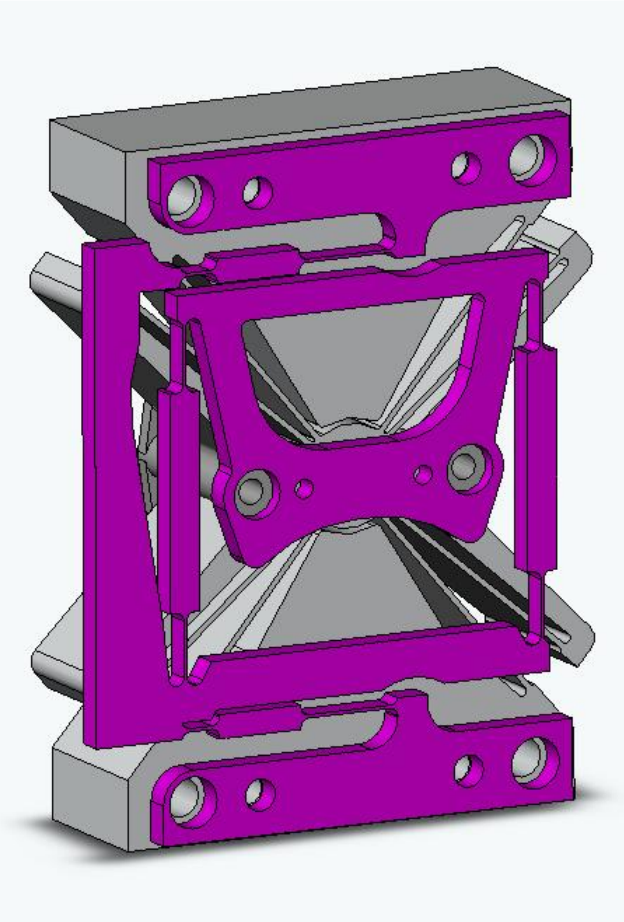
FLEXURE-MECHANISM DESIGN PRINCIPLES

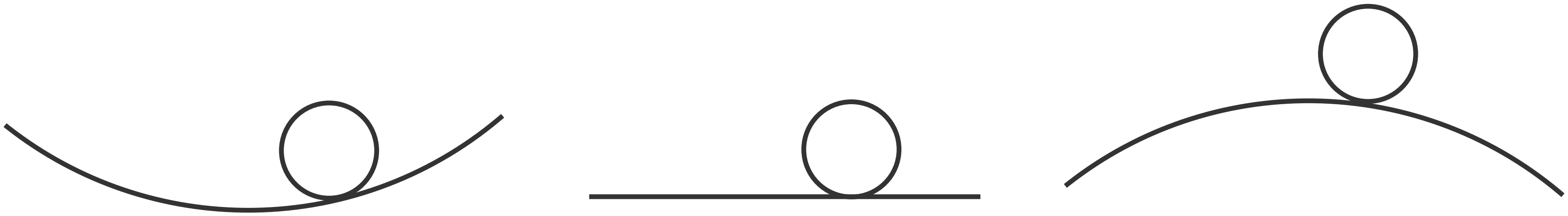


Prof. Simon Henein, Dr. Etienne Thalmann

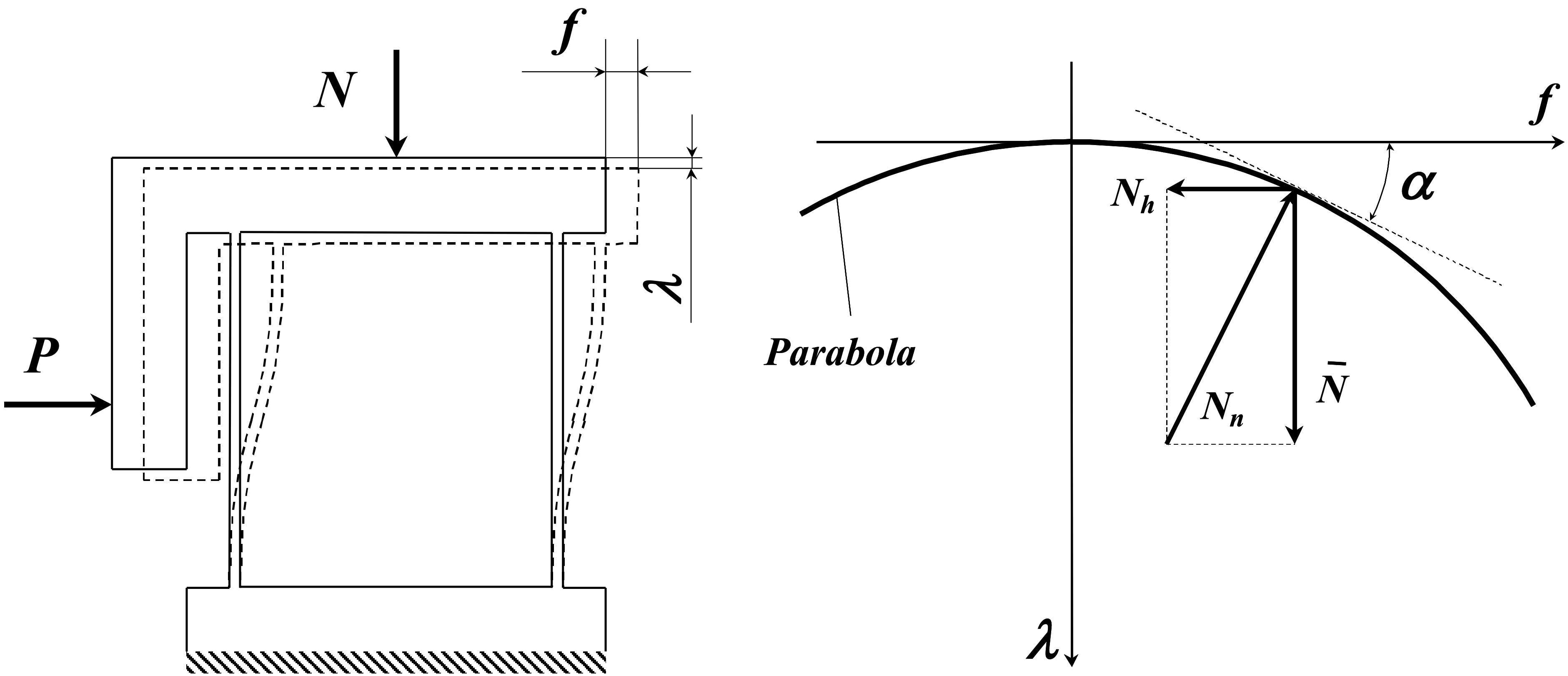
Contents

- Flexure-based mechanisms
  - Stiffness compensation and bistability
  - Rectilinear & circular mechanisms
  - Flexures with large reduction factors
  - Elastic energy storage maximization
  - Examples of flexure-based parallel robots
- Prospects & conclusion

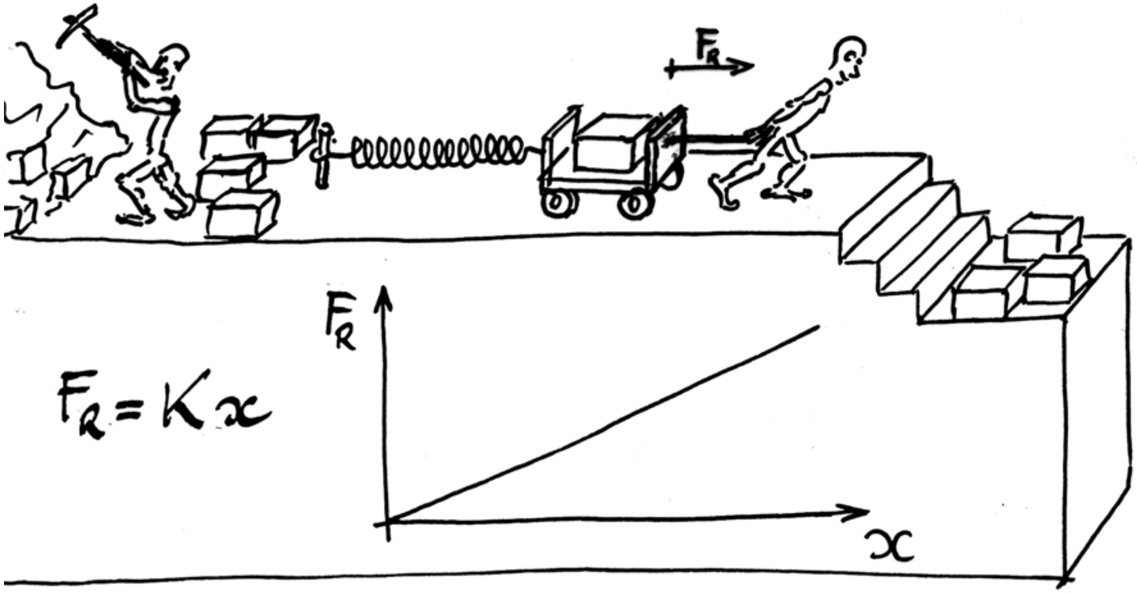
Stiffness compensation and bi-stability

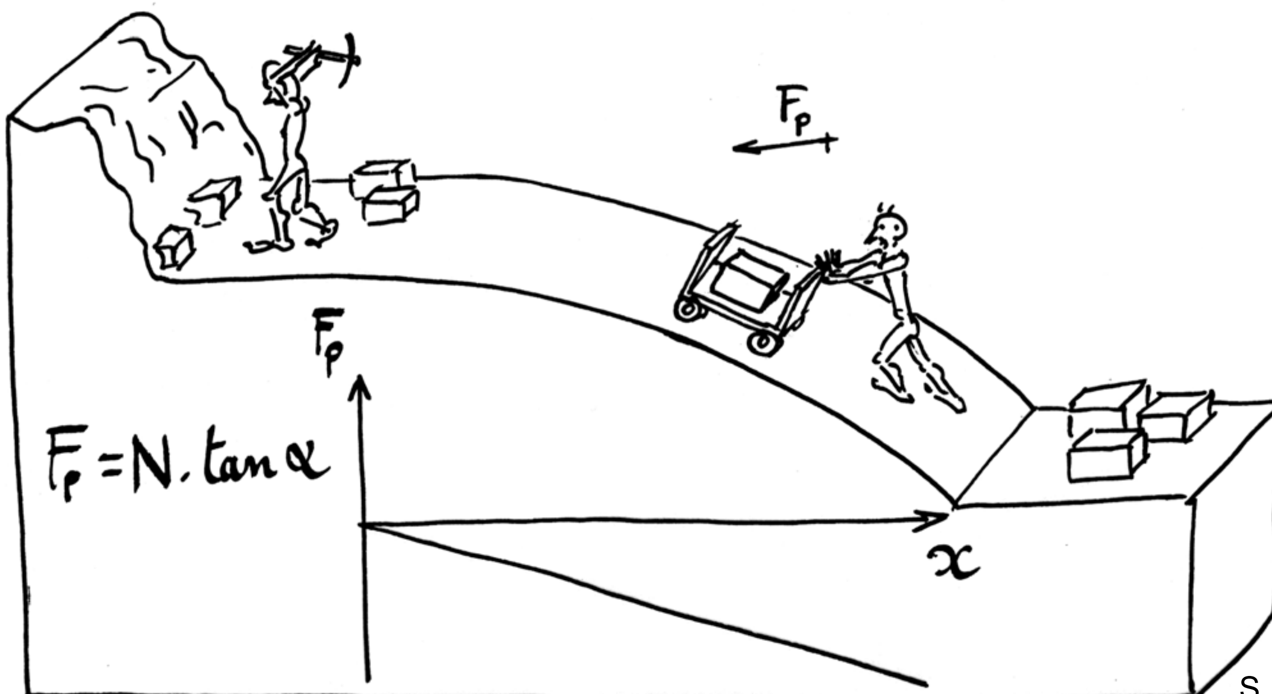


Parallel spring stage with transverse load

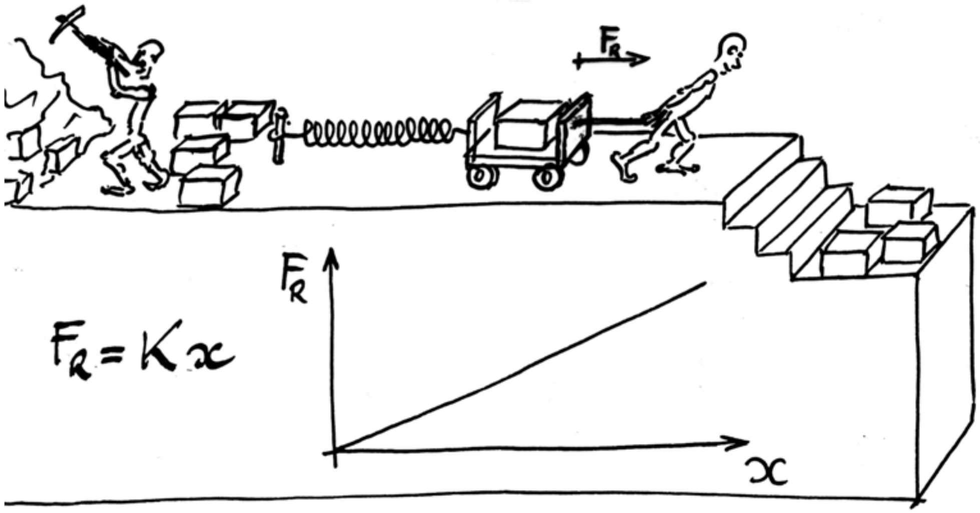


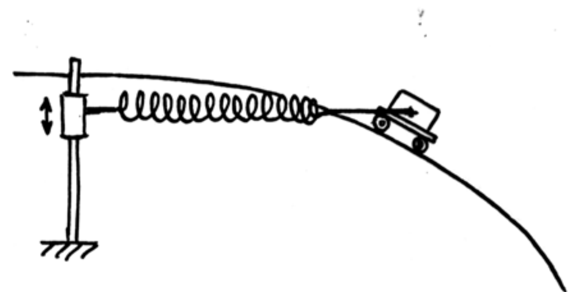
The stiffness $K = \dfrac{P}{f}$ depends on the load *N*

