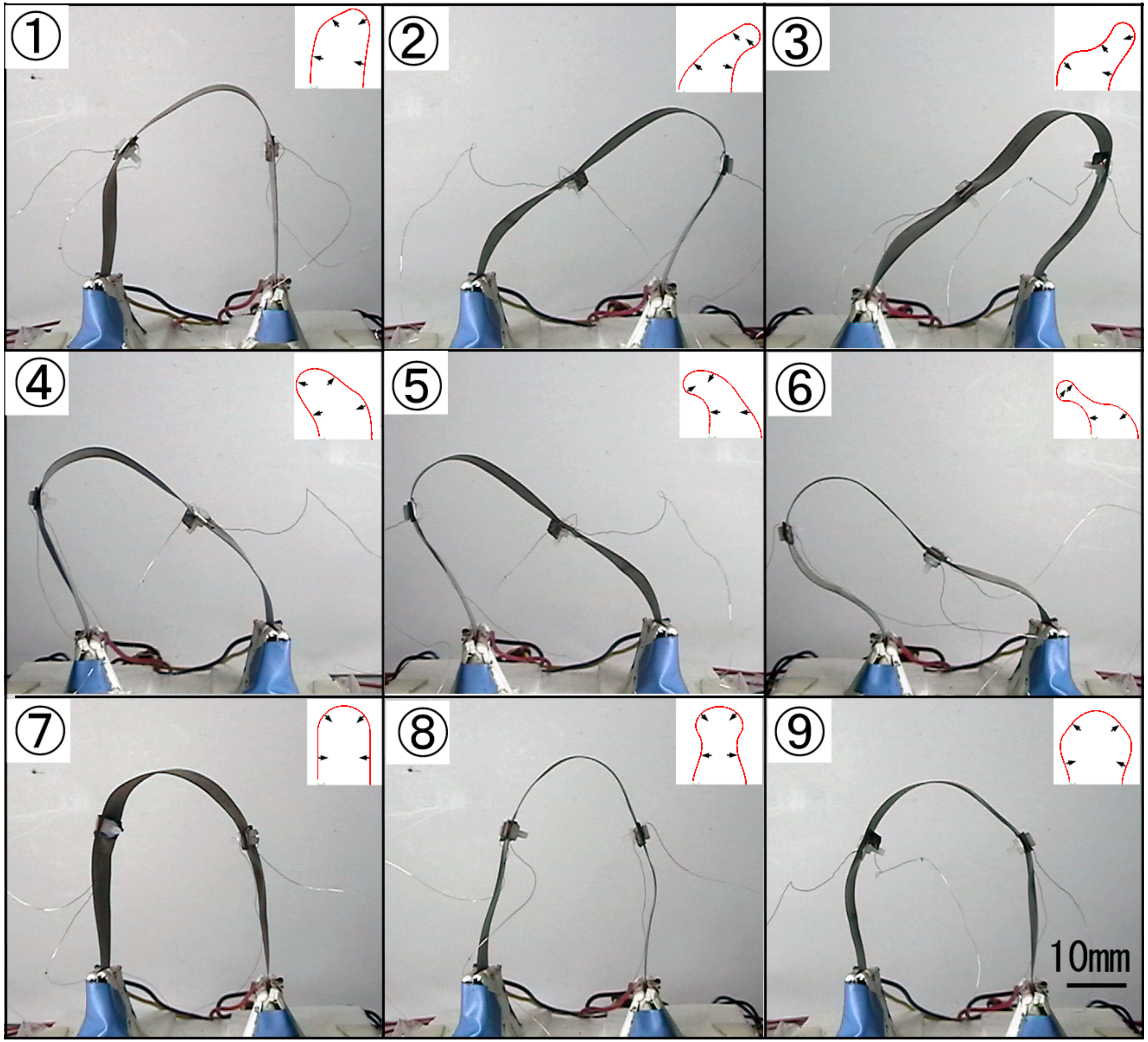
Materia
•Ion exchanging membrane
•Metal electrodes

1. High power to weight ratio
2. Self actuating smart structure
3. Multi DOF, batch fabrication
4. Possibility to use as sensor
5. Low voltage, high durability…