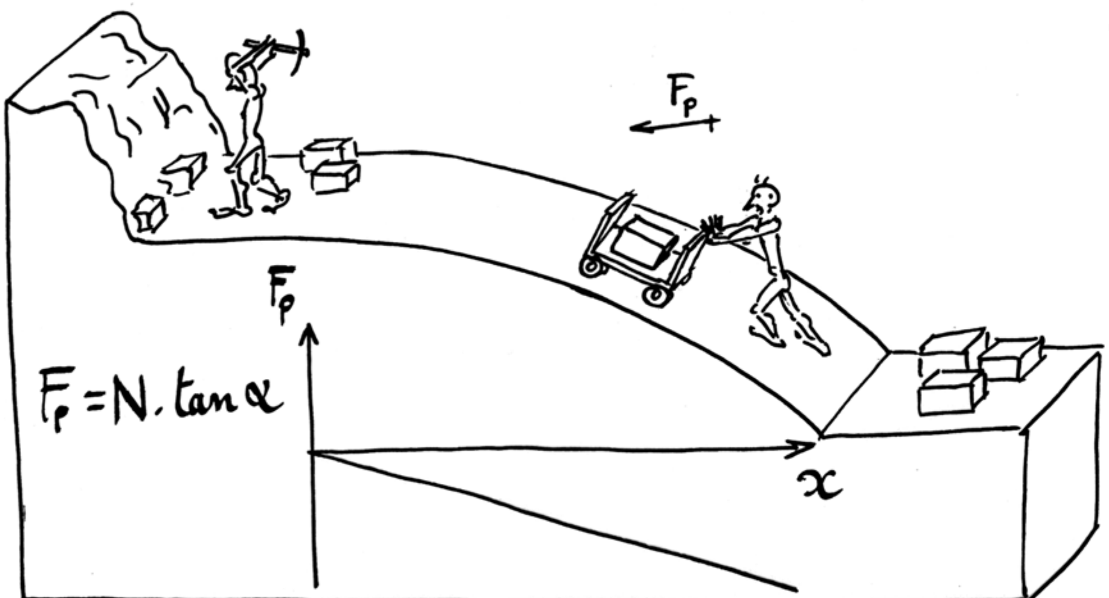

F_R
F_R
$F_R = K x$
x

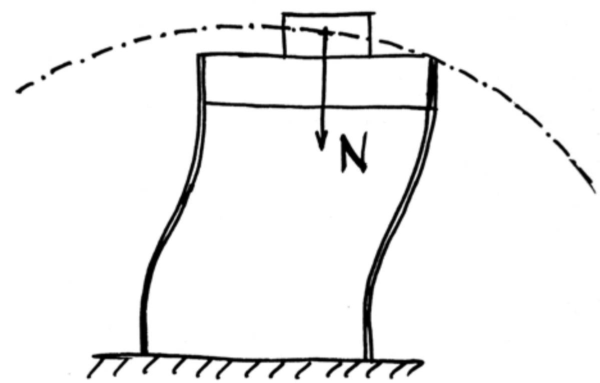

F_p
F_p
$F_p = N . \tan\alpha$
x

Zero stiffness flexure

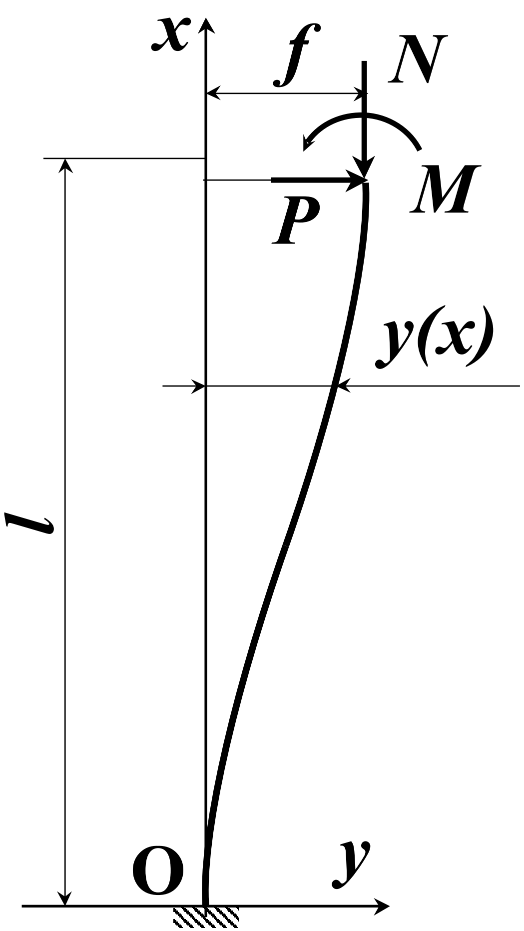


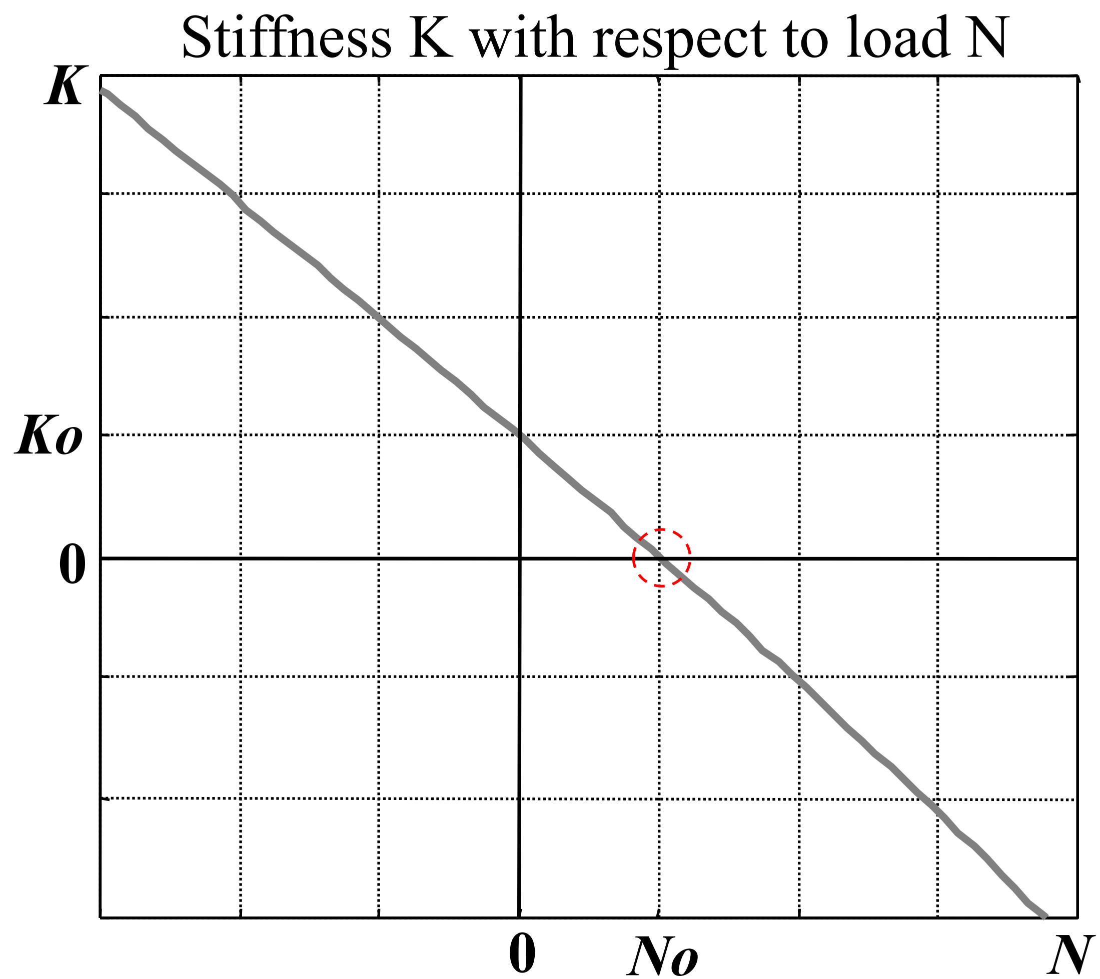


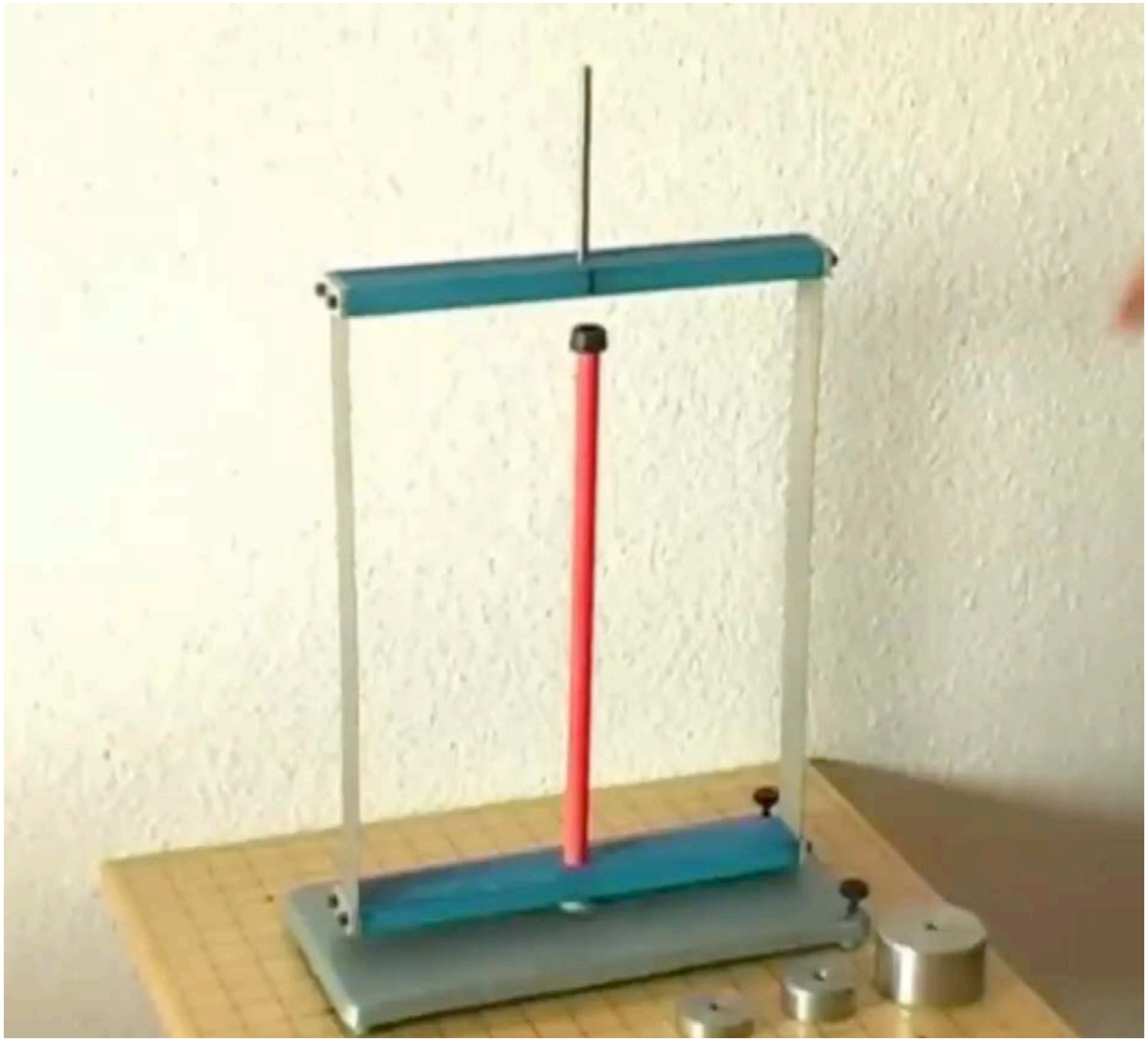




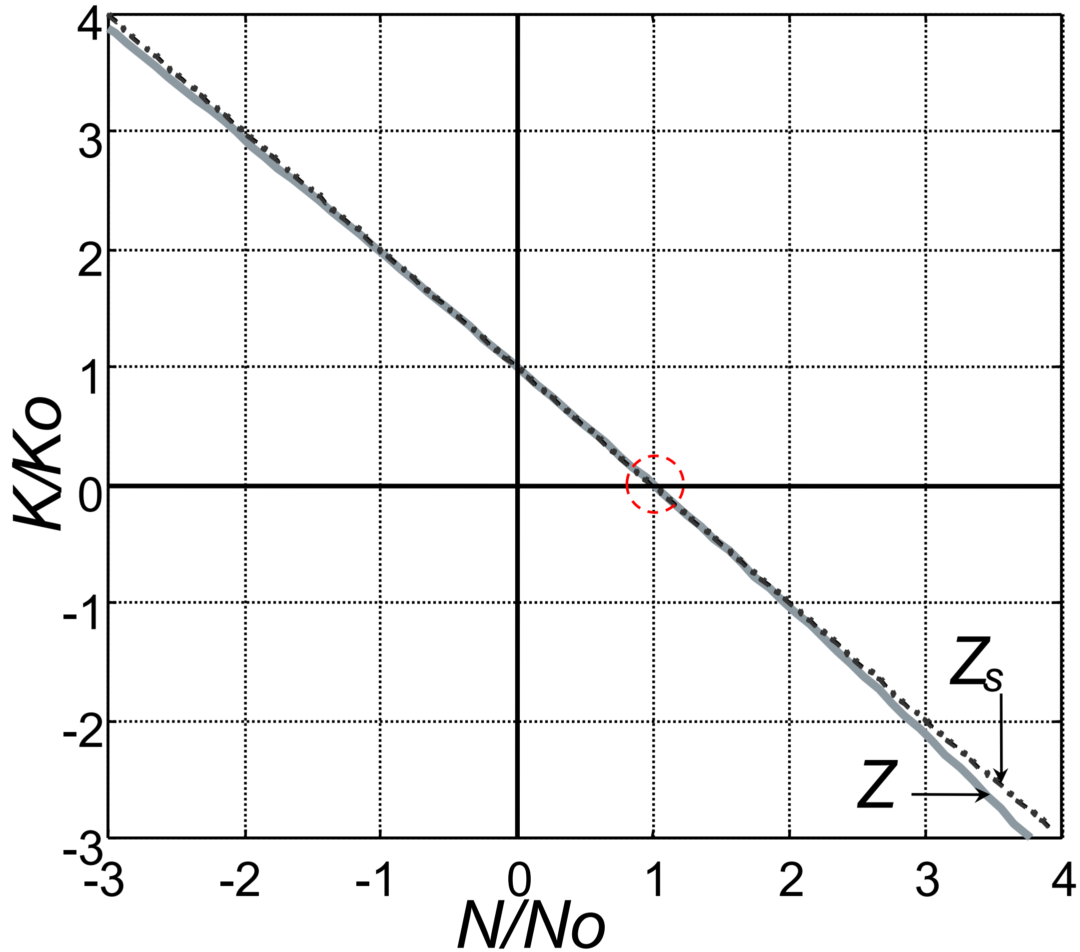
$$K = \frac{N}{\frac{2}{S}\tan\frac{Sl}{2} - l} \quad \text{with} \quad S = \sqrt{\frac{N}{EI}}$$







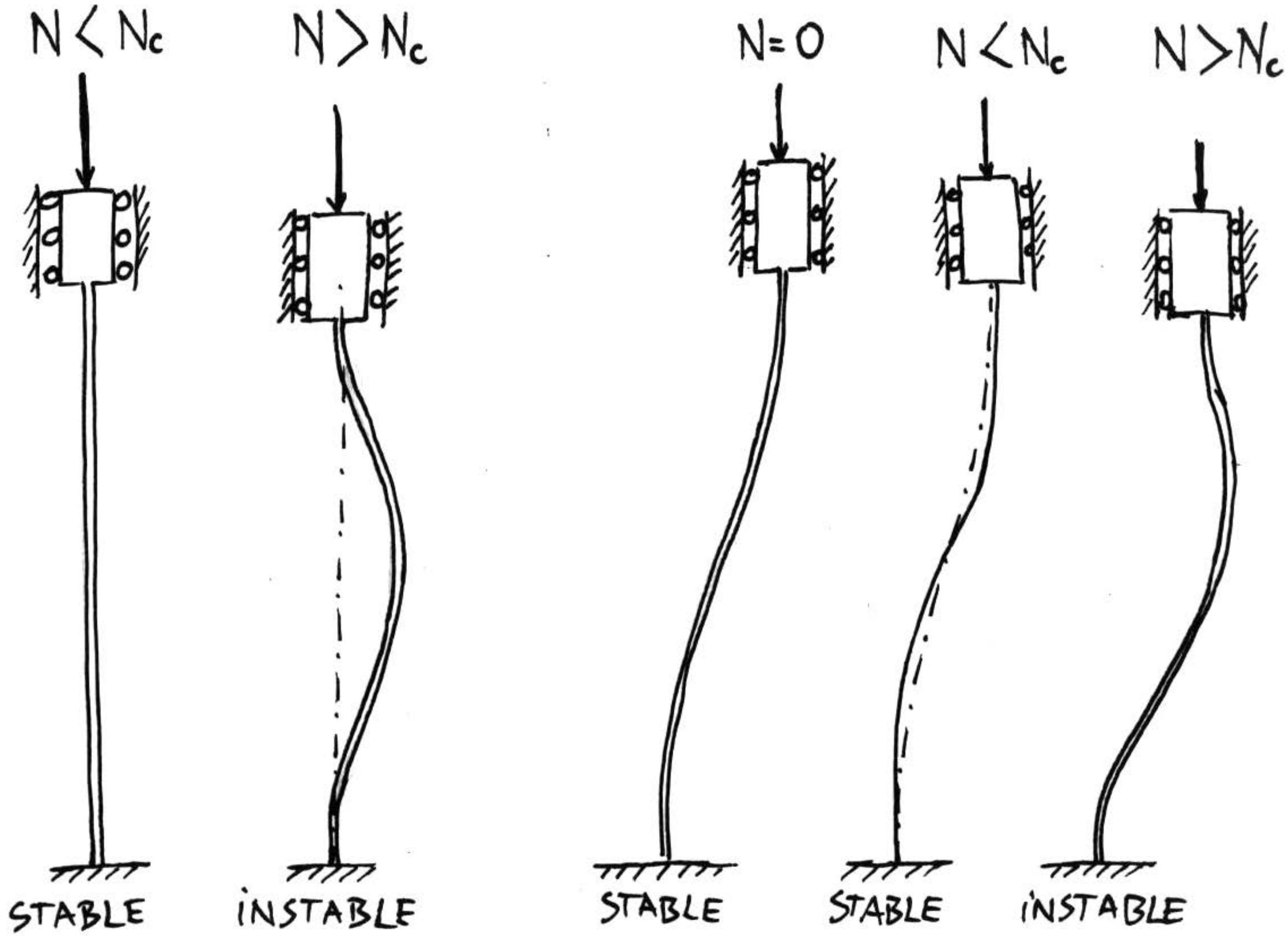
Normalized stiffness versus normalized load (for 2 blades)



$$N_c = 4N_o$$

$$K \cong K_0 - \frac{K_0}{N_0} N$$ with $$K_0 = \frac{24EI}{l^3}$$ and $$N_0 = \frac{2\pi^2 EI}{l^2}$$