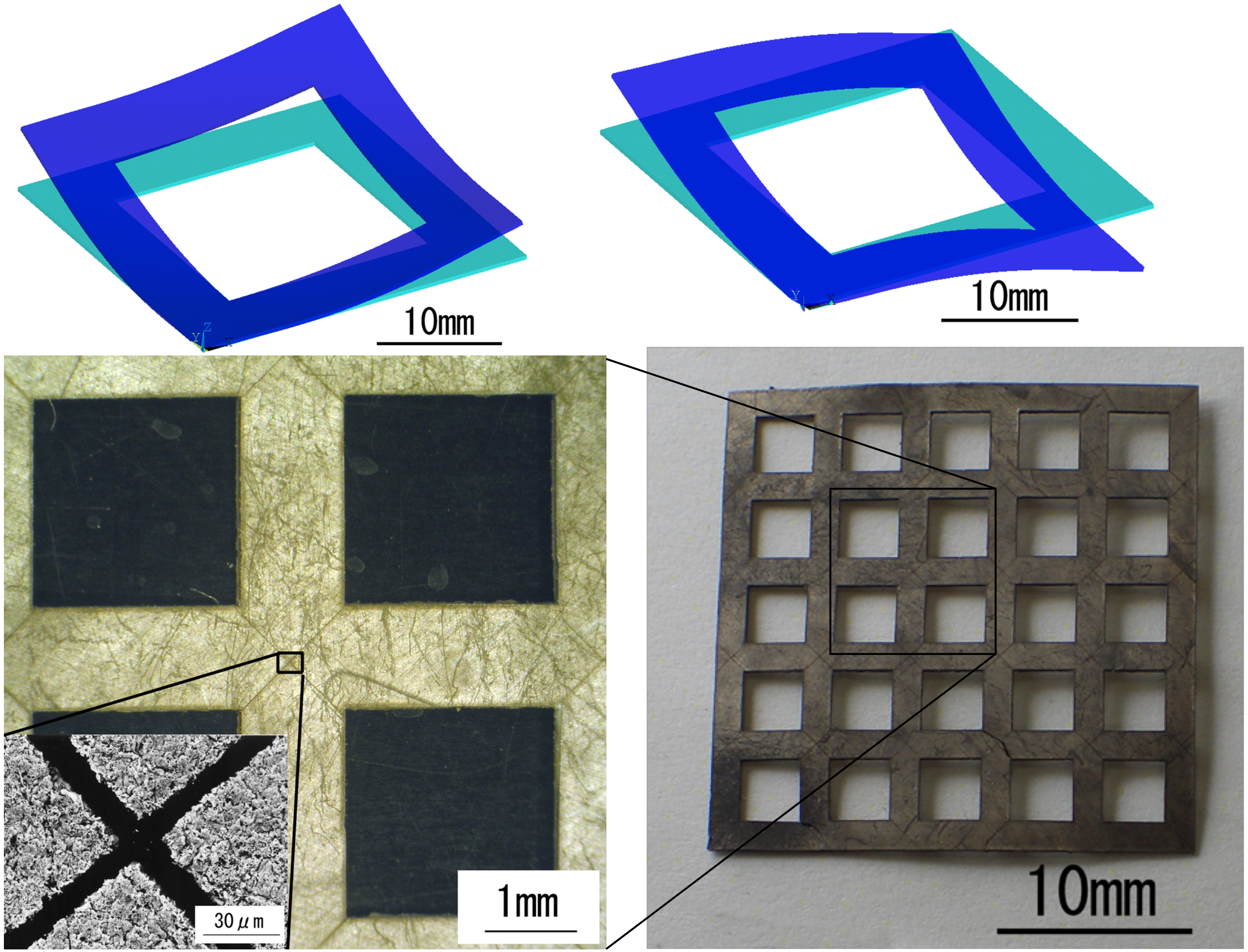


Process Flow




①
②
③
④
⑤
⑥
⑦
⑧
⑨
10mm

3-D object creator-Simulation and Fabrication-



Nanorobots ?

There's Plenty of Room at the Bottom

An Invitation to Enter a New Field of Physics

by Richard P. Feynman
December 29th 1959
at California Institute of Technology

http://www.zyvex.com/nanotech/feynman.html

Encyclopedia Brittanica on the head of a pin?

The head of a pin is 1.5 mm across.
Magnify by 25,000 diameters, gives the area of all pages of the Encyclopaedia.

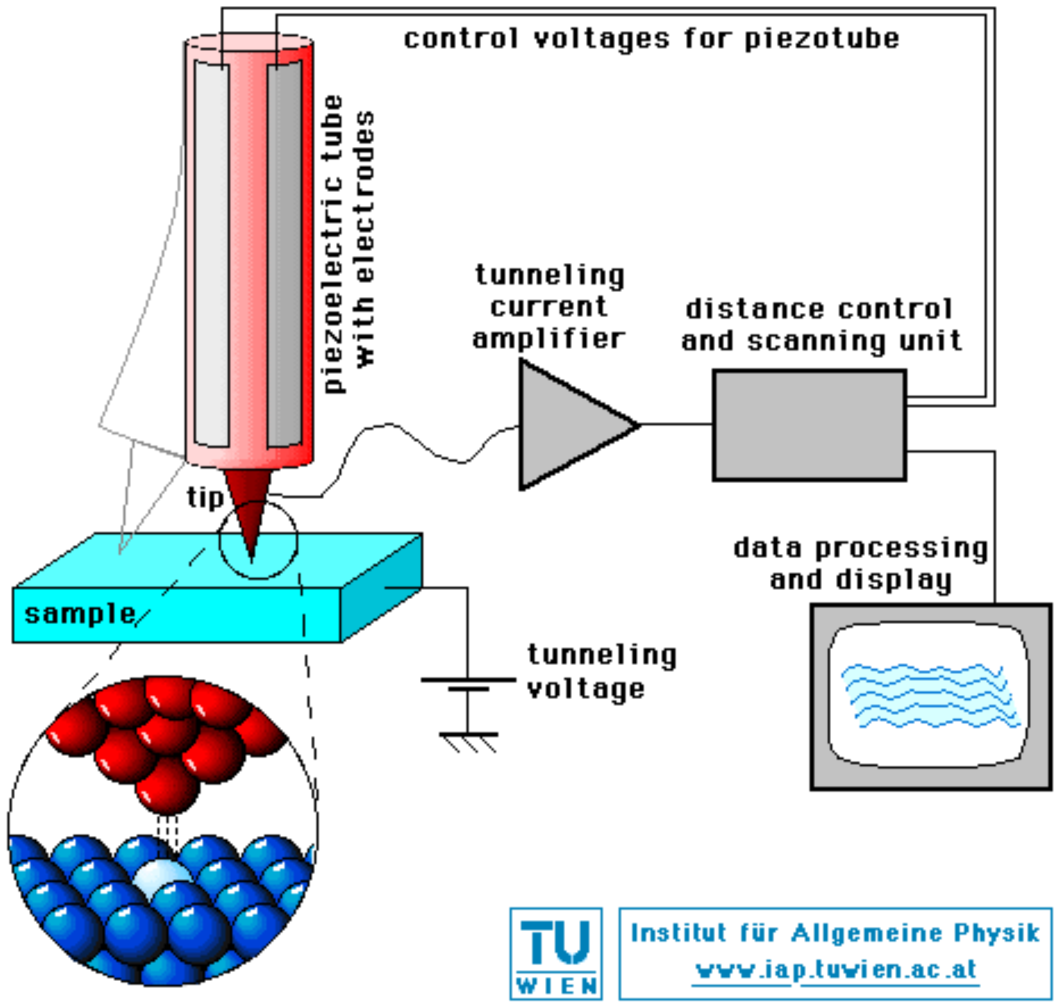
Is it possible to reduce the writing by 25'000?