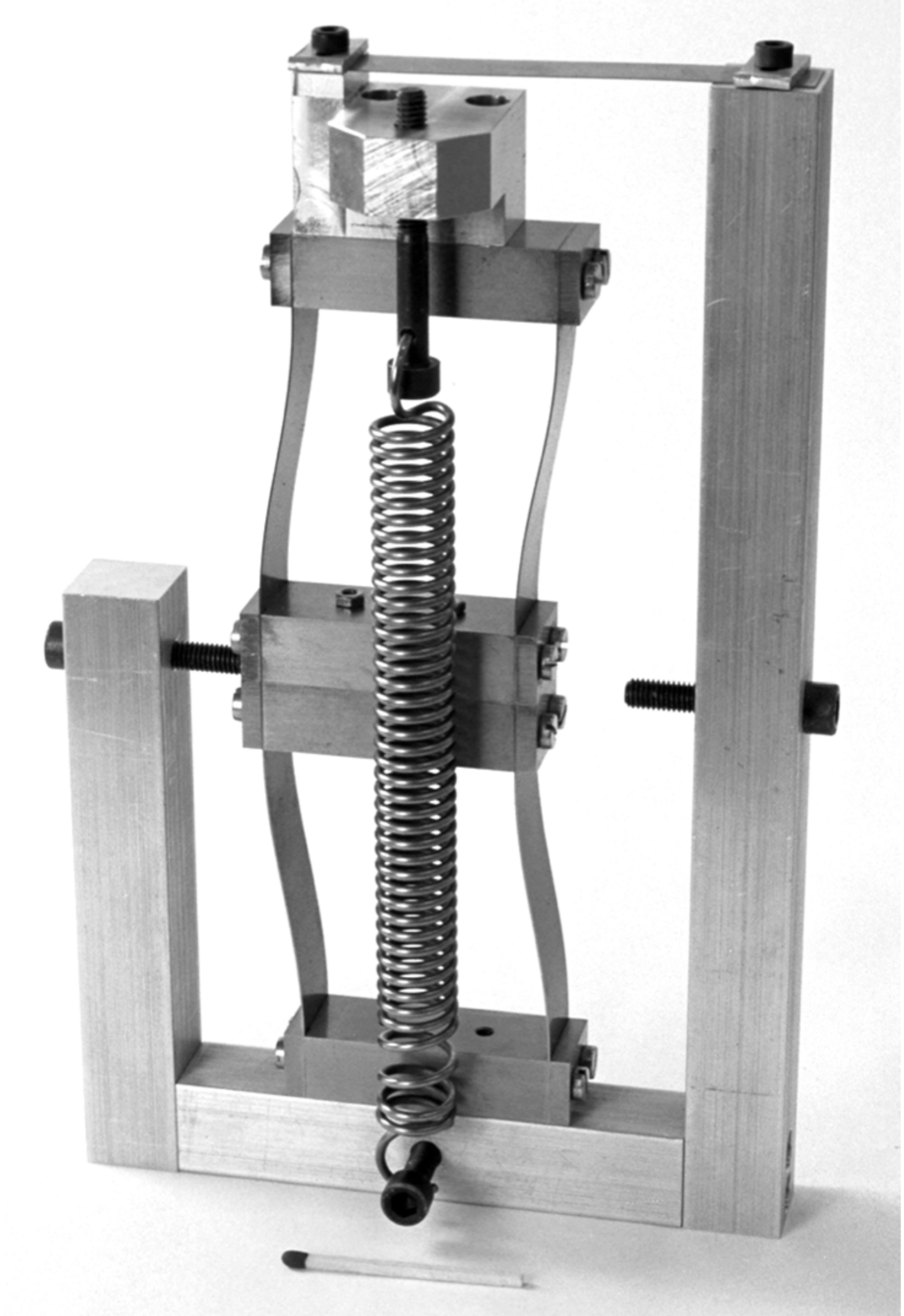
Buckling of a single blade



Critical Load: $$N_c = \frac{4\pi^2 E I}{l^2}$$

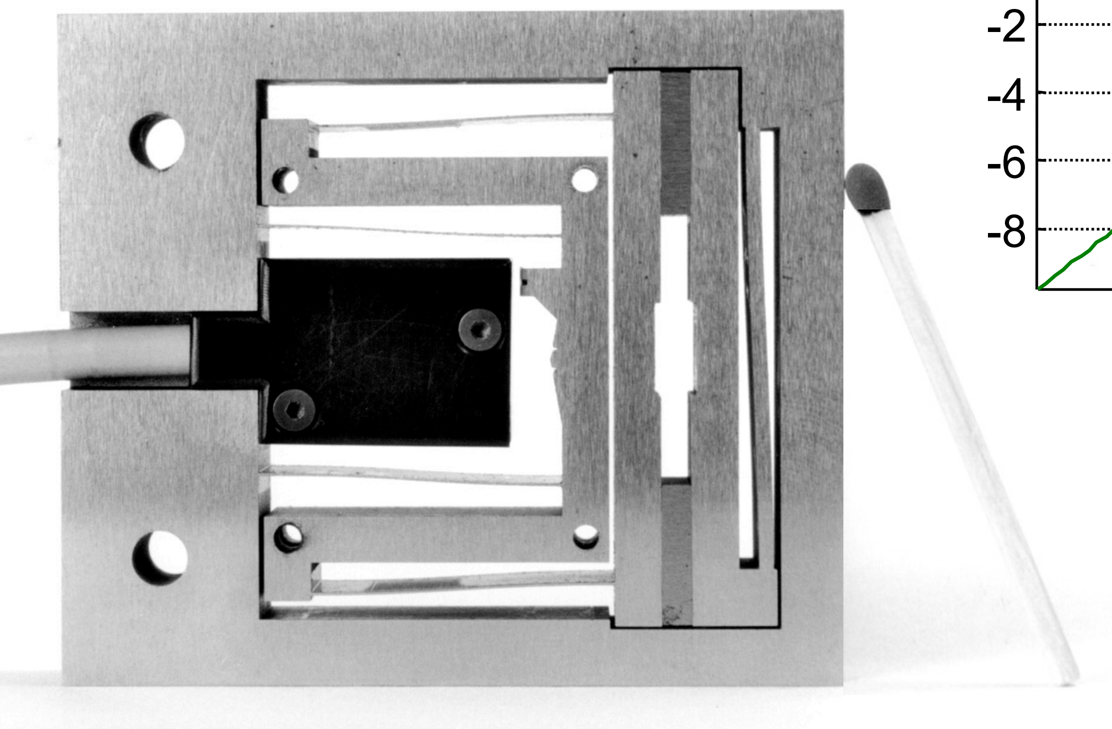
Tunable stiffness translation bearing

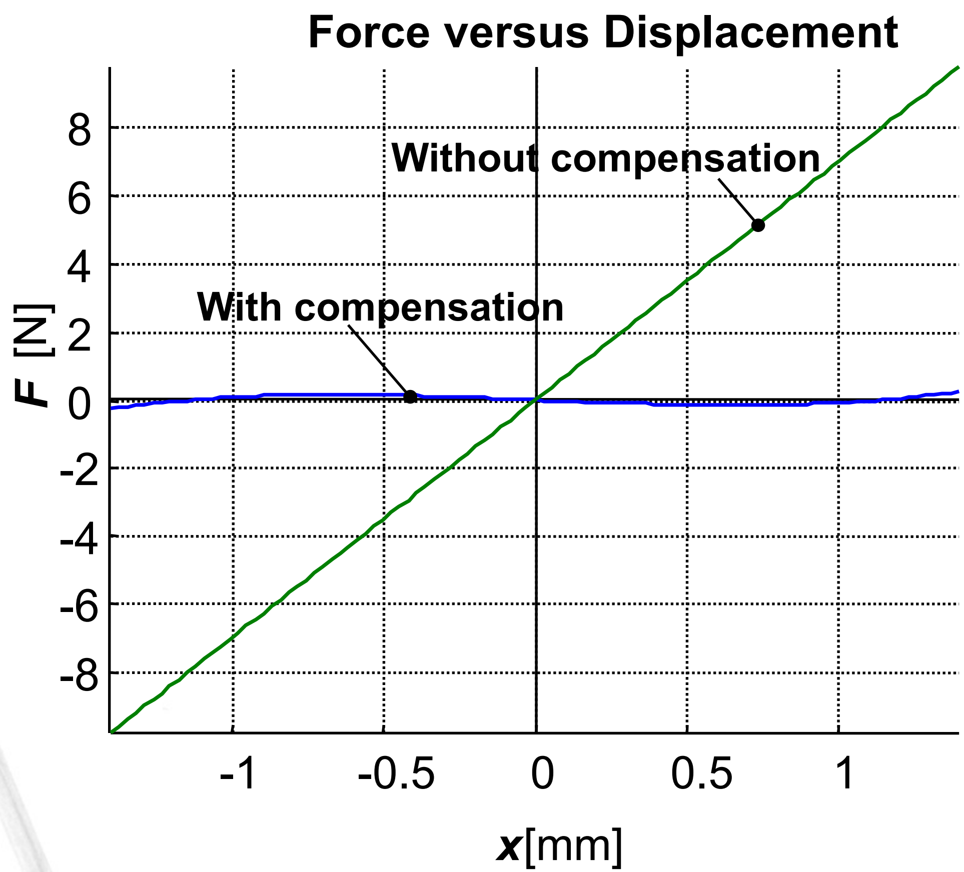
Demonstrator



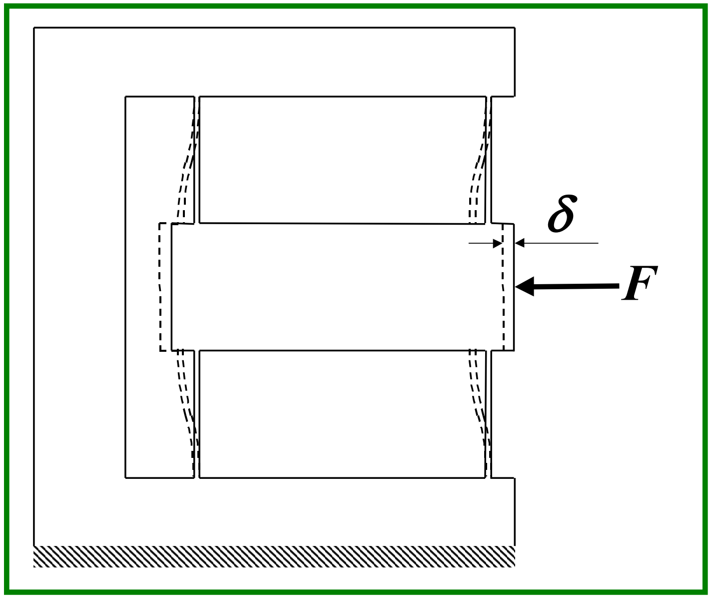
Tunable stiffness translation bearing

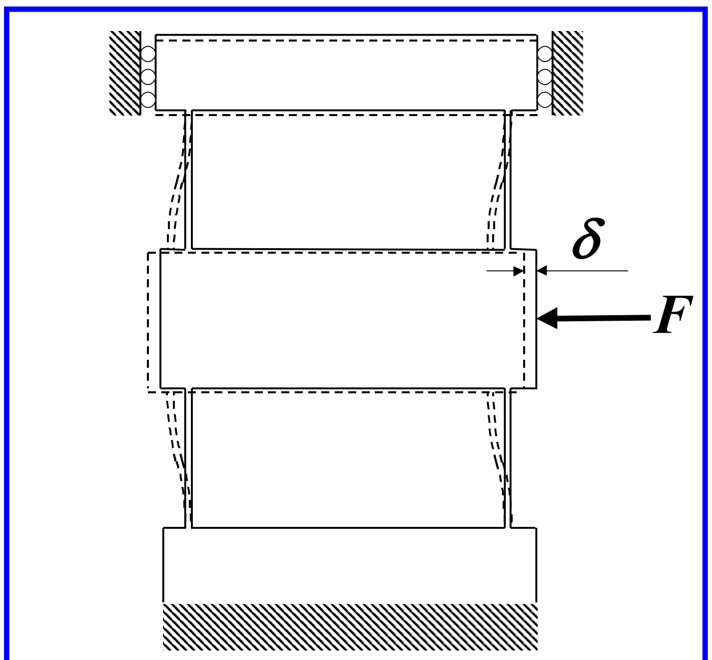
Monolithic design

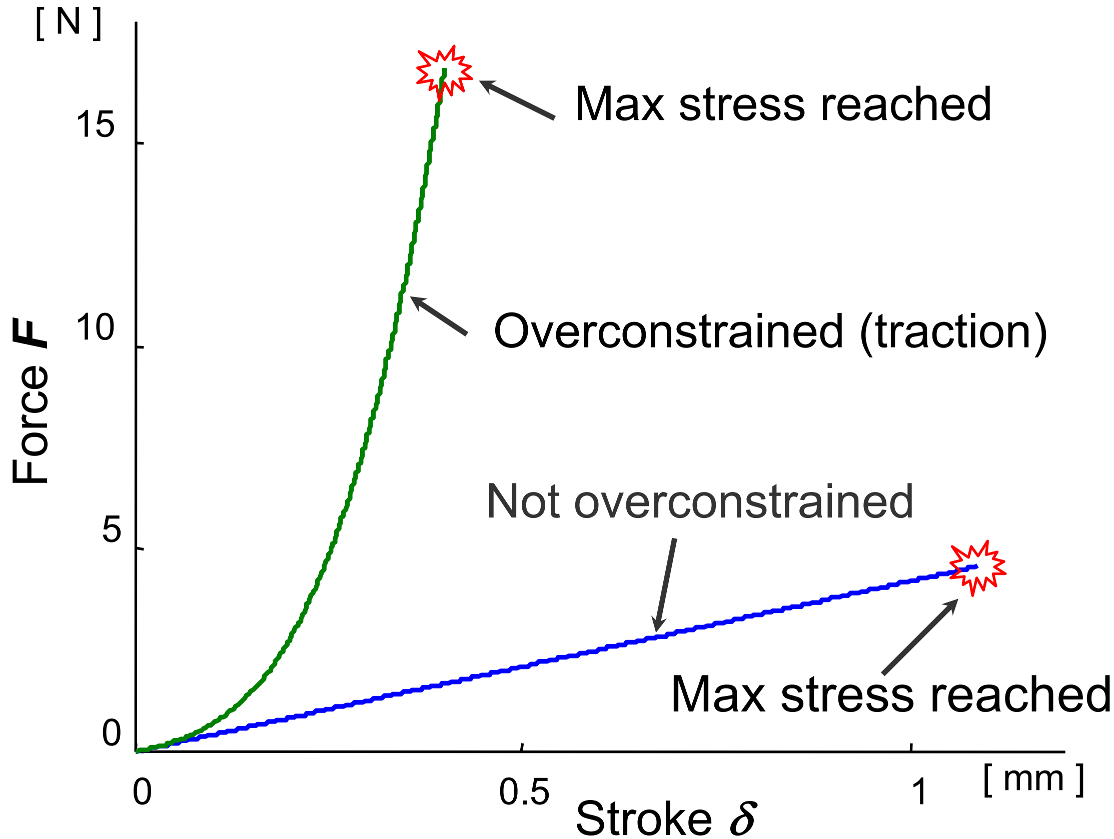




Overconstrained linear stage (4 blades)



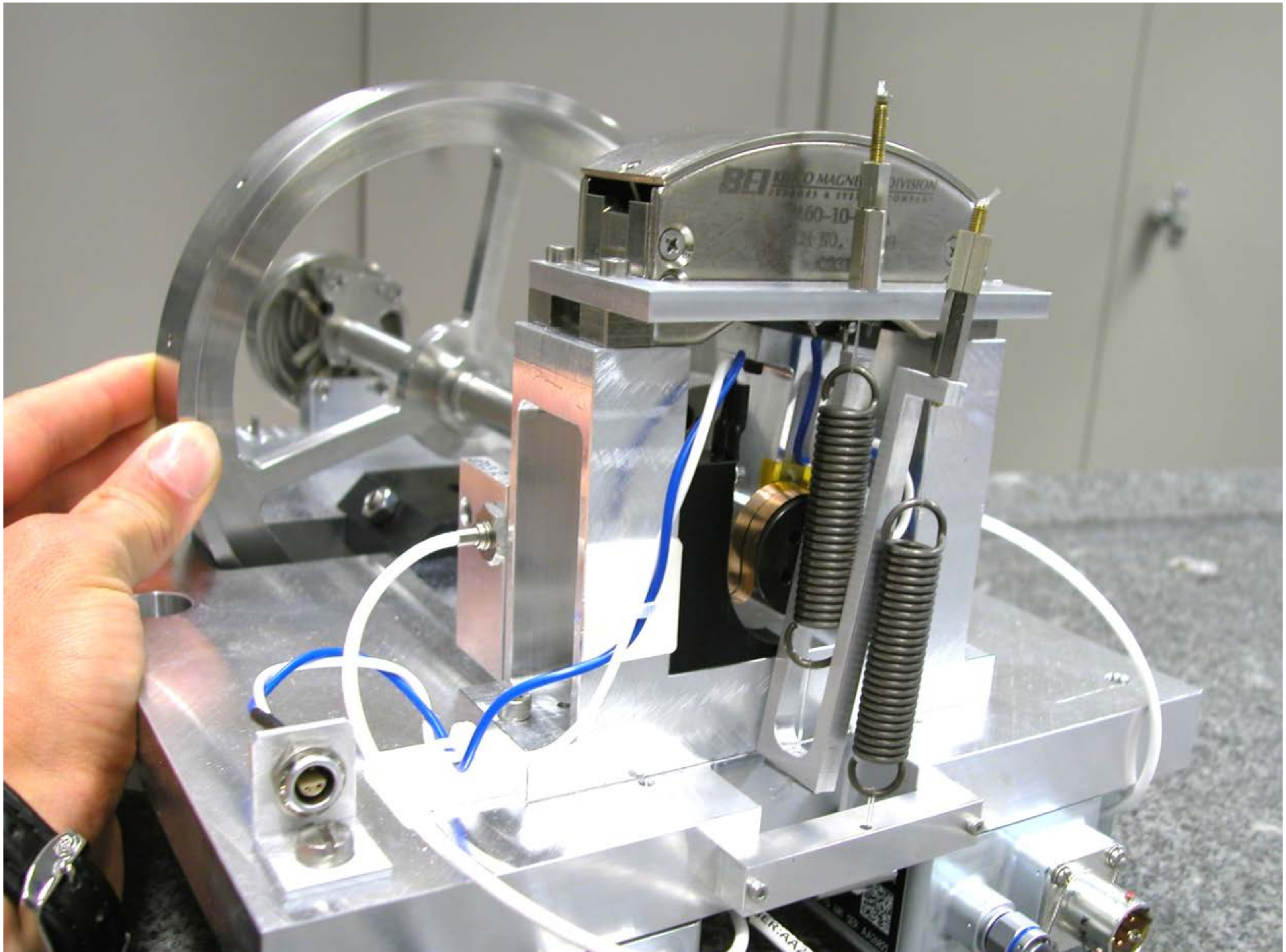




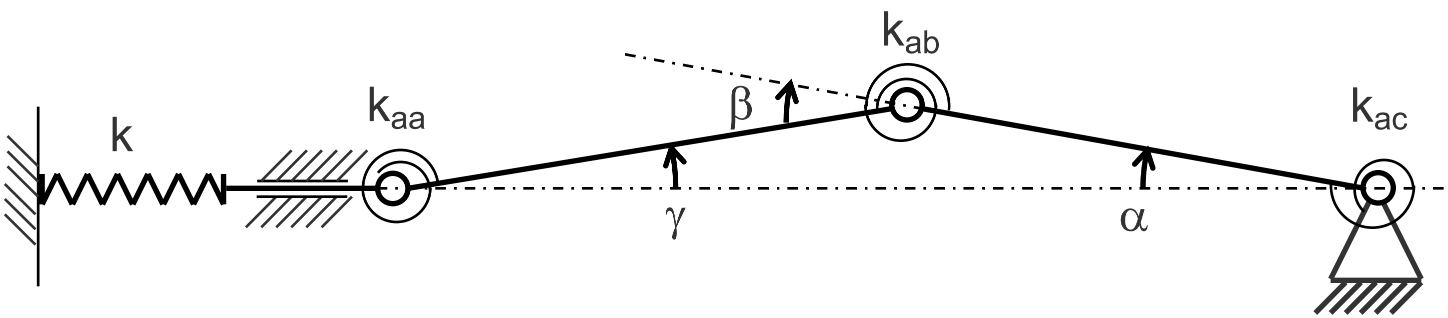
Overconstraints lead to:

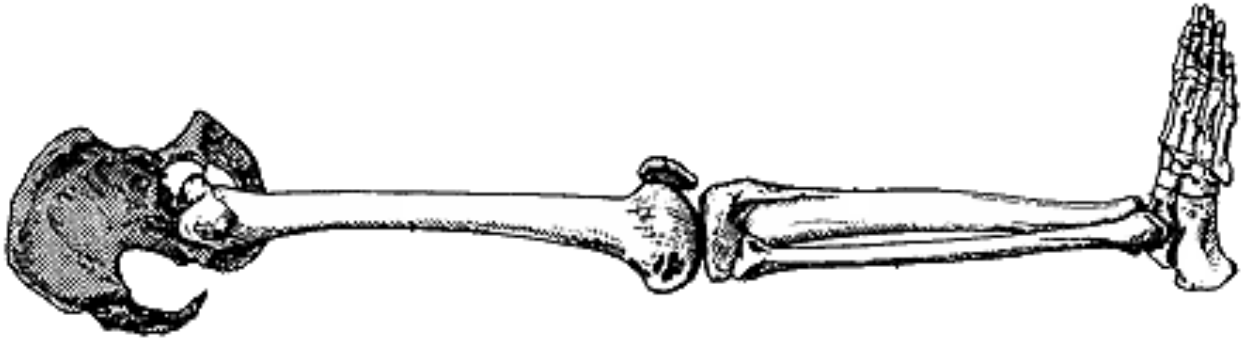
- Significantly reduced stroke
- Poorly controlled stiffness
- Amplified forces on the structures

Tunable stiffness pivot assembly

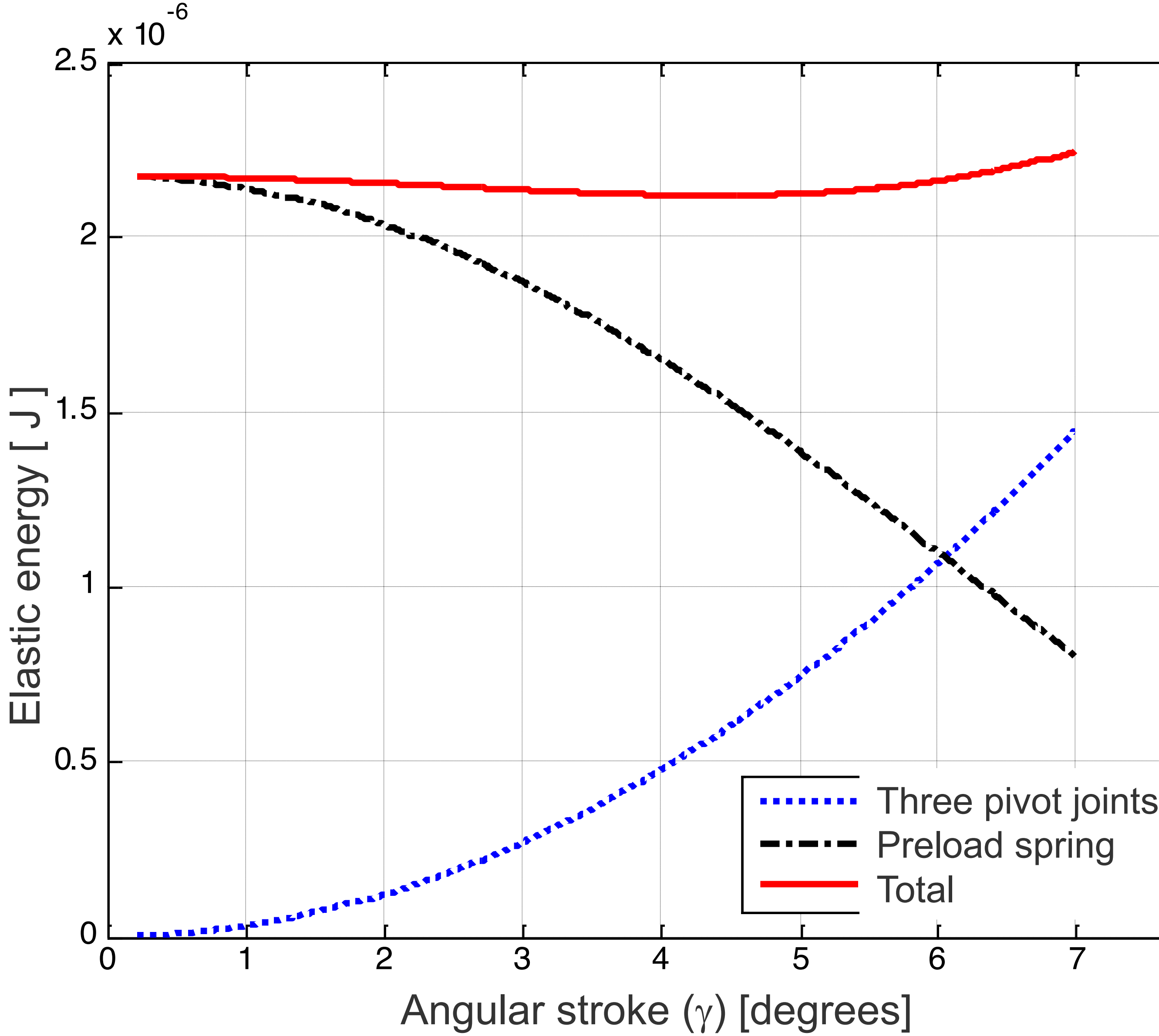


Leg 2D kinematics (Toggle joint)