The resolving power of the eye is about 200μ ---
that is roughly the diameter of a little dot on the fine half-tone photos.

Demagnify it by 25,000 times, still 80 angstroms in diameter---
32 atoms across, in an ordinary metal. In other words,
one dot (reduced 25'000 times) **still contains 1,000 atoms**.

Therefore there is enough room on the head of a pin to put all of the Encyclopaedia Brittanica.

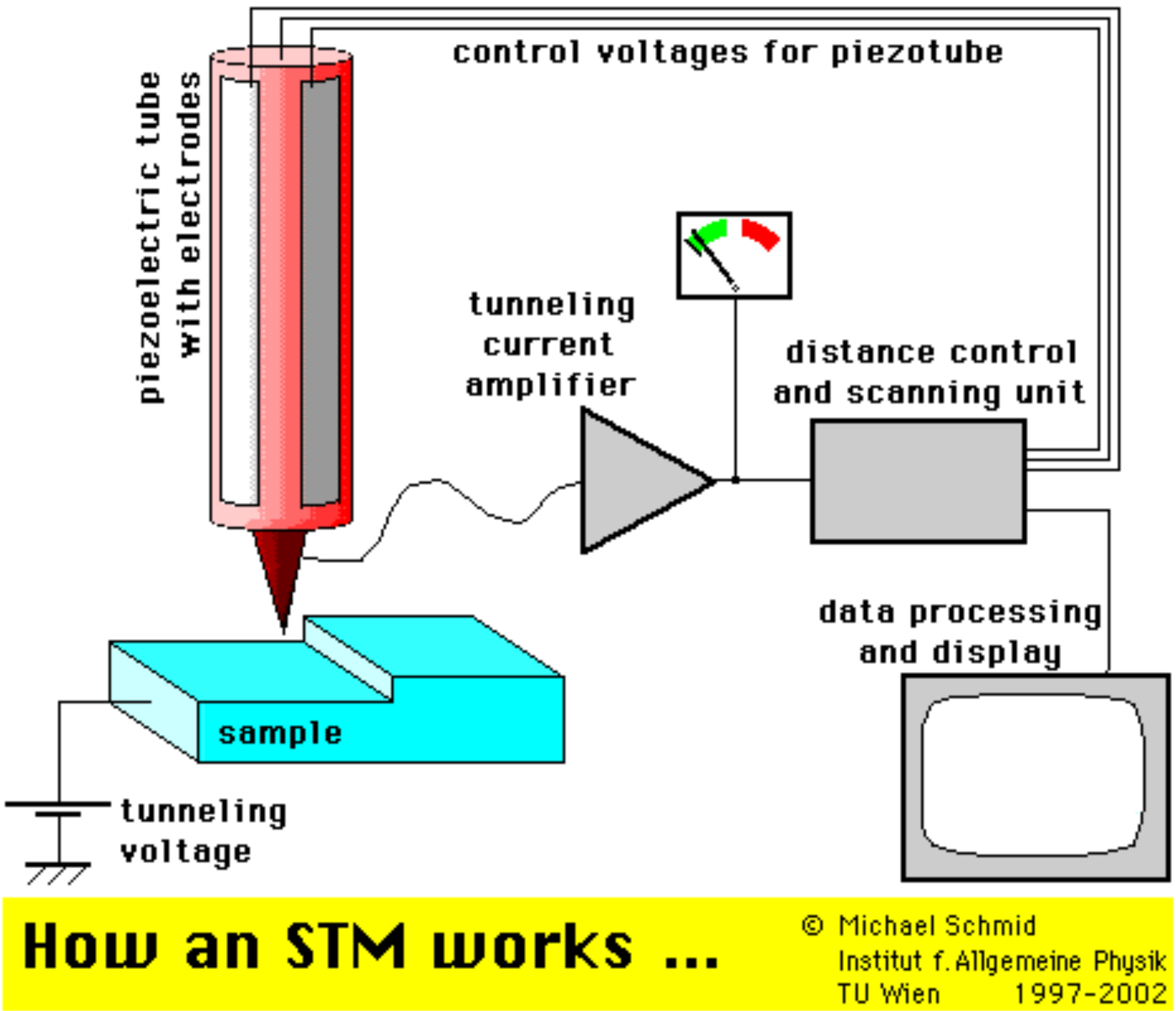
Scanning Tunneling Microscope STM



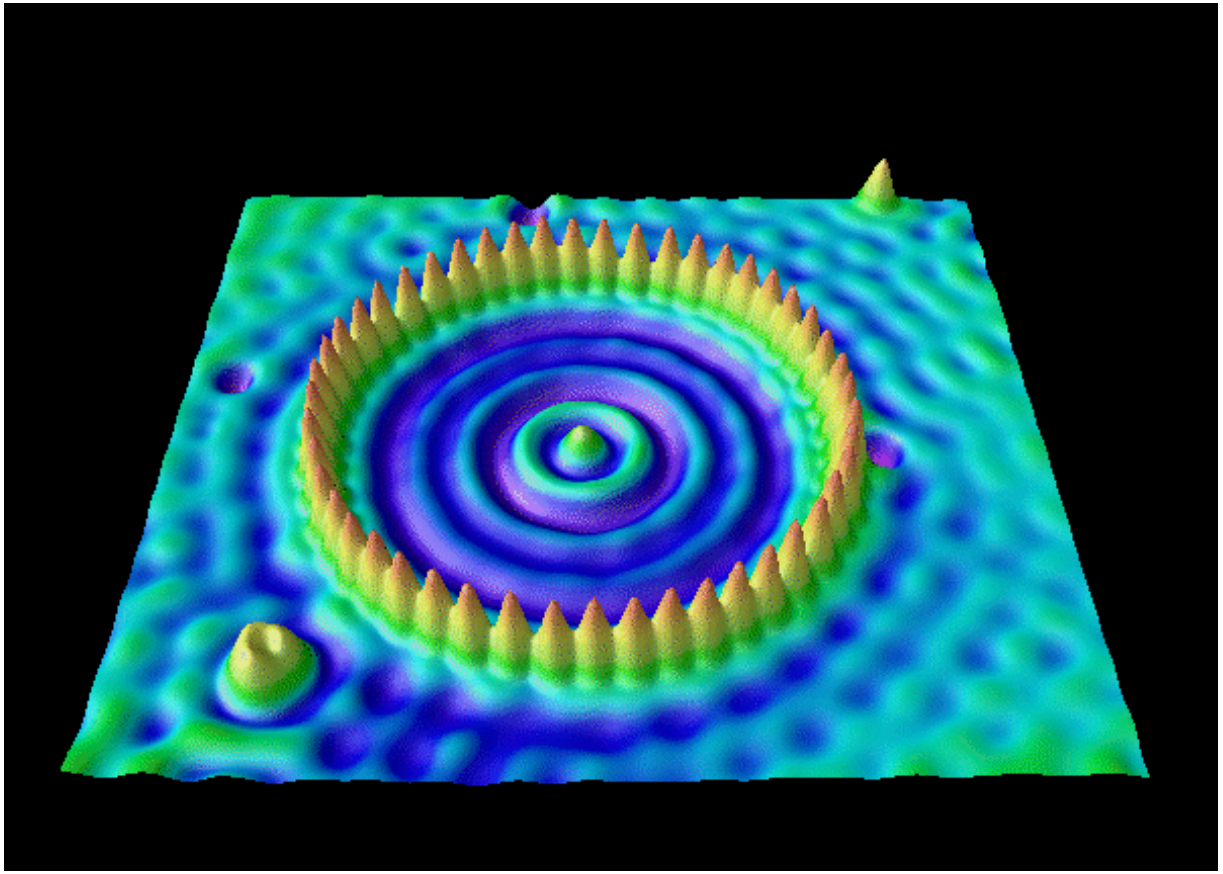
Prix Nobel 1986:
Laboratoires IBM, Rüschlikon

Heinrich Rohrer

Gerd Binnig

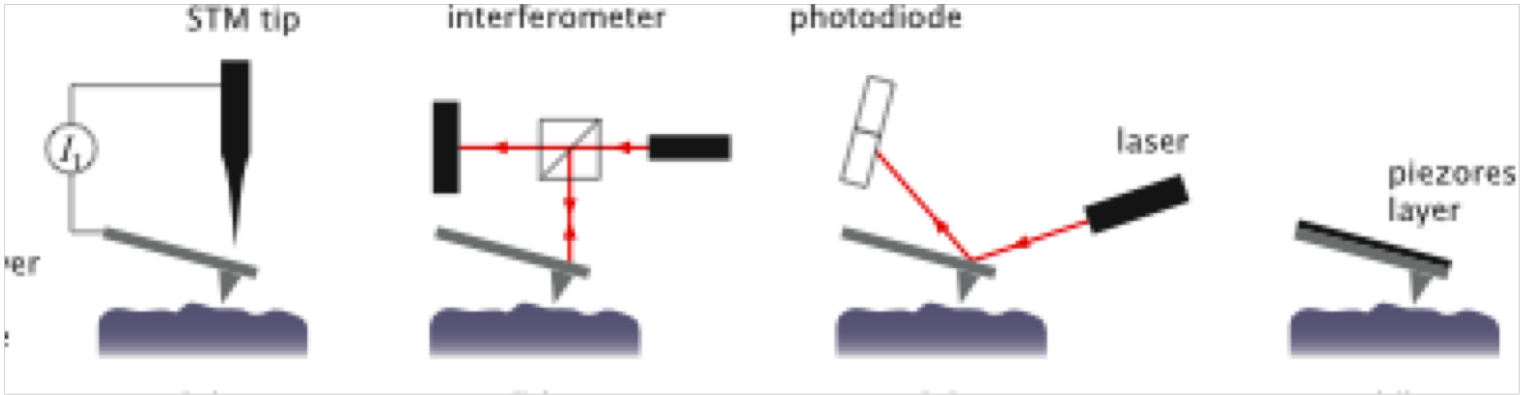

control voltages for piezotube
piezoelectric tube
with electrodes
tunneling
current
amplifier
distance control
and scanning unit
data processing
and display
sample
tunneling
voltage
How an STM works ...
© Michael Schmid
Institut f. Allgemeine Physik
TU Wien 1997-2002

Effets quantiques: P.ex.
Ondes de densité de charge
Image STM d'un anneau d'atomes de métal