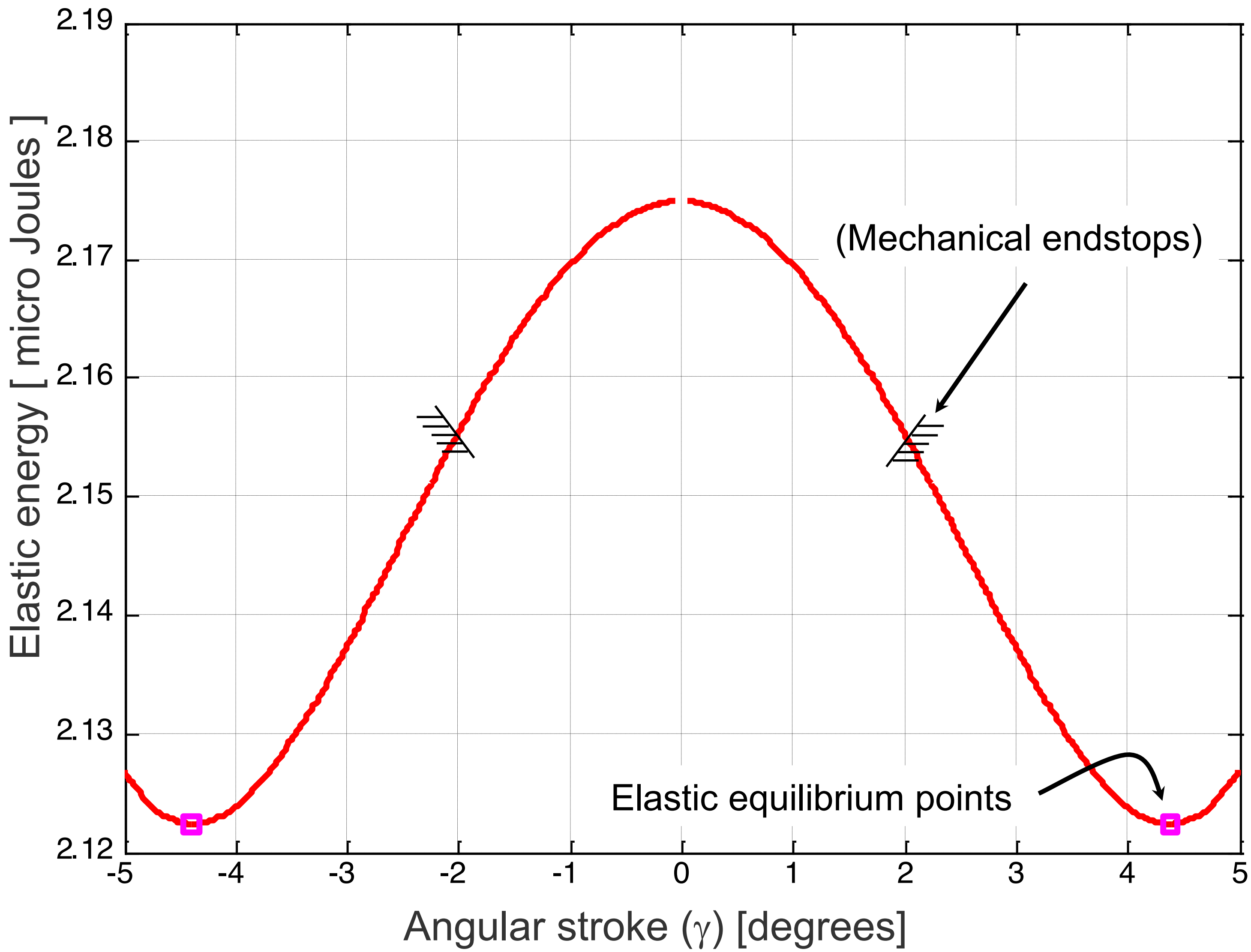




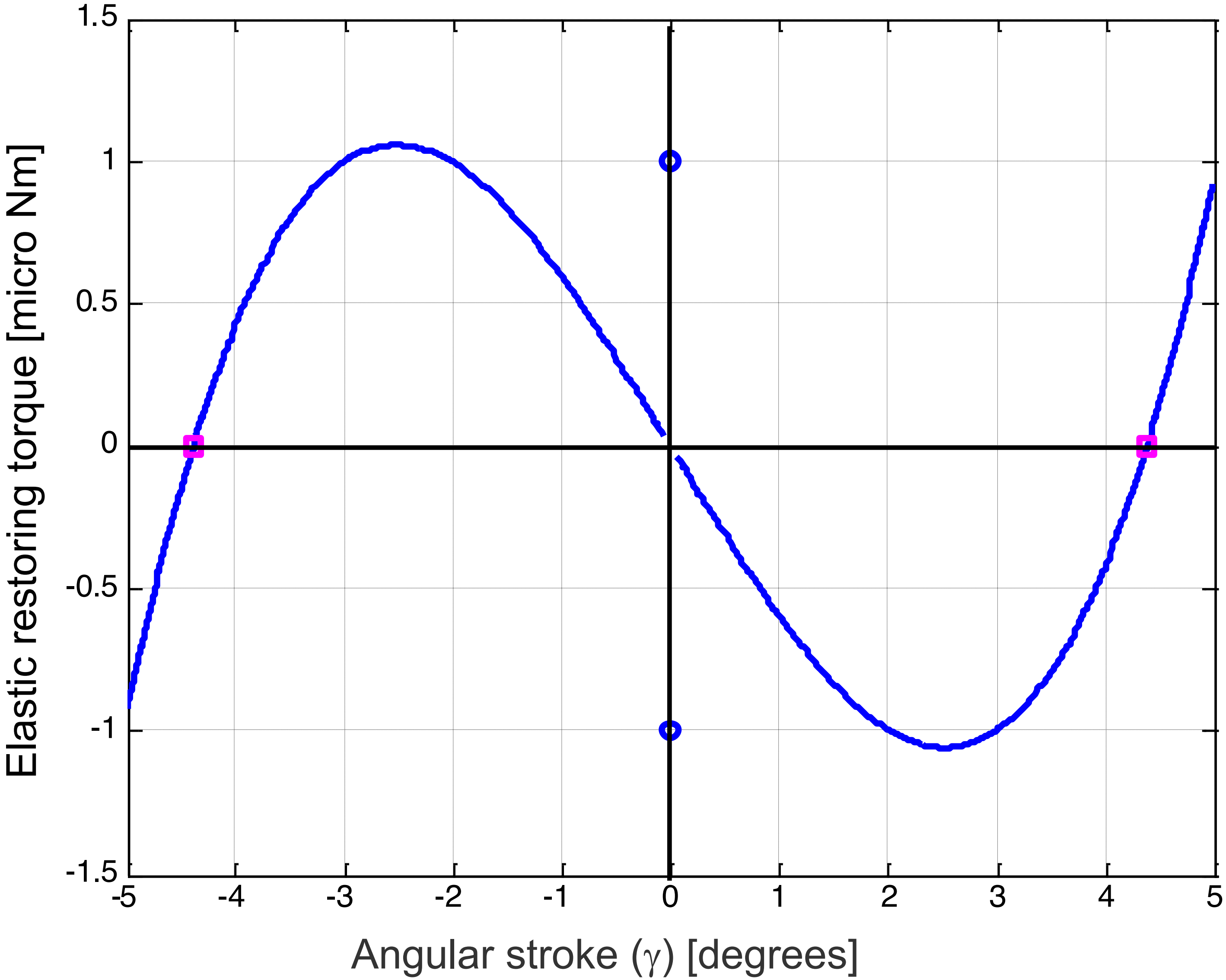
Sum of elastic energies



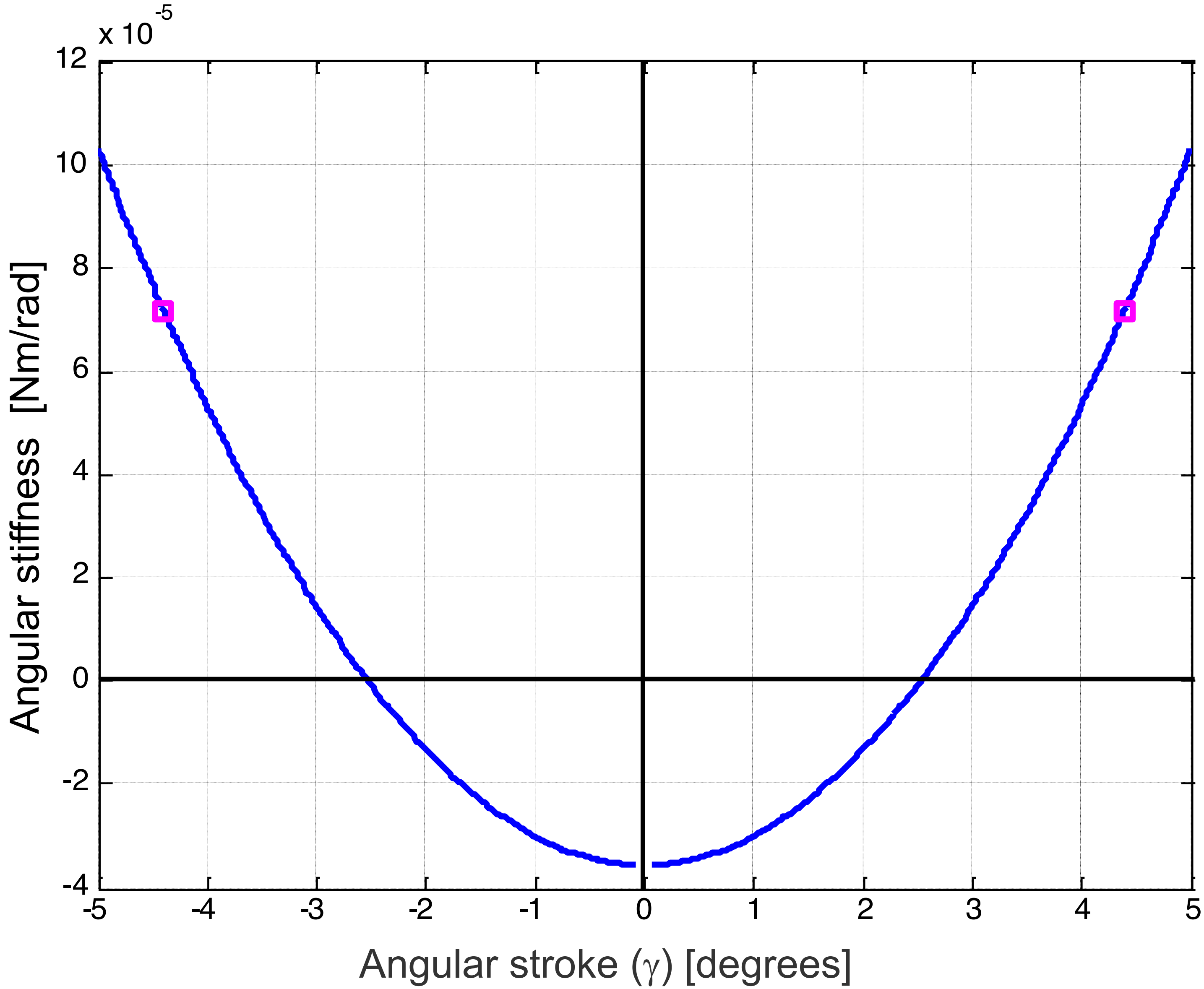
Total elastic energy



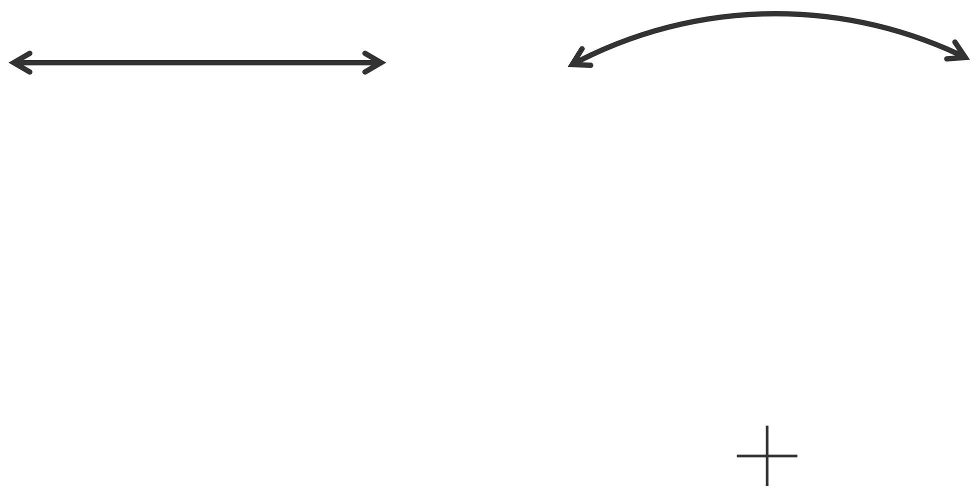
Elastic restoring torque



Angular stiffness

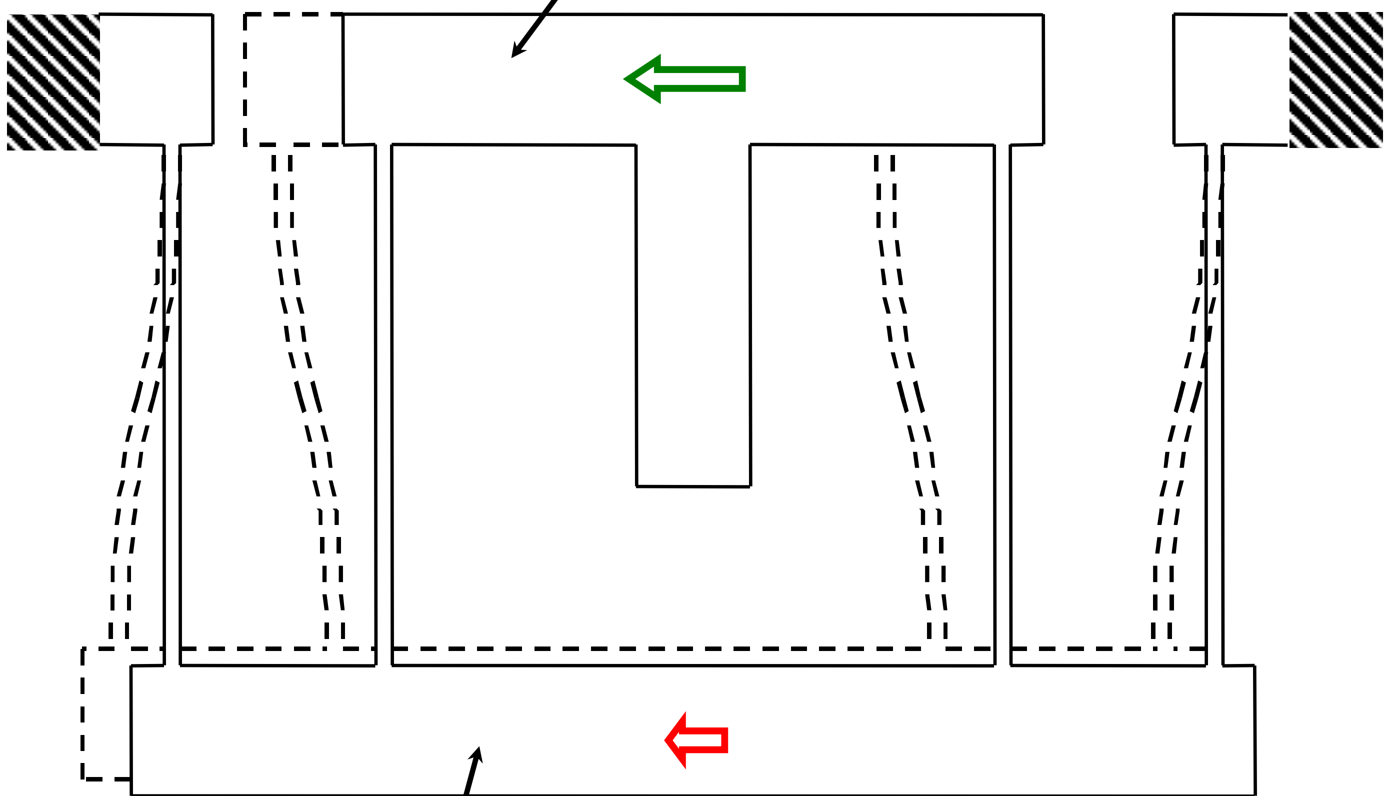


Rectilinear and circular mechanisms



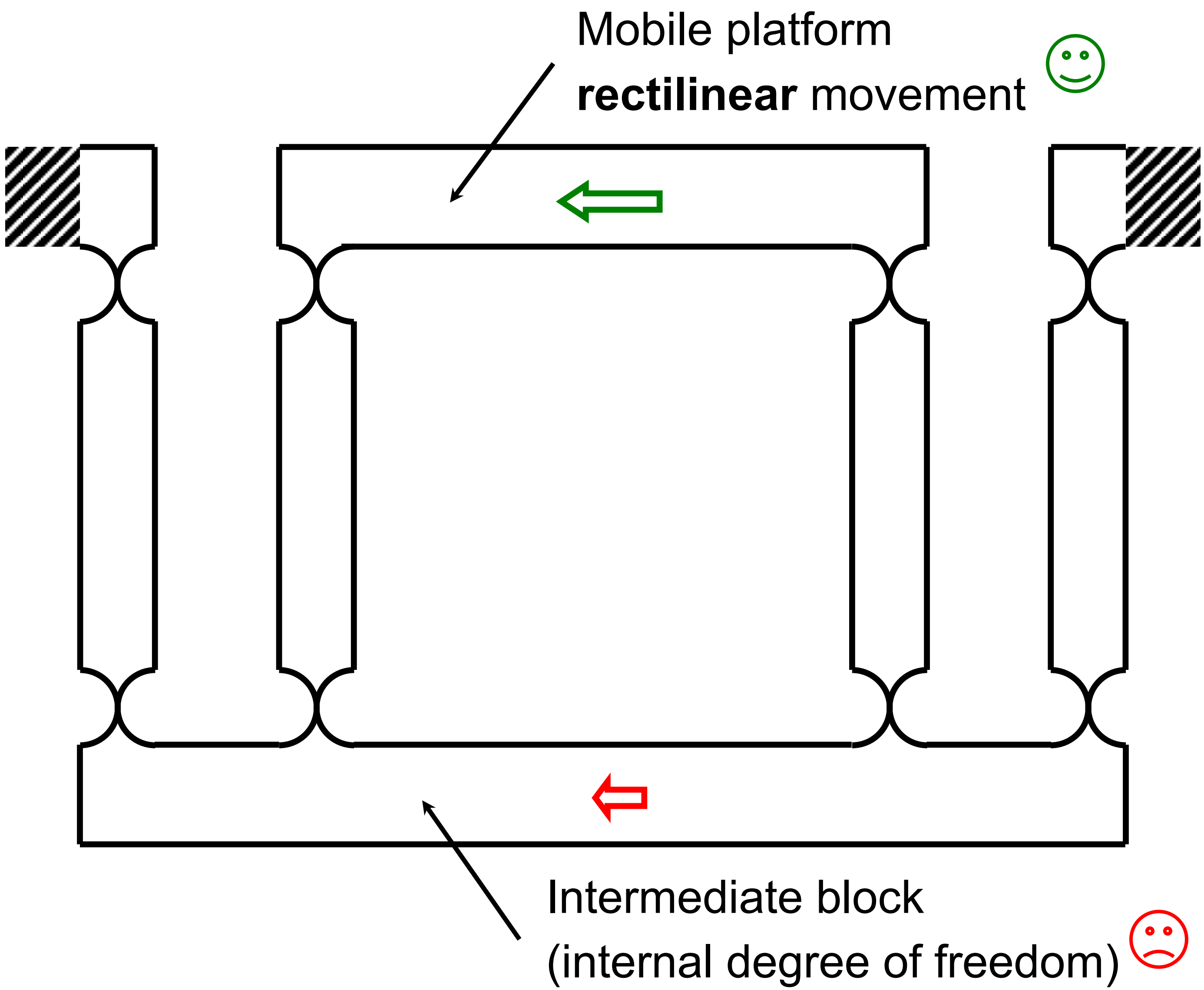
Compound parallel spring stage (2 DOFs)

Mobile platform
rectilinear movement



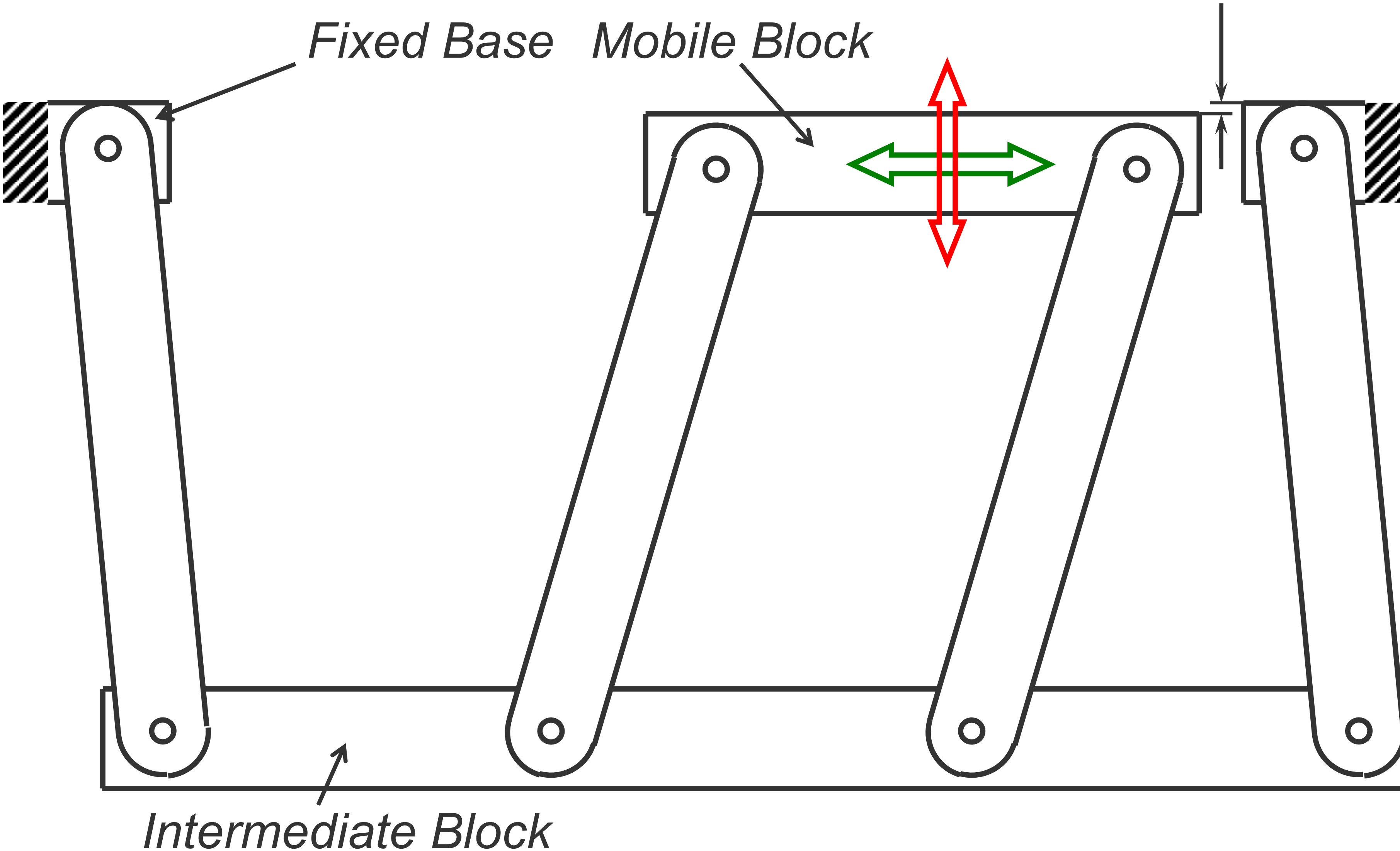
Intermediate block
(internal degree of freedom)

Compound parallel spring stage (2 DOFs)

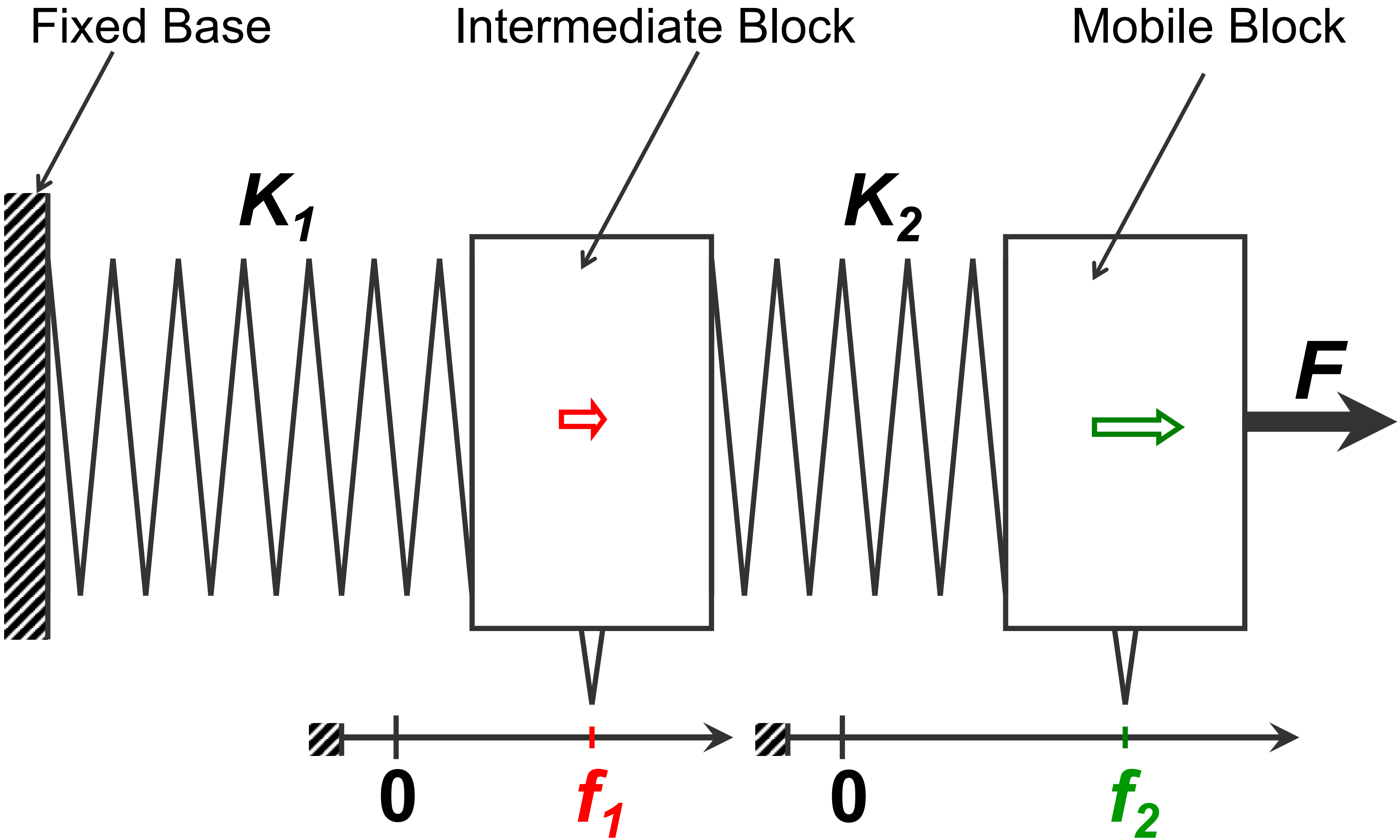


Analog structure with ideal joints

2D: **DOF = 2** ; M = 8 – 3 x 2 = 2 ; DOH = 0

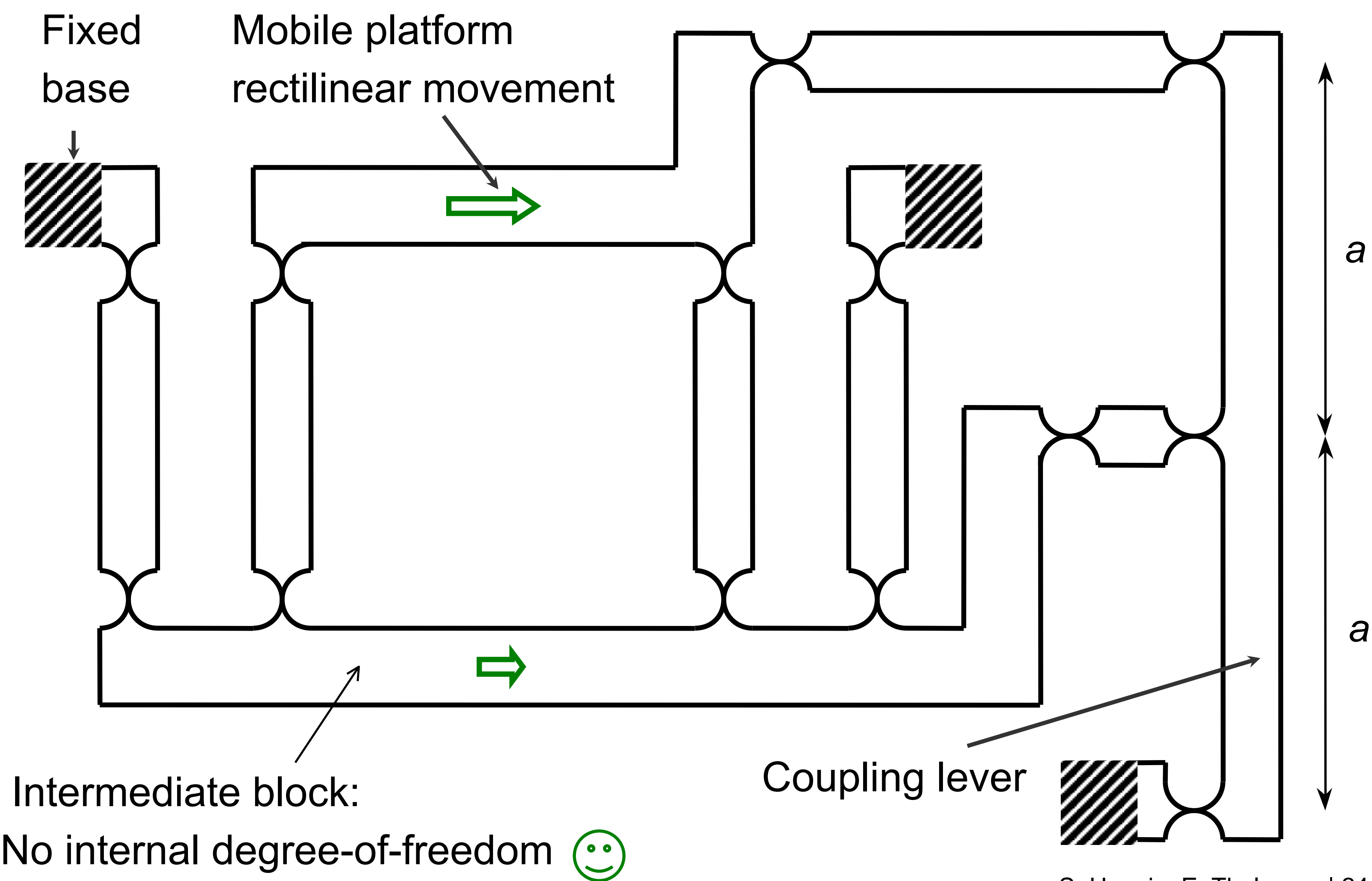


Movement of the intermediate block



Suppression of the internal degree-of-freedom

2D: **DOF = 1** ; M = 13 – 4x3 = 1 ; DOH = 0

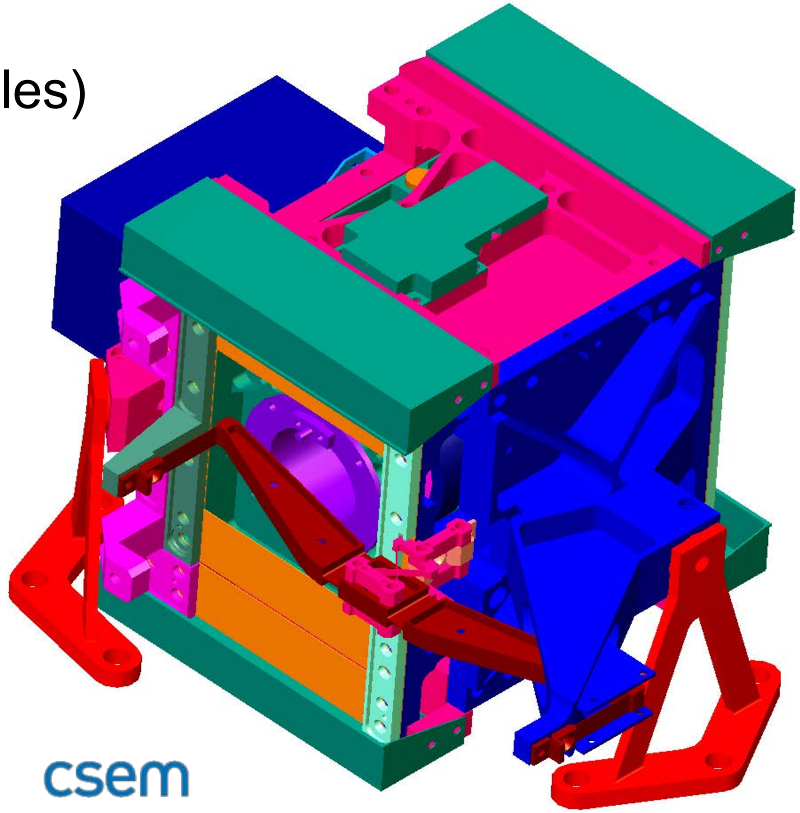


Suppression of the internal degree-of-freedom

DOF = 1

Example: Corner Cube Mechanism

- Rectilinear guiding for interferometer scanner
- Stroke: ± 12 mm
- Lateral error off-axis <1 μm
- 2.5 Hz constant velocity travel
- Lifetime : 5 years non-stop ($5 \cdot 10^8$ cycles)



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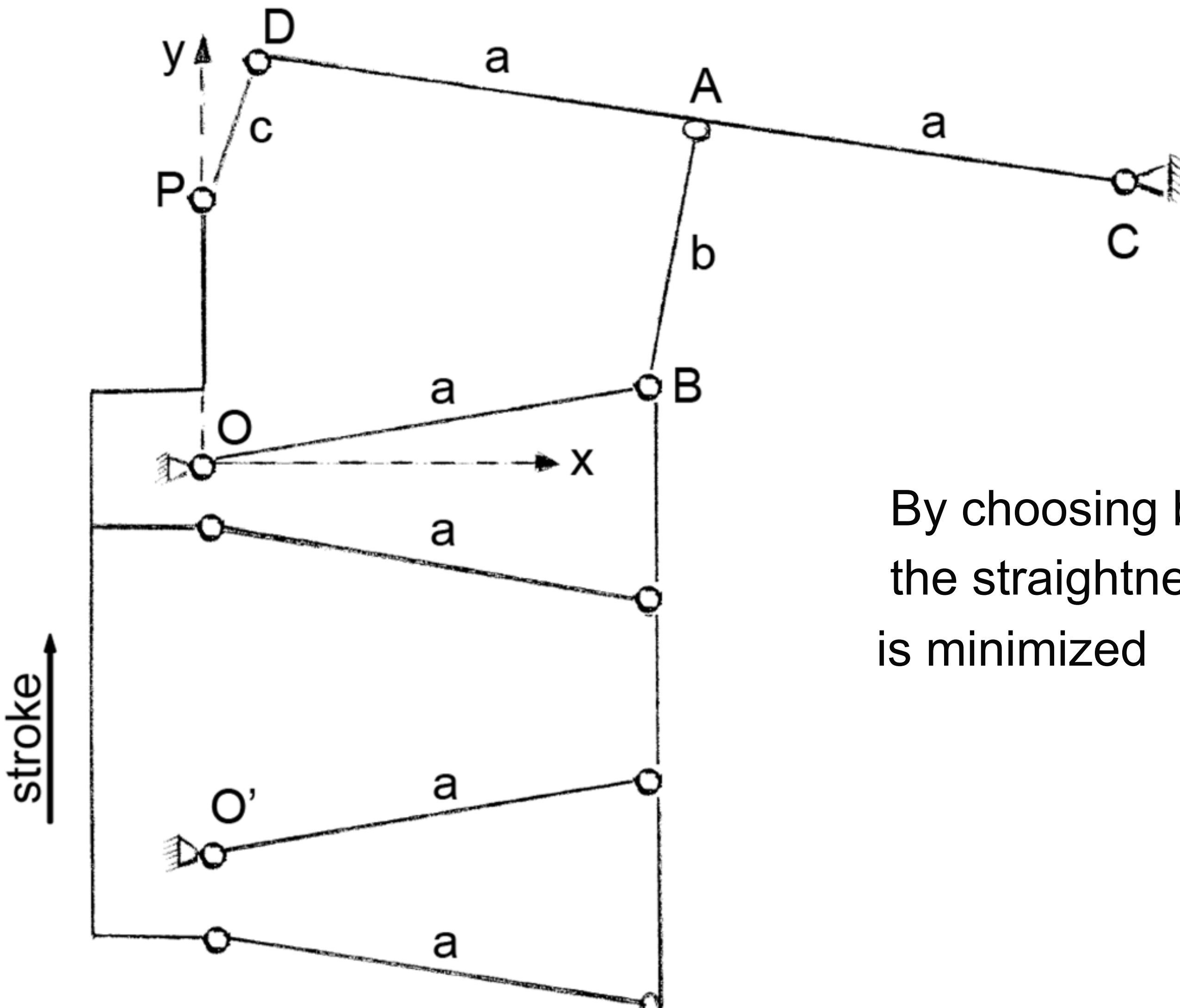
Rectilinear mechanisms

13 pivots optimized rectilinear mechanism

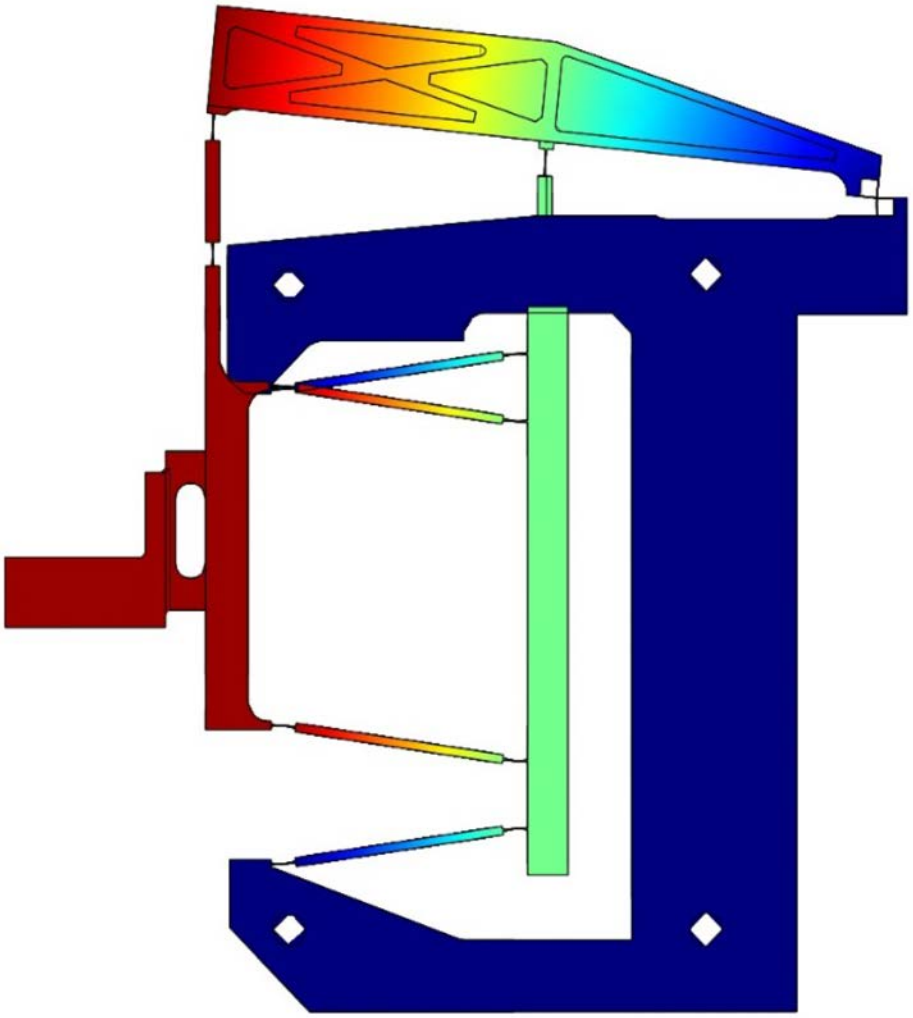


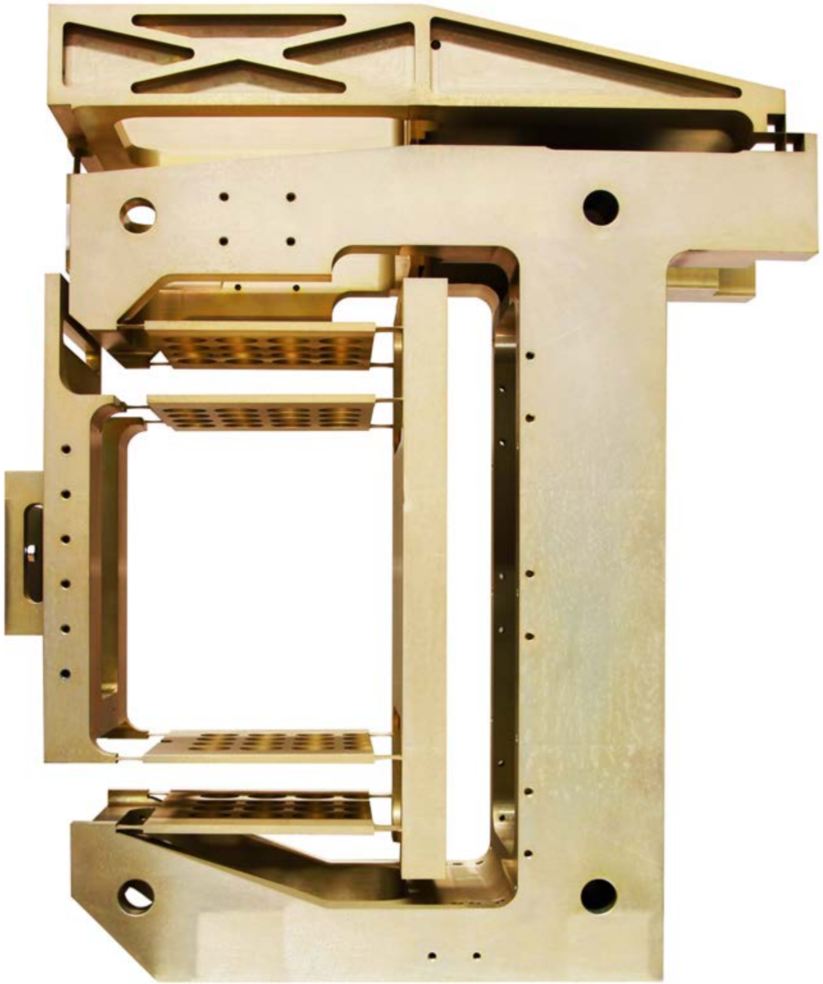
By choosing b = 2c the straightness error is minimized

F. Cosandier, Conception d'axes motorisés rectilignes d'ultra-haute précision, thèse EPFL n° 5665, 2012

Rectilinear mechanisms

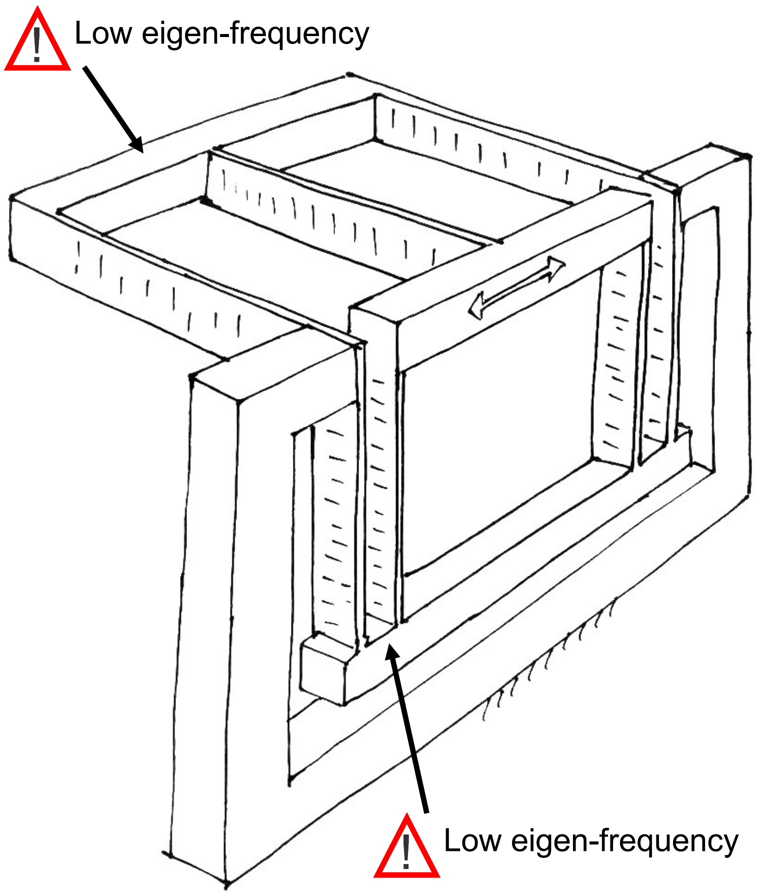
13 pivots optimized rectilinear mechanism