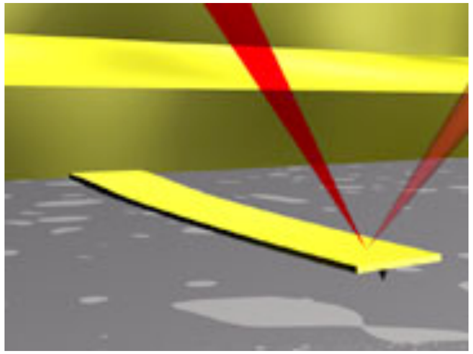


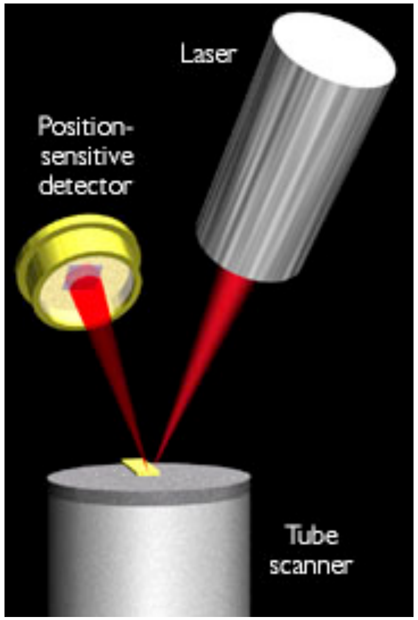
Atomic Force Microscope AFM

Microscope à effet de force atomique

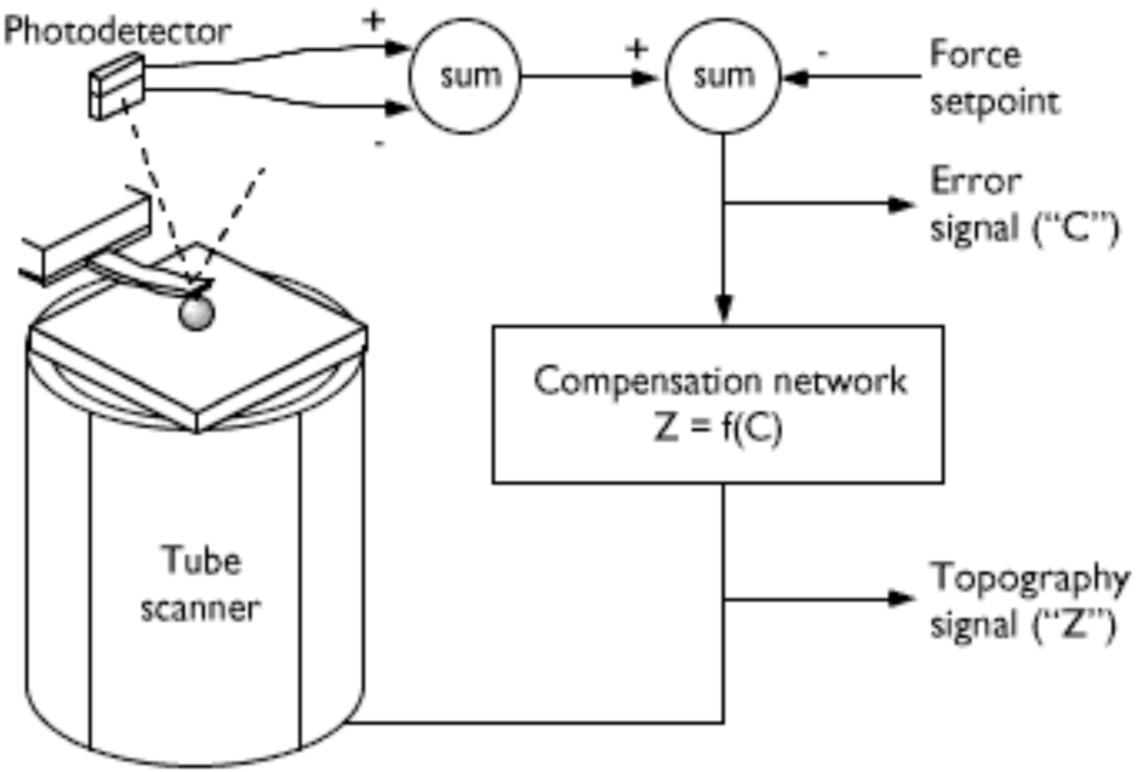


Atomic Force Microscope AFM





Boucle de contrôle, mode contact