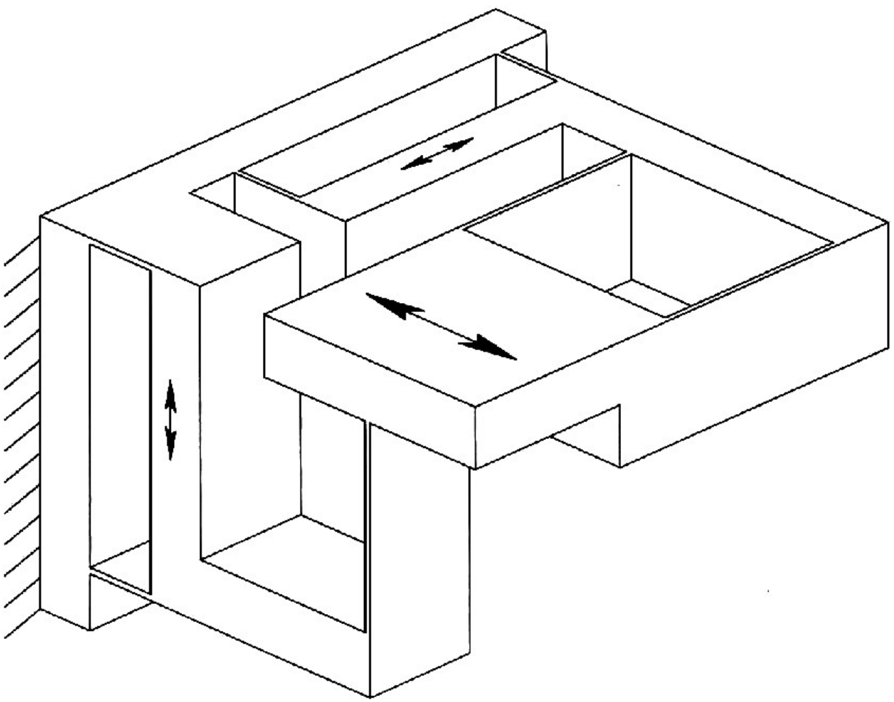




F. Cosandier, Conception d‘axes motorisés rectilignes d‘ultra-haute précision, thèse EPFL n° 5665, 2012

Rectilinear mechanisms
Sarrus Mechanism

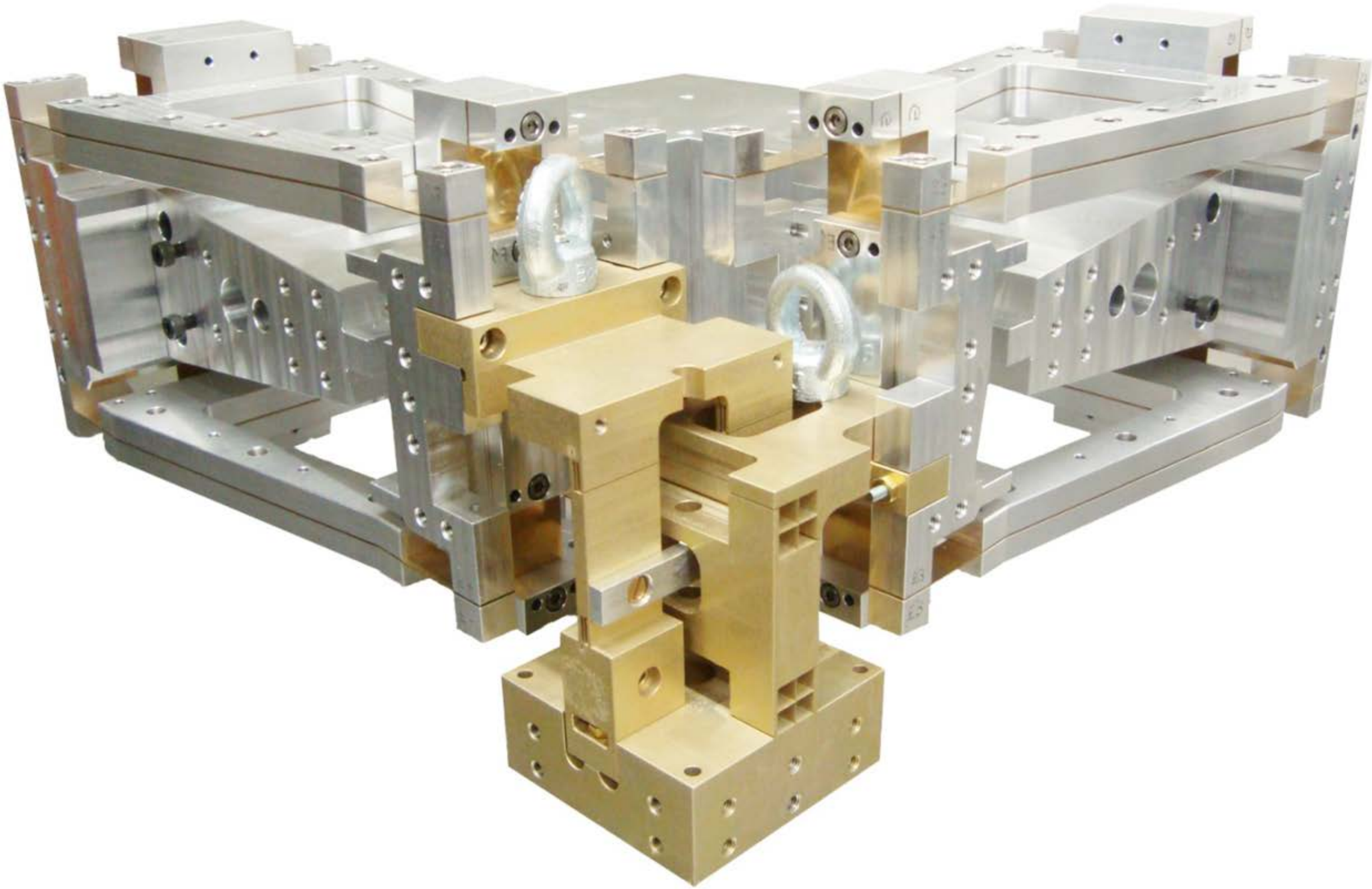




Flexure-based Sarrus mechanism

Rectilinear mechanisms

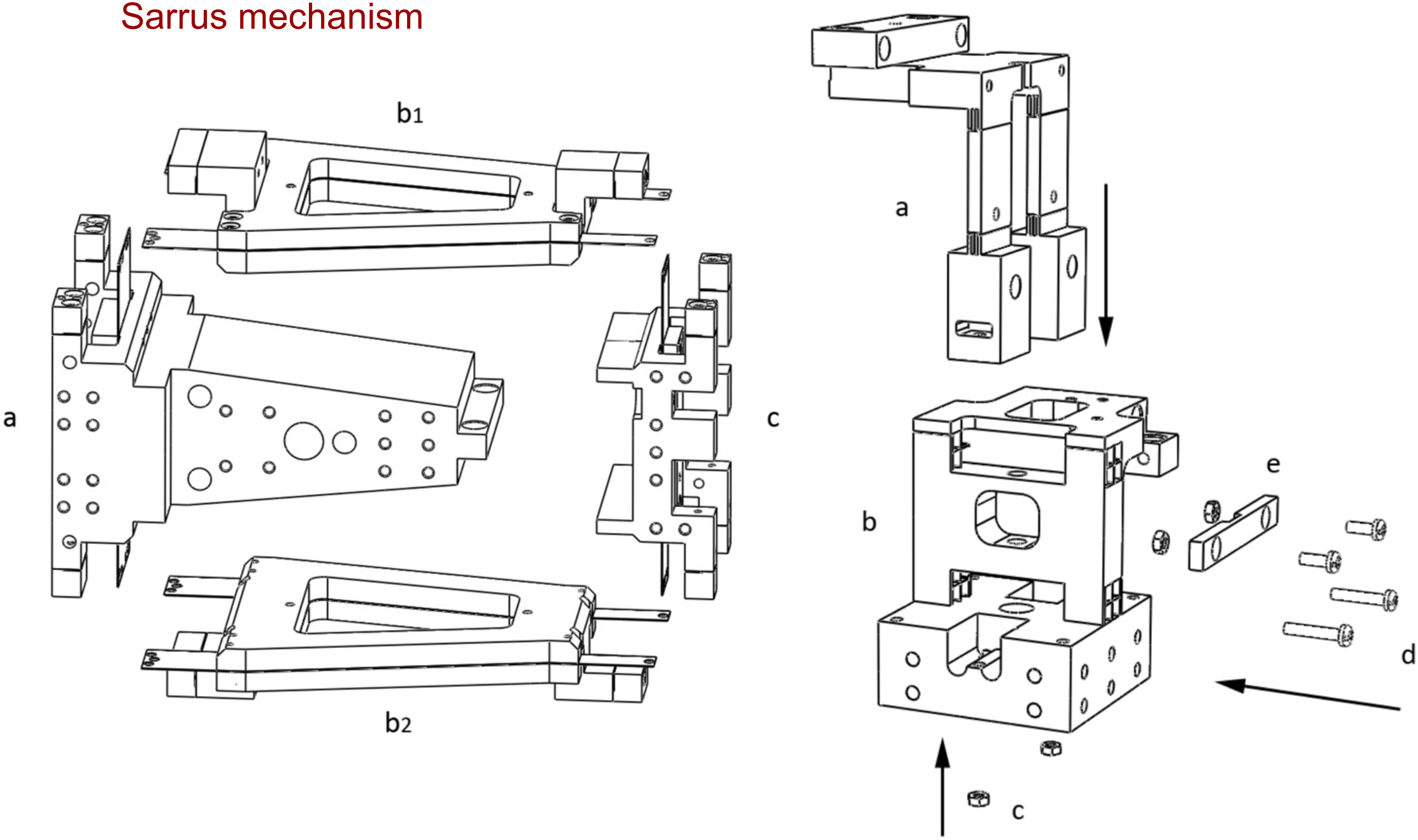
Sarrus mechanism



F. Cosandier, Conception d'axes motorisés rectilignes d'ultra-haute précision, thèse EPFL n° 5665, 2012

Rectilinear mechanisms

Sarrus mechanism

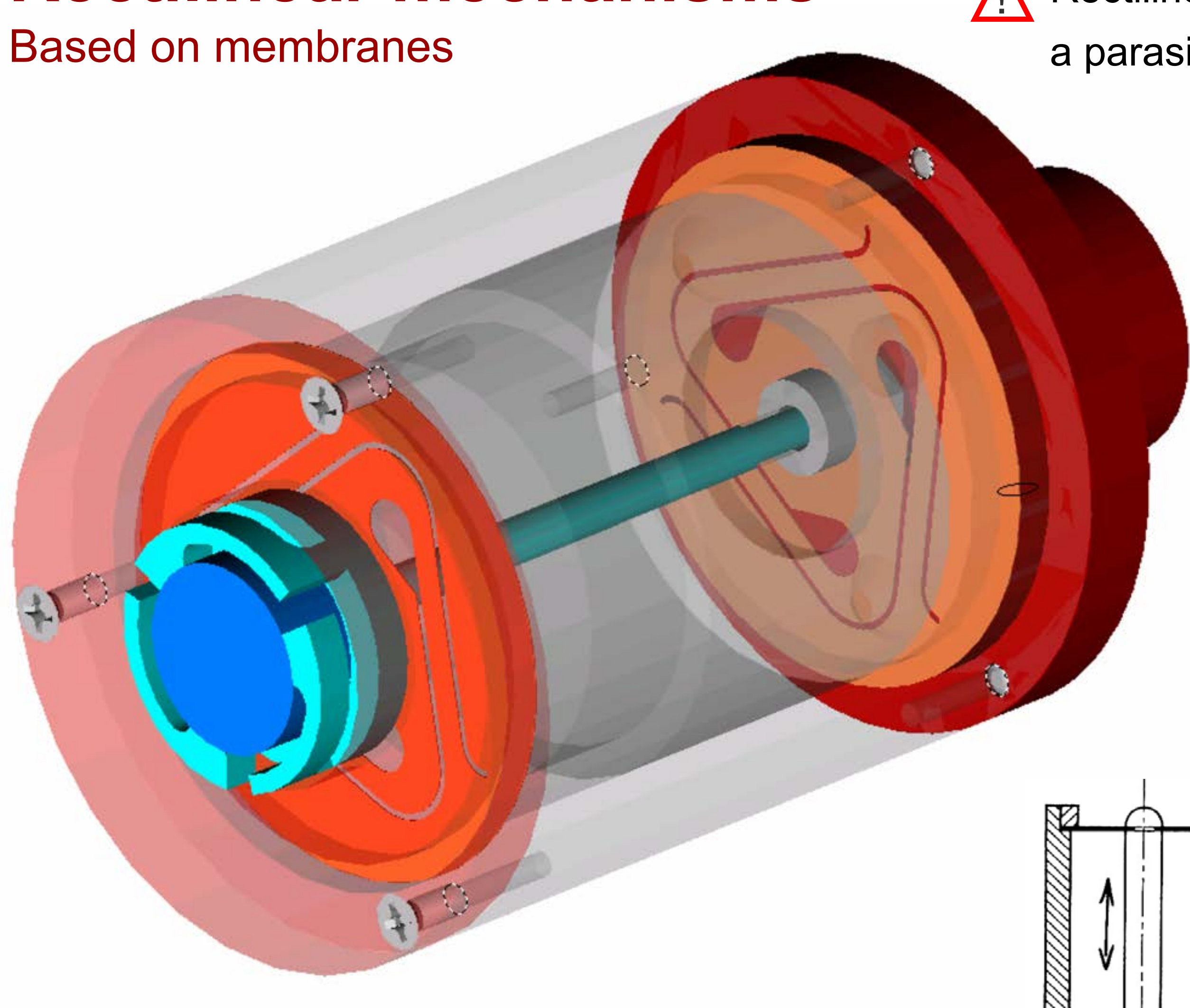


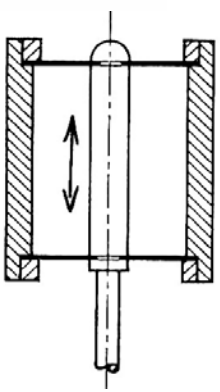
F. Cosandier, Conception d'axes motorisés rectilignes d'ultra-haute précision, thèse EPFL n° 5665, 2012

Rectilinear mechanisms

Based on membranes

⚠ Rectilinear, but accompanied by a parasitic axial rotation

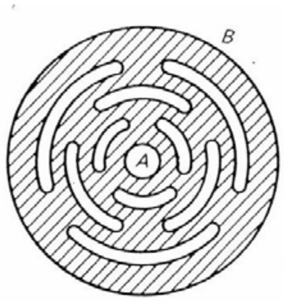




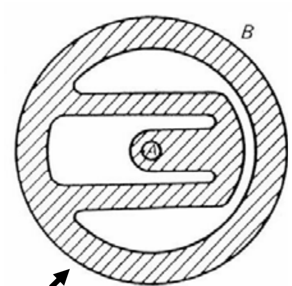
e.g. Interferometer:

- Diameter: 34 mm
- Stroke: +/- 0.5 mm

Variety of membranes

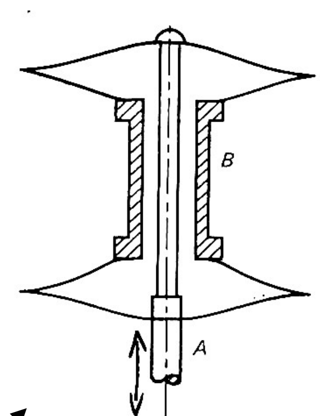


"spider"

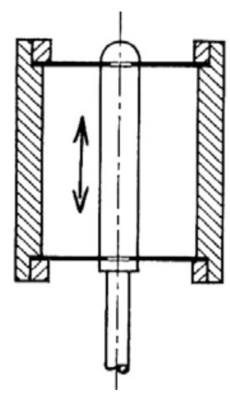


Not rectilinear

Low radial stiffness



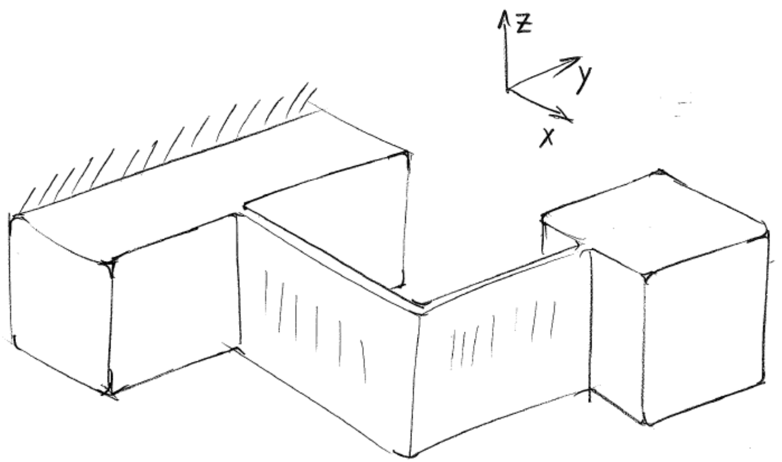
Low radial stiffness
with all membranes

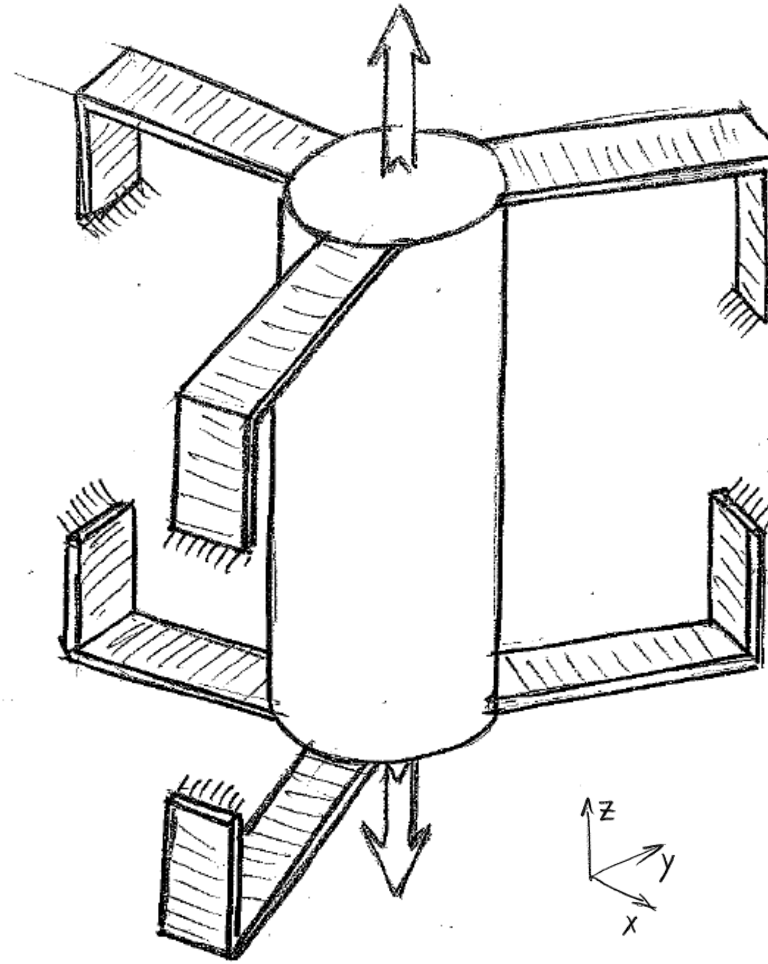


Rectilinear,
but accompanied by parasitic axial rotation

Rectilinear mechanisms

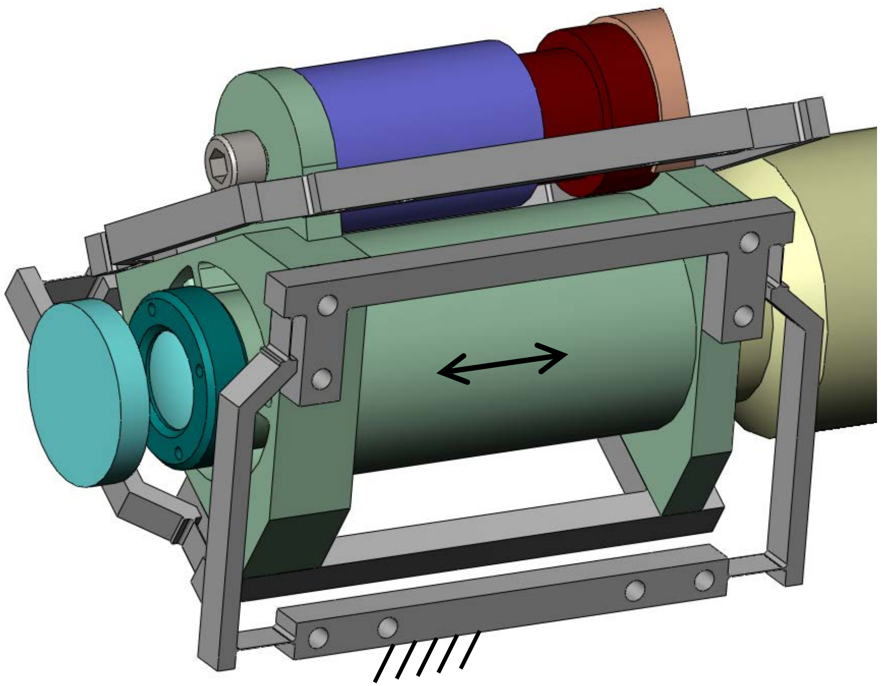
Based on “corner-blades”

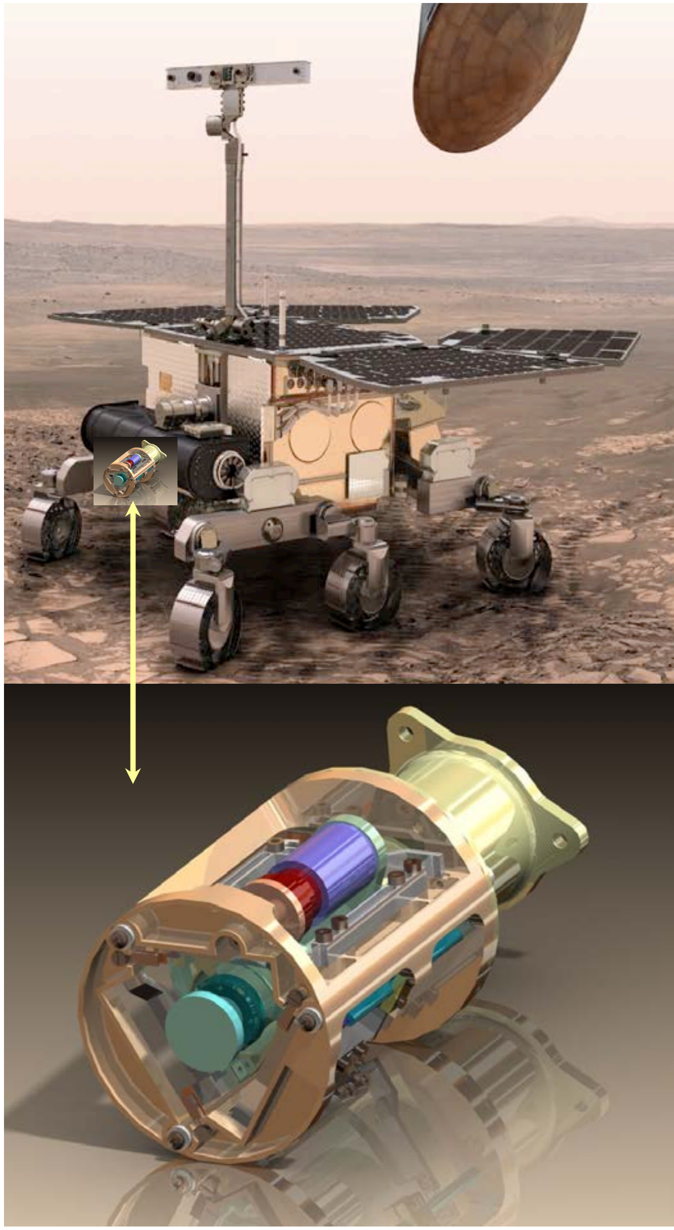




Rectilinear mechanisms

Close-up Imager (CLUPI Instrument)
European Mars Mission EXOMARS (ESA)



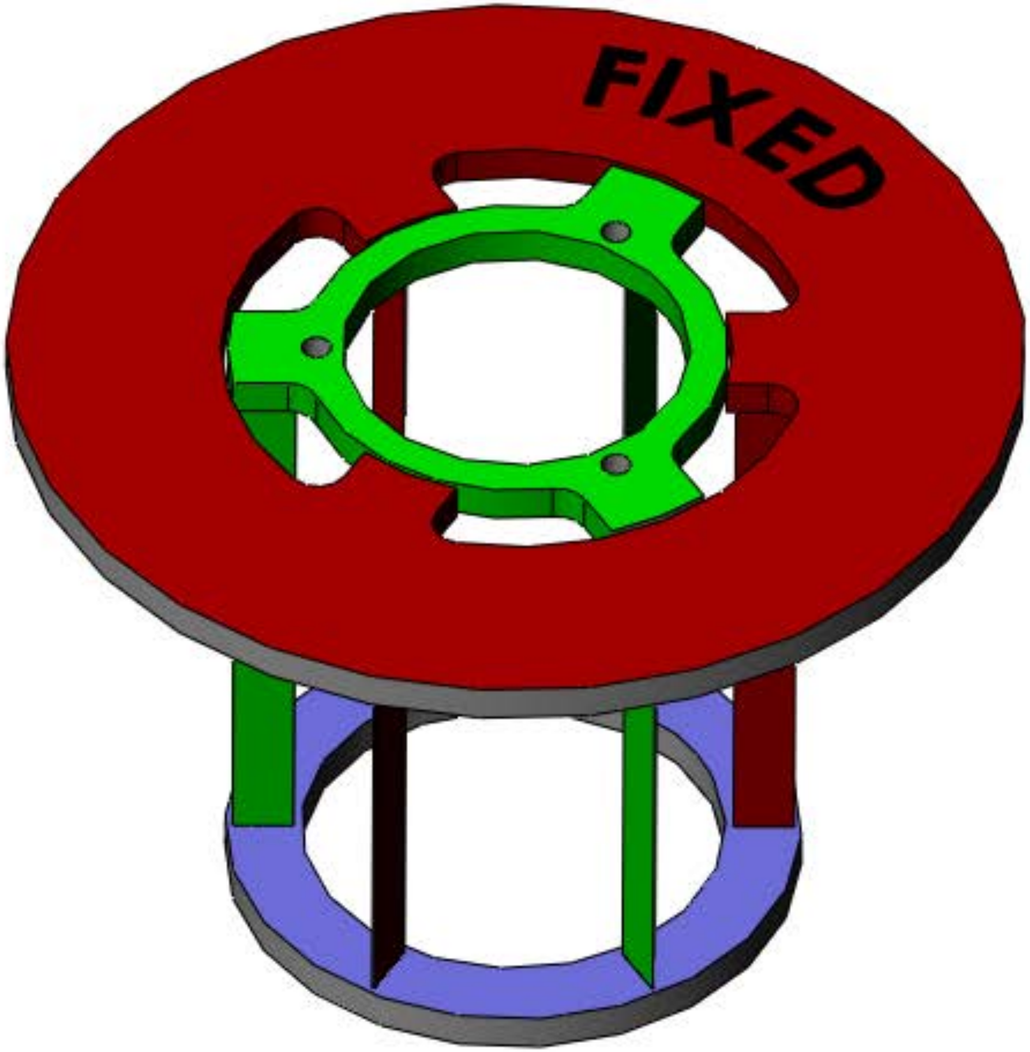


SPACE-X
Space Exploration Institute
Neuchâtel, Jean-Luc Josset
www.space-x.eu

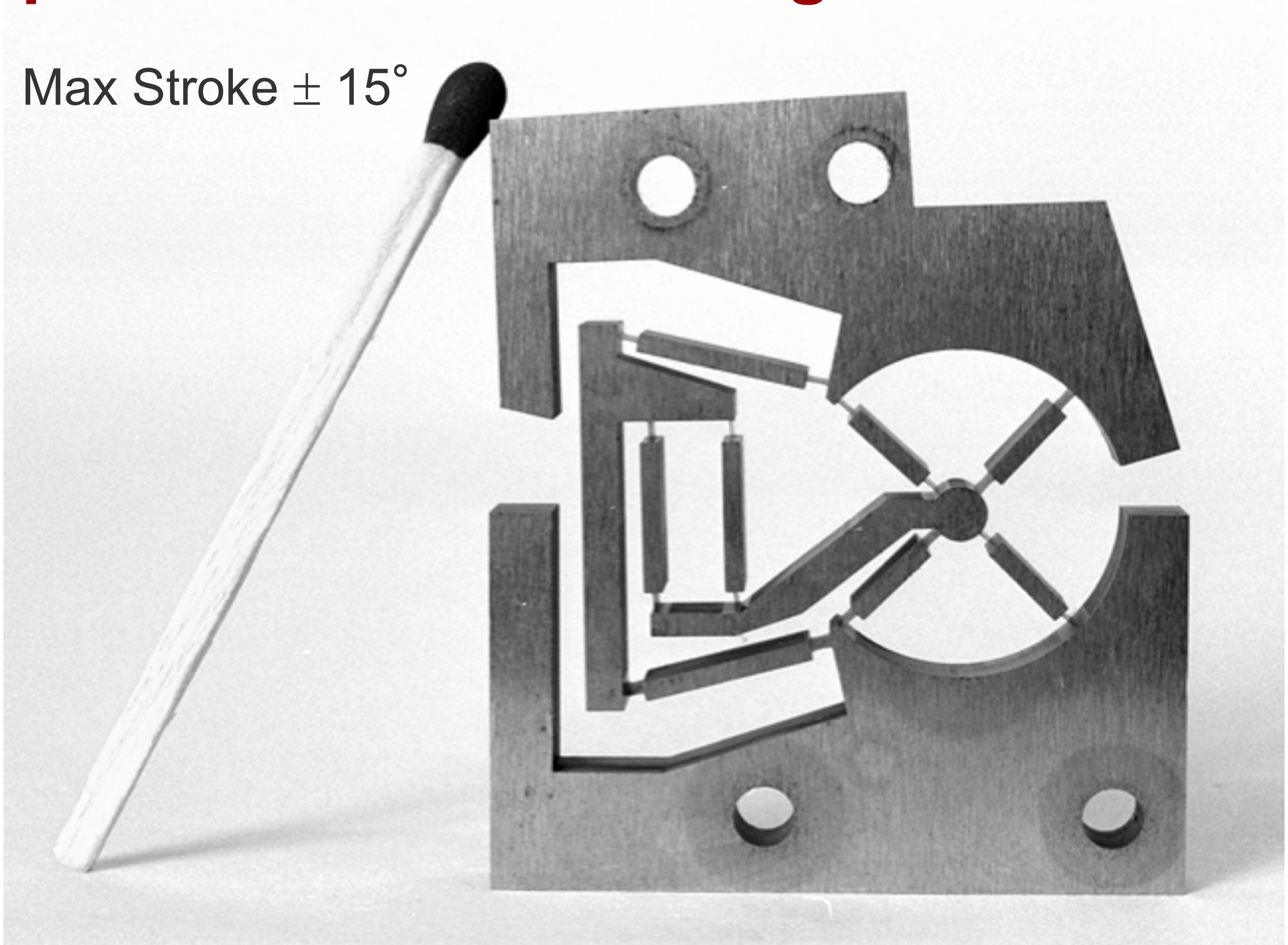
L. Giriens
S. Henein
Ph. Schwab
P. Spanoudakis

Circular mechanisms

Compound squirrel cage



Suppression of internal degrees-of-freedom



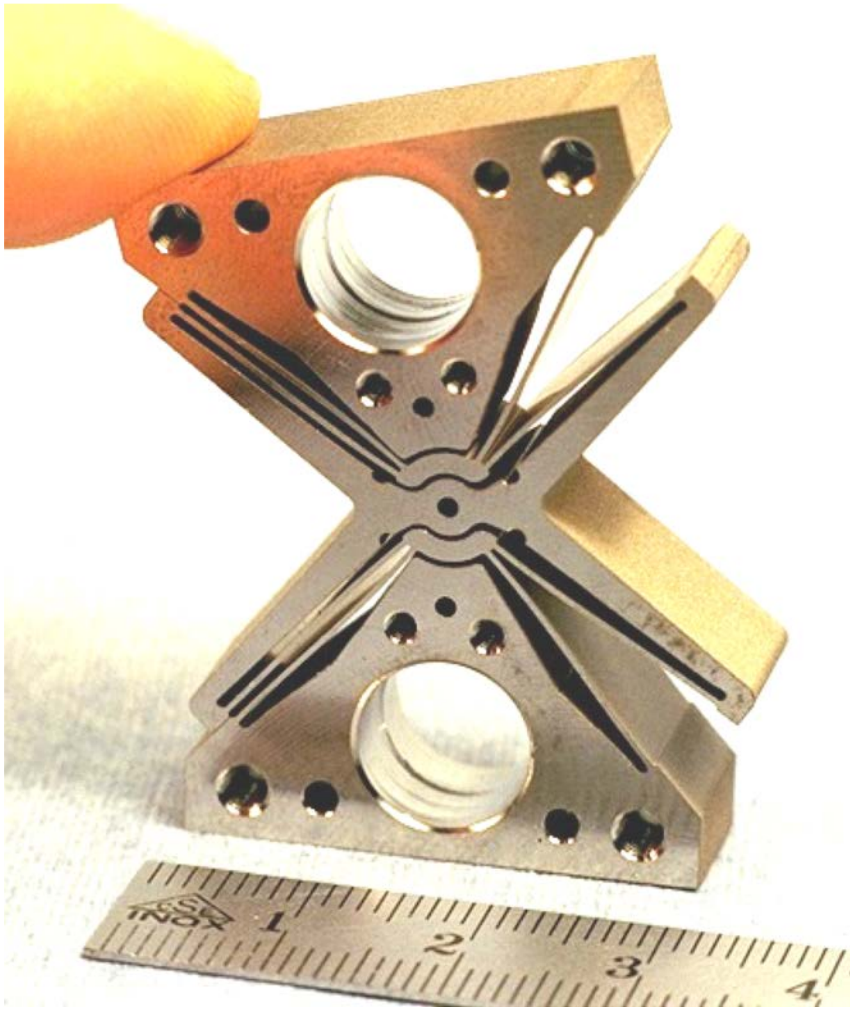
- Radial stiffness **with** coupling kinematic chain: 5.3 N/um
- Radial stiffness **without** coupling kinematic chain: 0.6 N/um

} **Improvement factor ≈ 9**

[S.Henein et al. (1998), Pivot flexible à grande course angulaire et à rigidité élevée, European Patent N° 98123953.6, Holder: Sysmelec SA]

Circular Mechanisms

Butterfly Pivot



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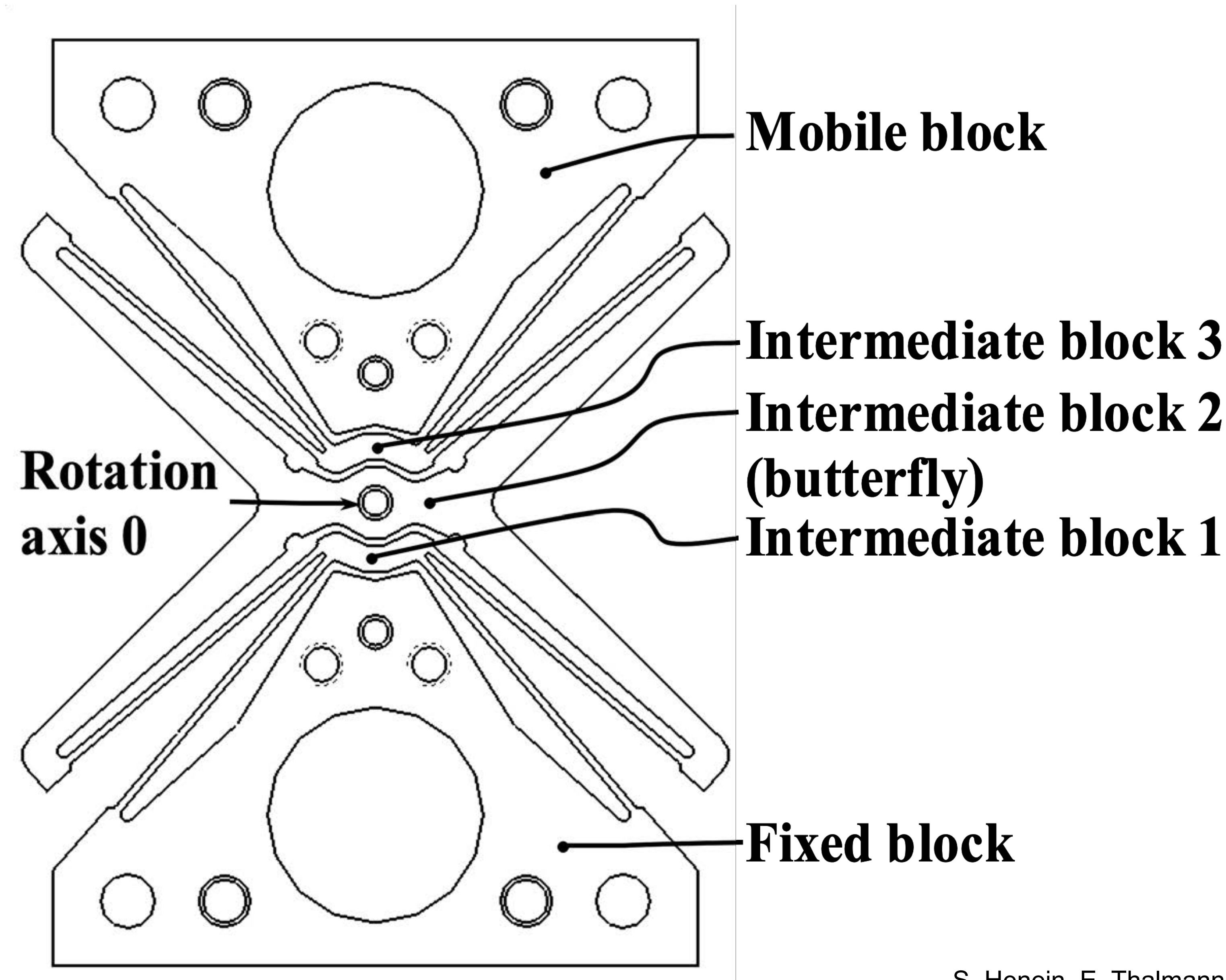
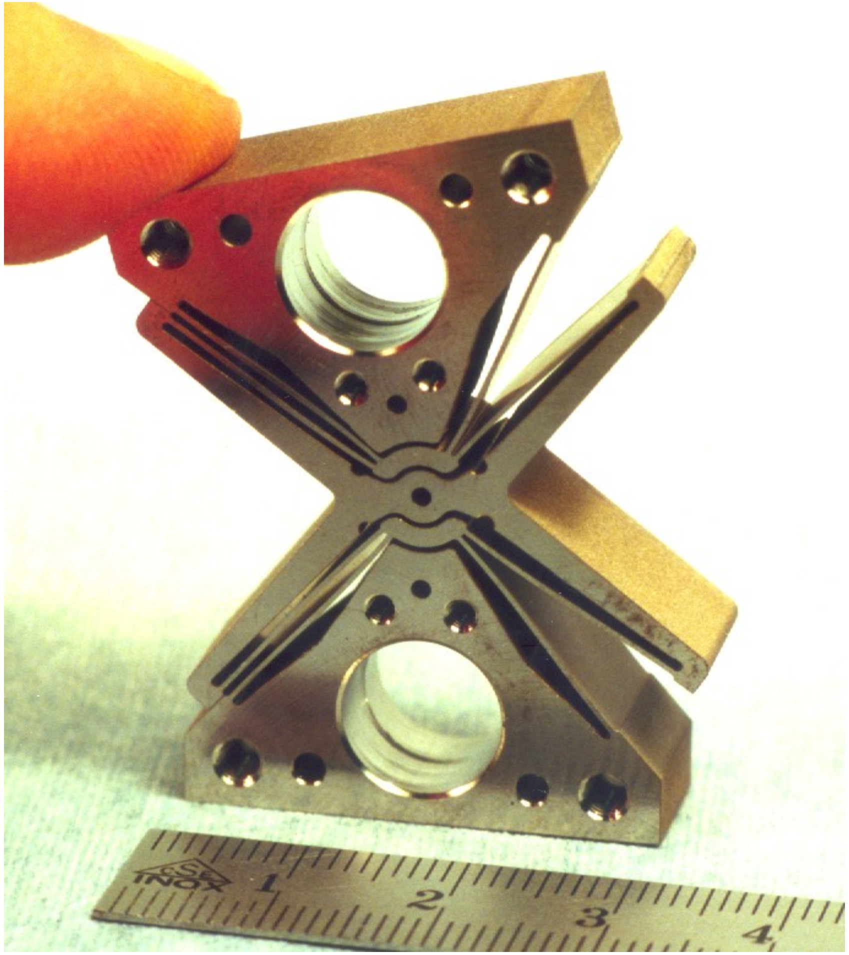
MOTION		
Angular range		±10°
Centre parasitic shift at 10°		1 μm
Pivot characteristics		
Material		Ti-6Al-4V
Monolithic construction		
Manufacturing Process		Wire EDM
Dimensions	**Height**	43 mm
	Width	30 mm
	Thickness	10 mm
	Blade length	15 mm
	Blade thickness	0.35 mm
STIFFNESS		
Rotary stiffness (θ_X)		1.0 Nm/rad
Rotational stiffness (θ_y)		5000 Nm/rad
Rotational stiffness (θ_z)		5000 Nm/rad
Axial (translation) stiffness (K_x)		6.5 Nm/μm
Lateral (radial) stiffness (K_y K_z)		0.7 Nm/μm

[S.Henein et al. (2003), Flexure Pivot for Aerospace Mechanisms, ESA SP-524, Proc. 10th European Space Mechanisms & Tribology Symp.]

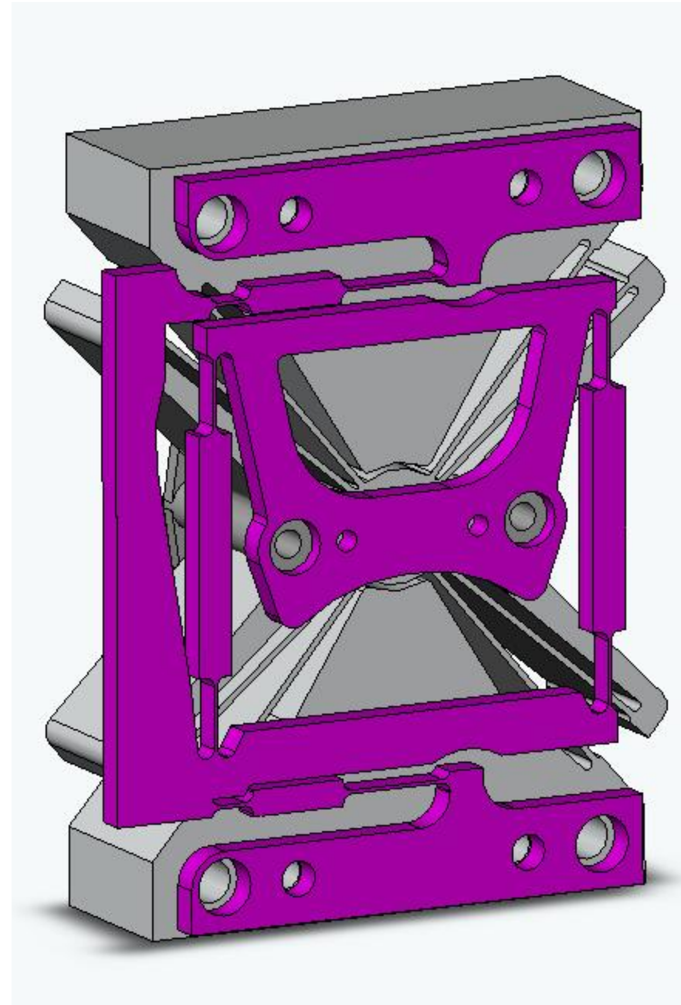
Butterfly Pivot : Topology and Kinematics



Suppression of internal degrees-of-freedom



“Butterfly” internal mode frequency 320 Hz

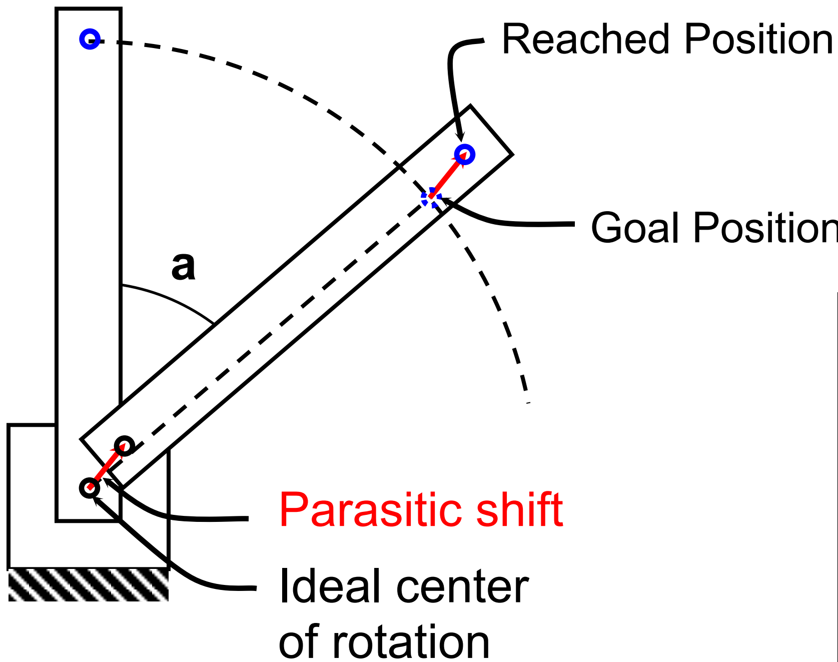


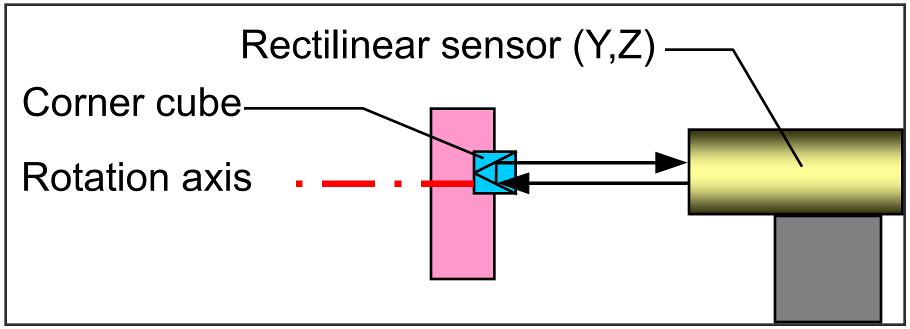
“Butterfly” internal mode frequency above 2000 Hz

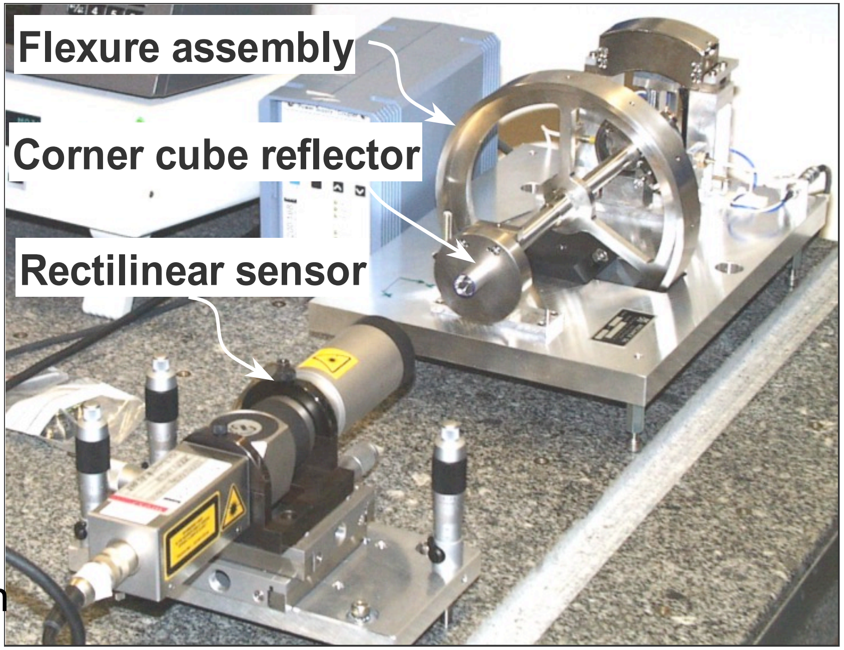
Parasitic center shift

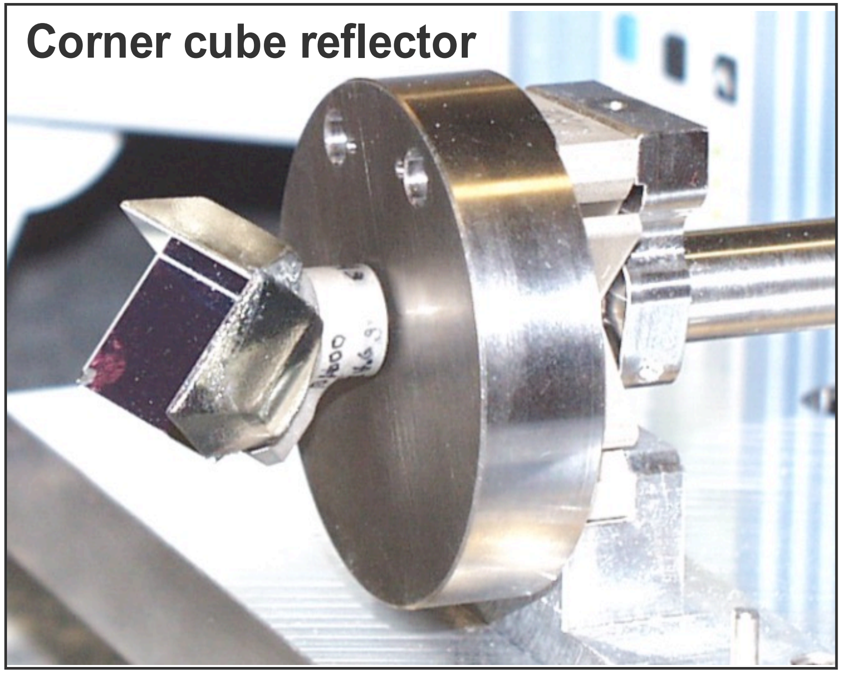
Butterfly pivot < 2 microns
for ± 10° stroke.