Force constante – déflection constante

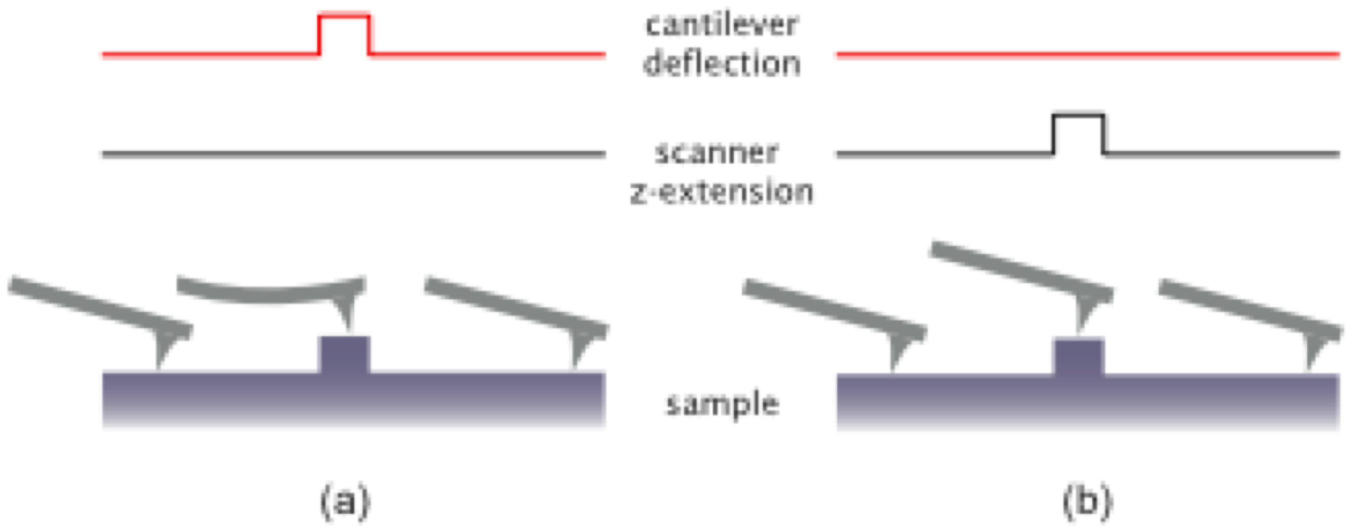
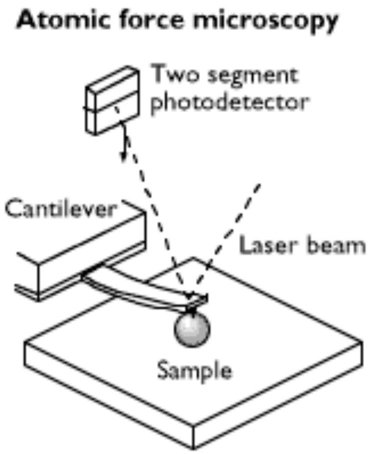
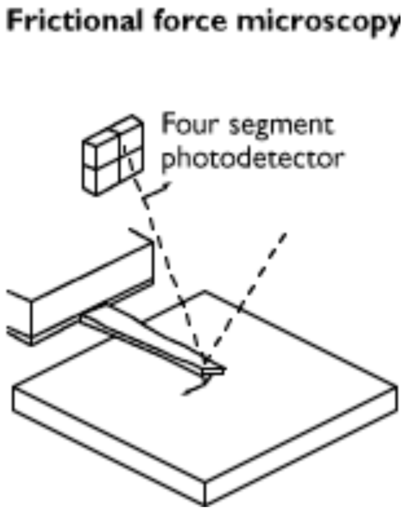
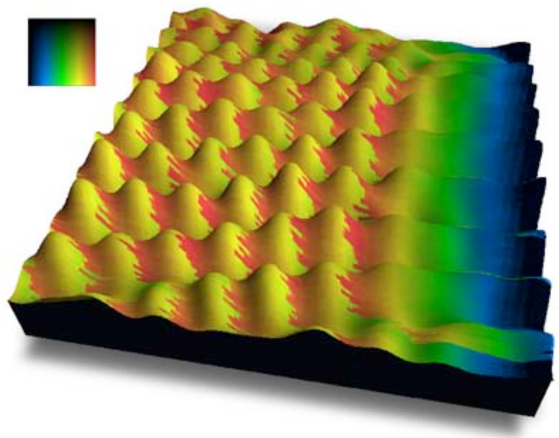


Fig. 2.7. (a) Constant-height (deflection) mode and (b) constant-force mode.

Autres modes

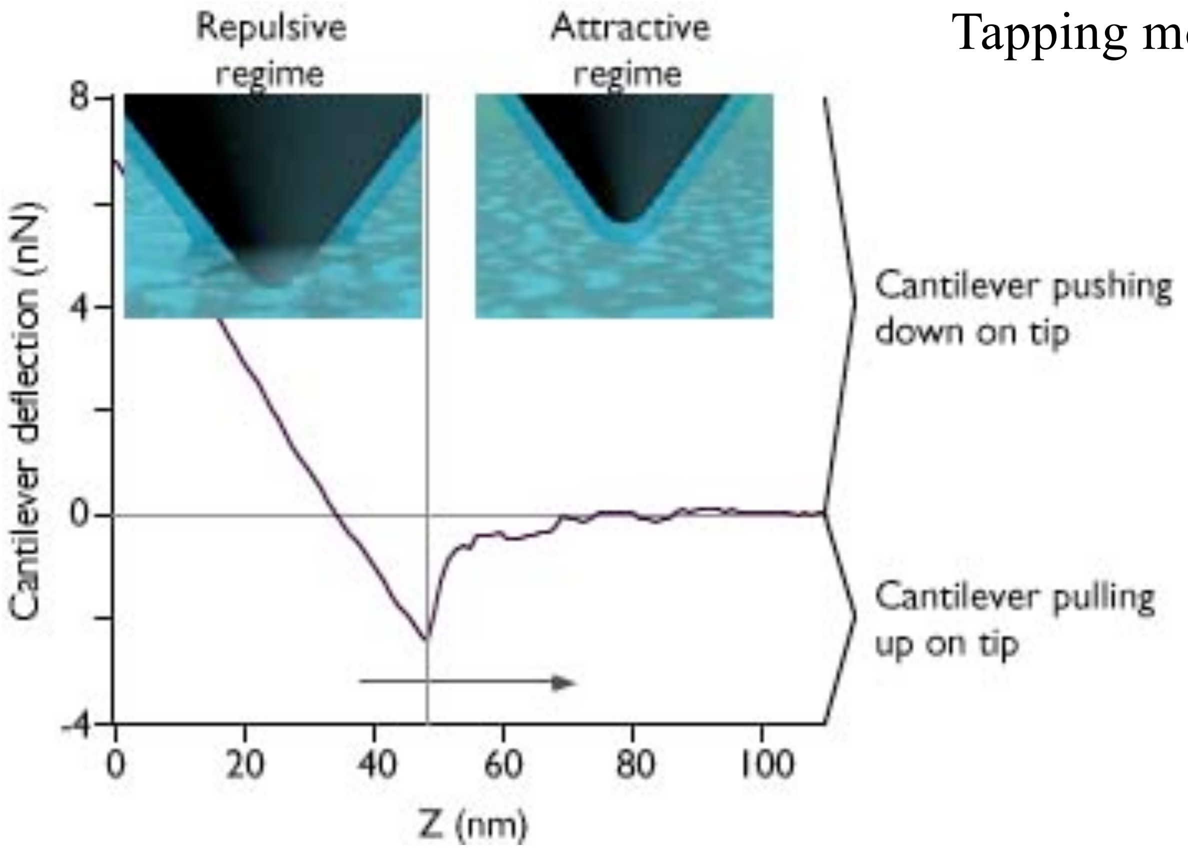




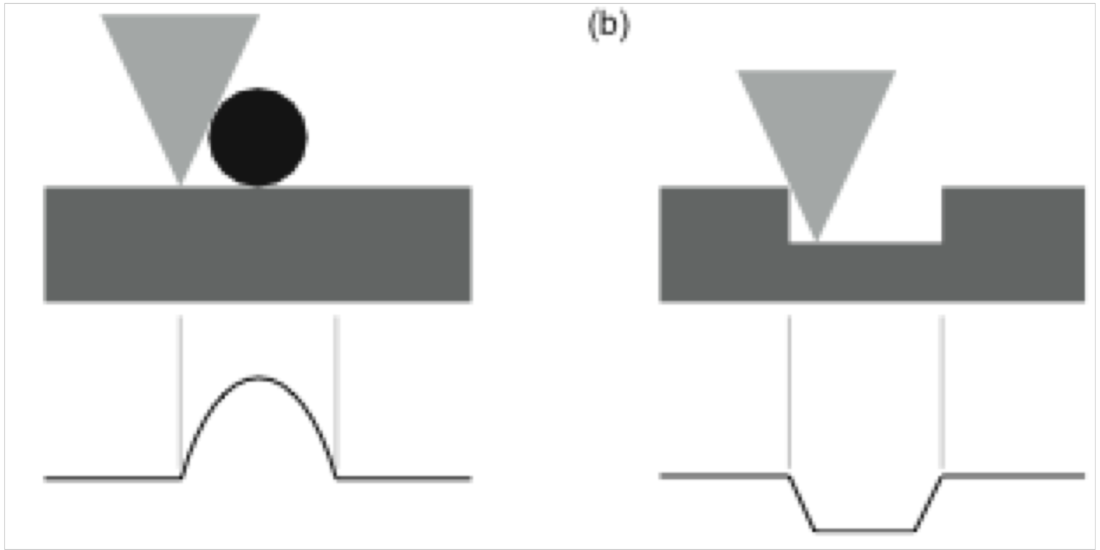


Force répulsive

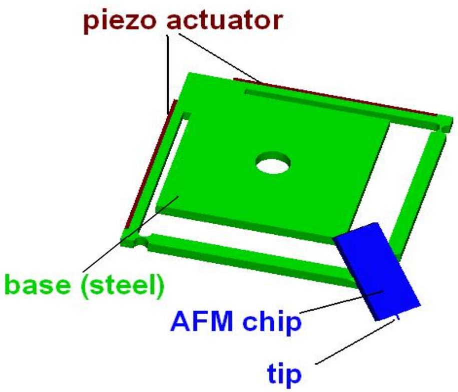
Non-contact mode
(Resonance,
Lock-in amp.)
Tapping mode …

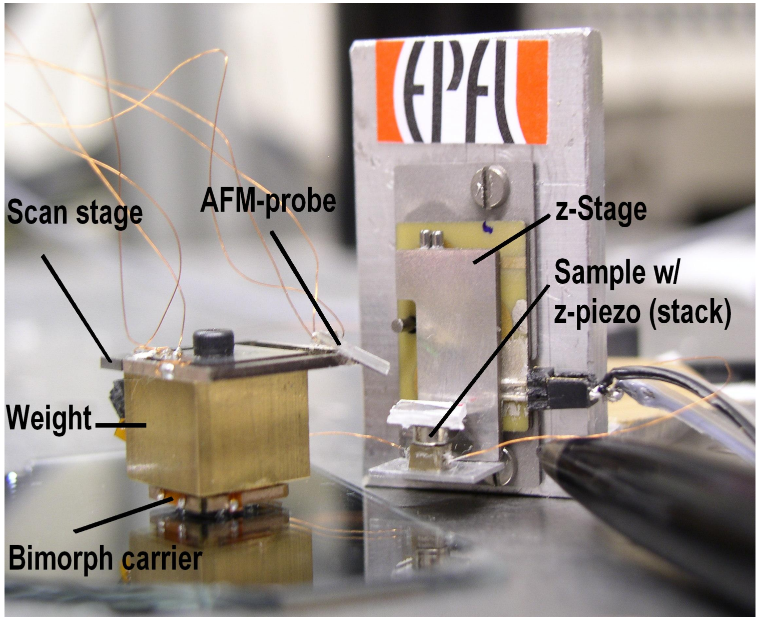


Convolution de la forme de la pointe avec l'échantillon

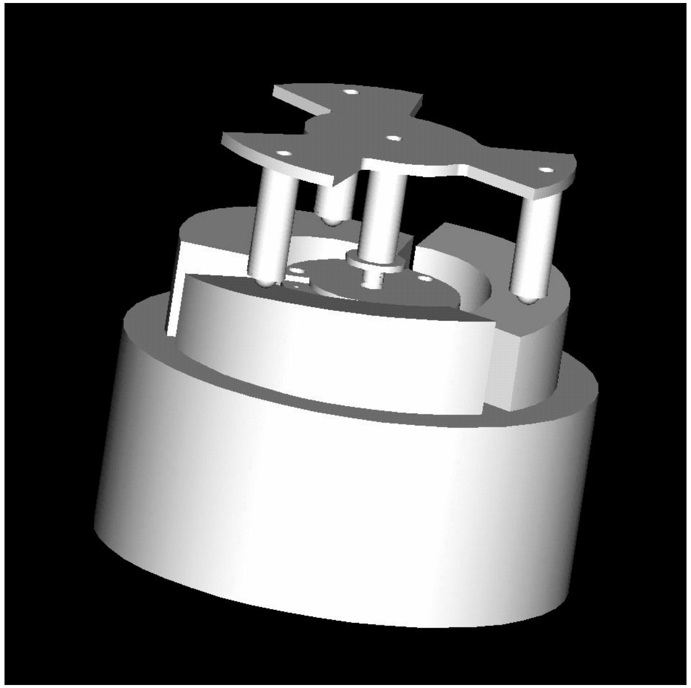


Scanner AFM


piezo actuator
base (steel)
AFM chip
tip


Scan stage
AFM-probe
z-Stage
Sample w/
z-piezo (stack)
Weight
Bimorph carrier
EPFL

Besocke's "Beetle" STM



Symetric structure:

4 pzt tubes
Three pillars,
central column
with scanning tip

First resonance 1.6 kHz
Thermal drift < 1 nm/min

Look for high eigen frequency!

Nanometer precision from 0° to 1000° K !