(Classical cross spring pivot of similar size produces 75 microns shift for ± 10° stroke)

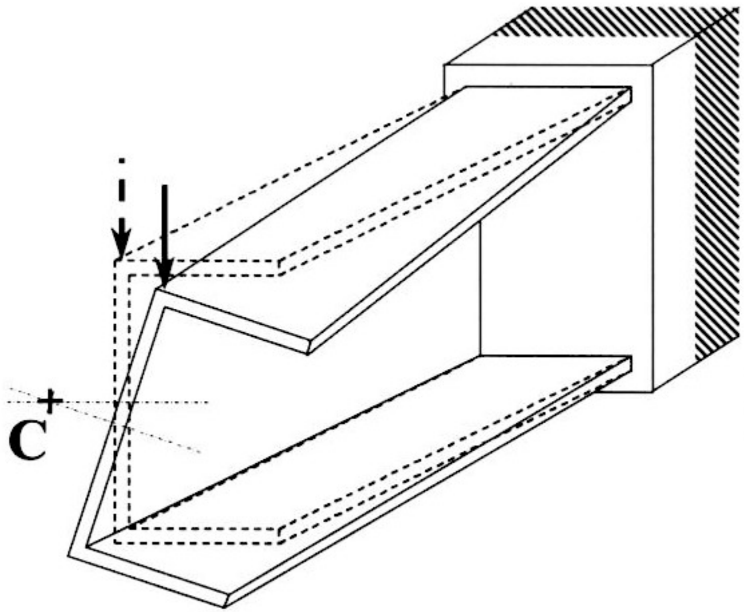


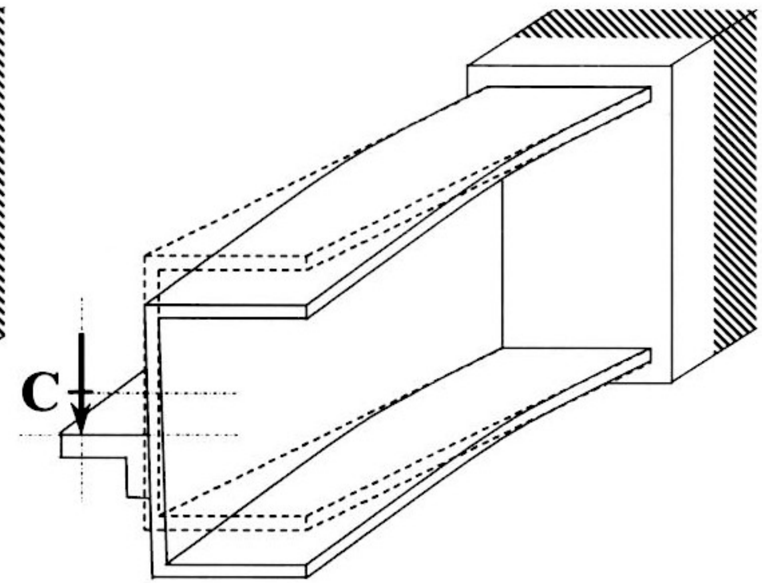


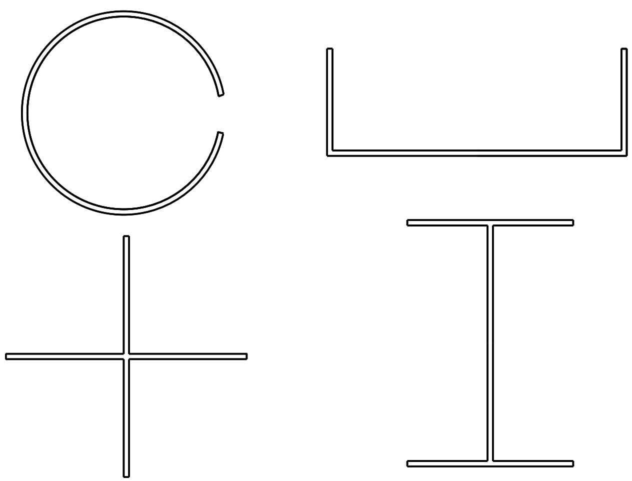


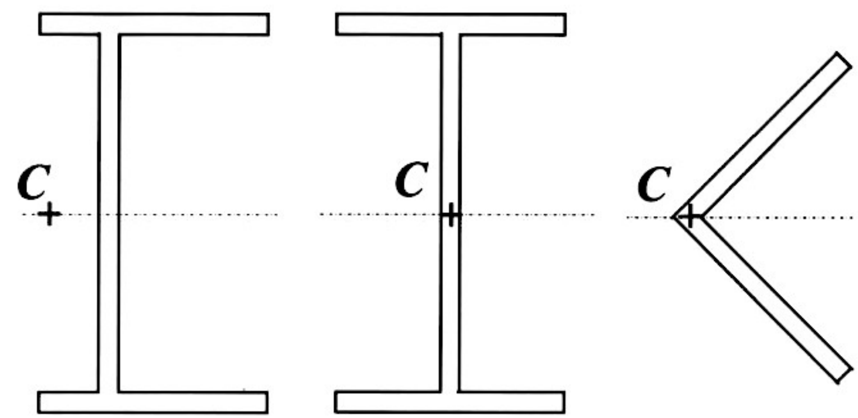


Torsion bars







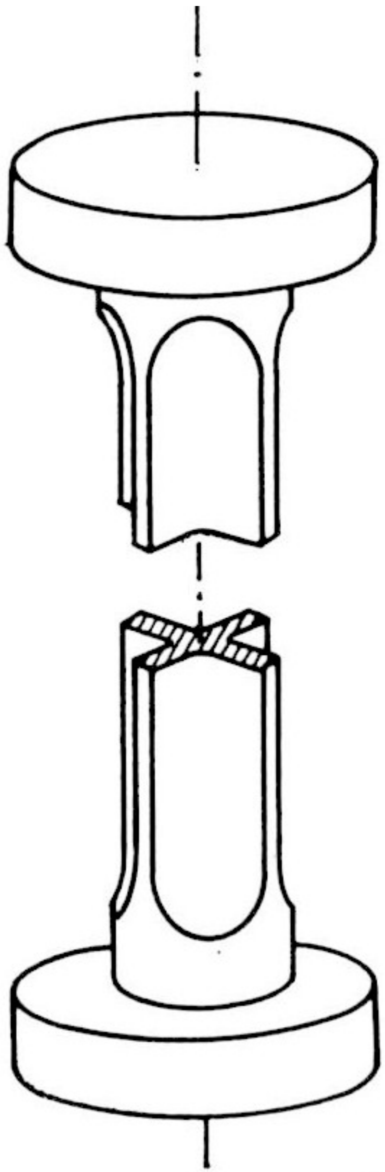


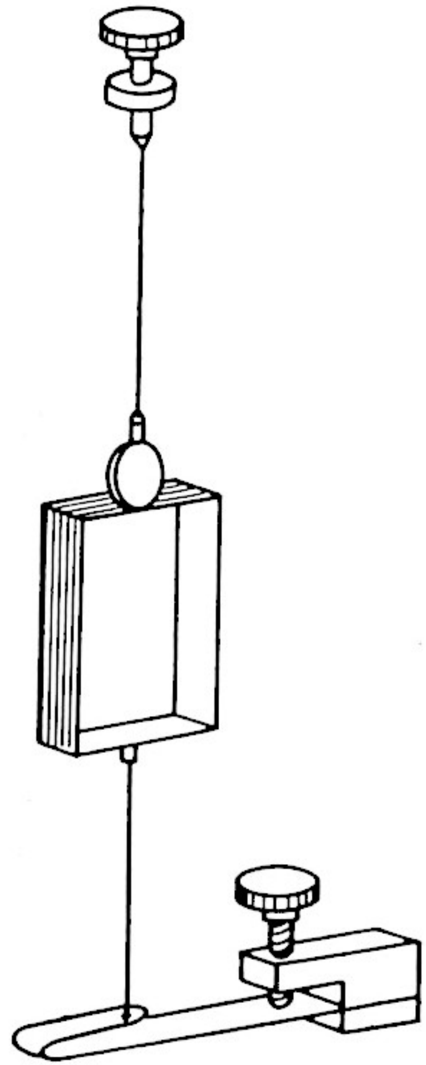
Shapes with equal total cross-section and thin walls have approx. equal torsion stiffness

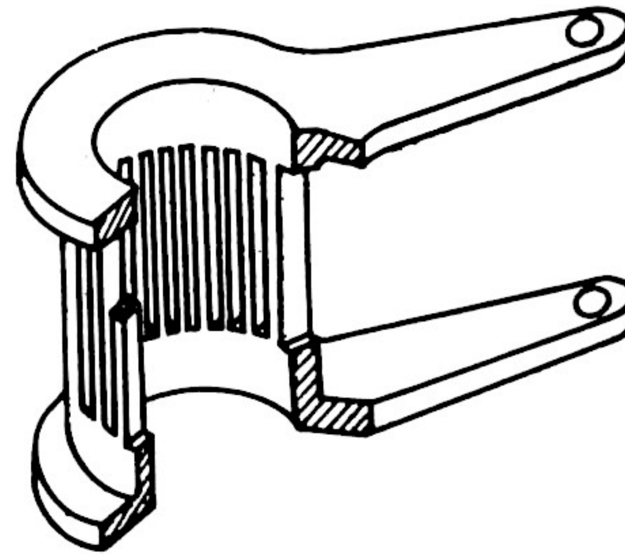
The location of the torsion axis depends on the shape of the cross-section

Torsion bars

(Bassière et Gaignebet, 1966)



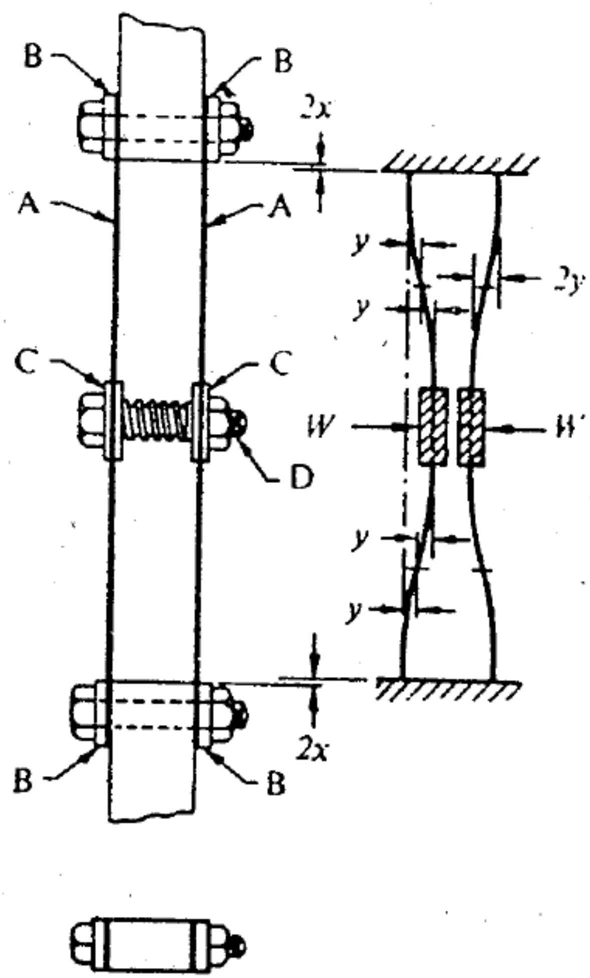




Flexures with large reduction factors

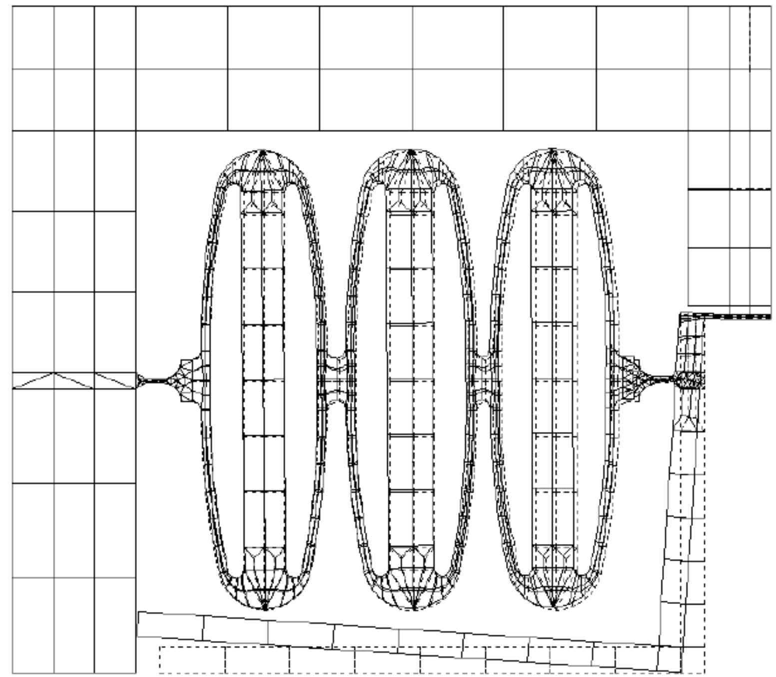
Examples of reduction and amplification mechanisms

Adjustable Strut



Application of spring strips to instrument design,
E. M. Eden, Notes of Applied Science No.15, 1956

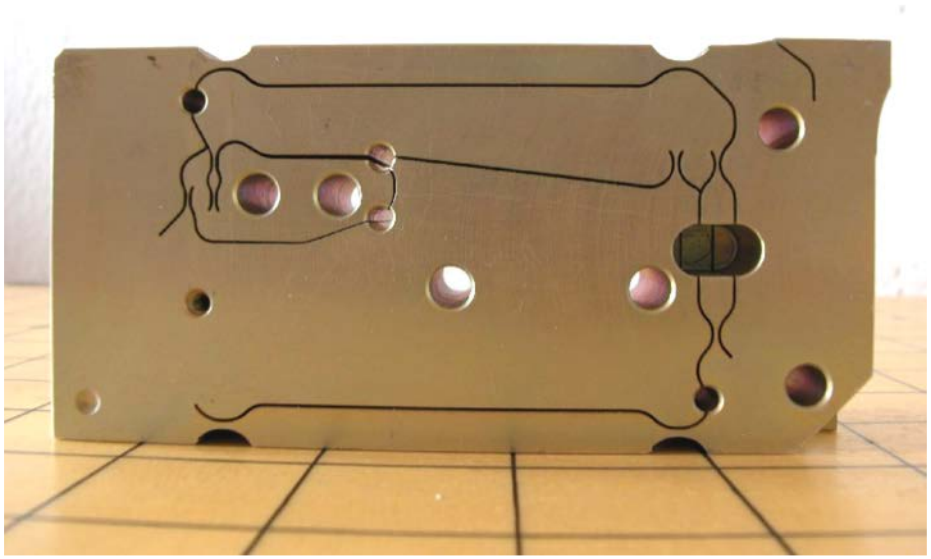
Elliptical motion amplifier

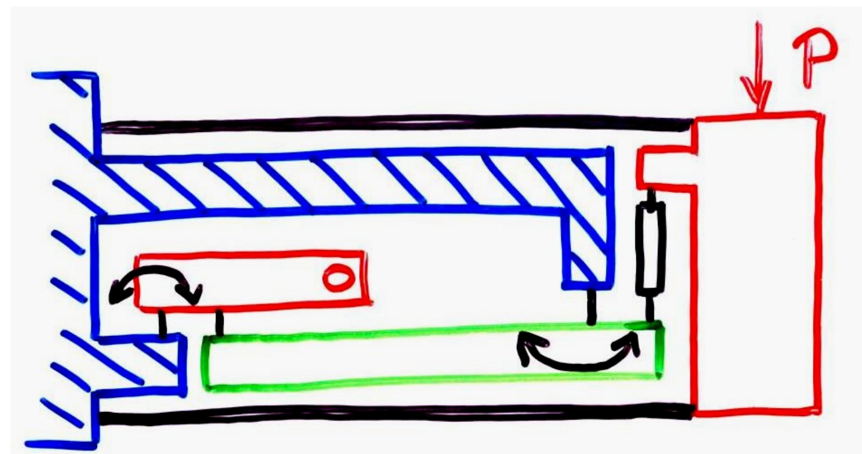


Super Amplified Piezoelectric Actuator,
N. Lehrmet, Flux Magazine,
Cedrat-Technologies, Jan. 2000

Examples of reduction and amplification mechanisms

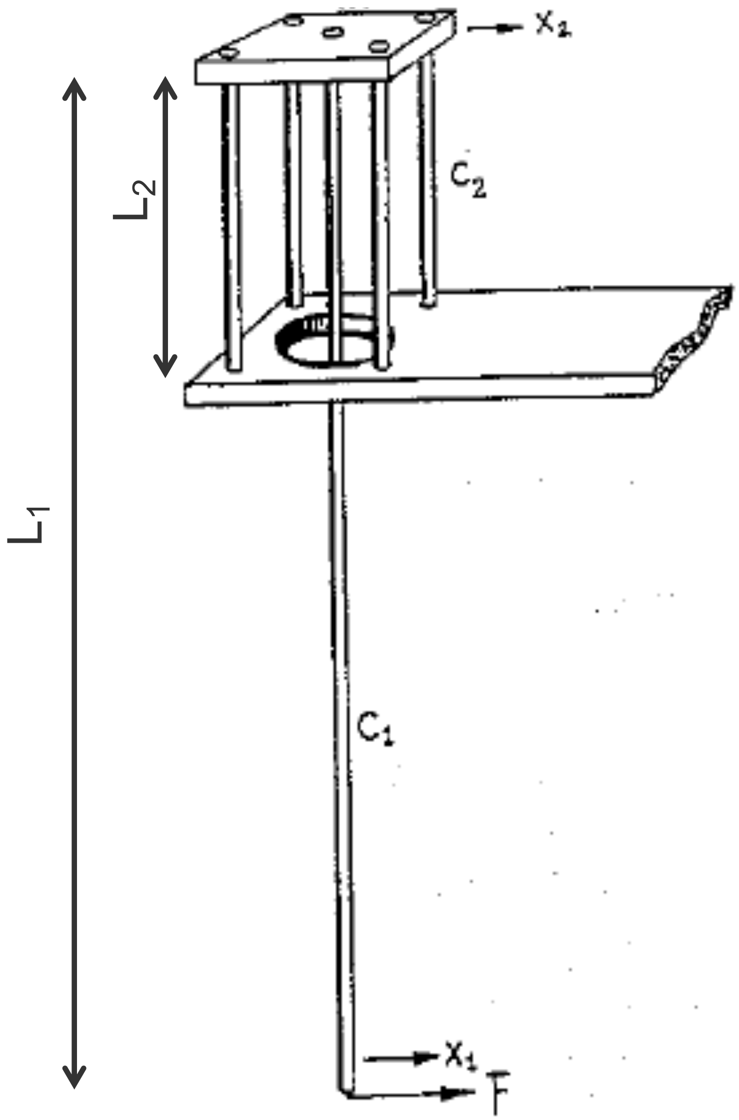
Flexible Cell for Precision Weighing Scales (Mettler-Toledo)





[E.Hungerbühler et al. (1994), Device for reducing the force in a force measuring apparatus, in particular a scale, US Patent 5,340,952]

Elastic reduction



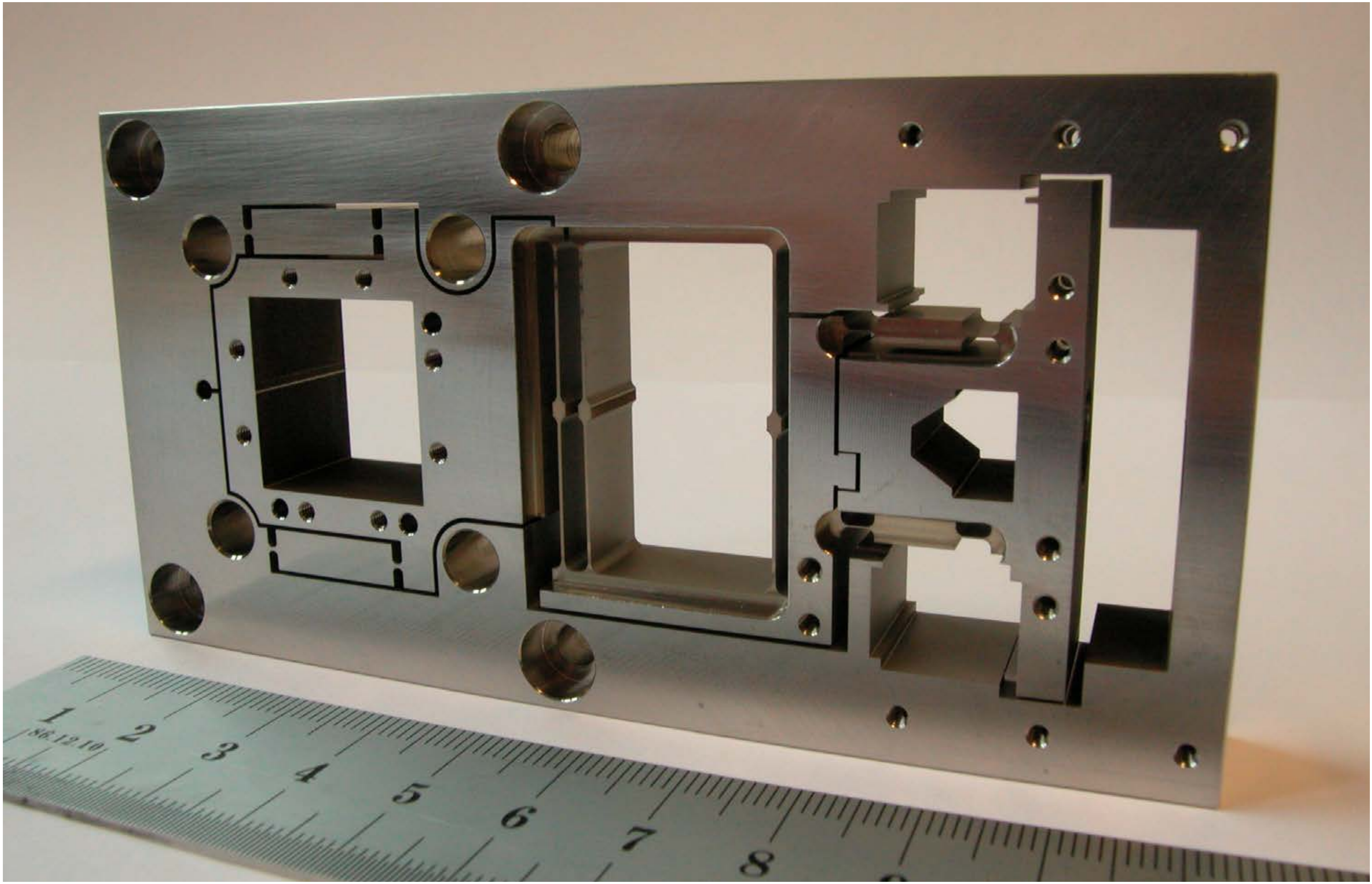
$$L1 = 3.97 \cdot L2$$

$$\Downarrow$$

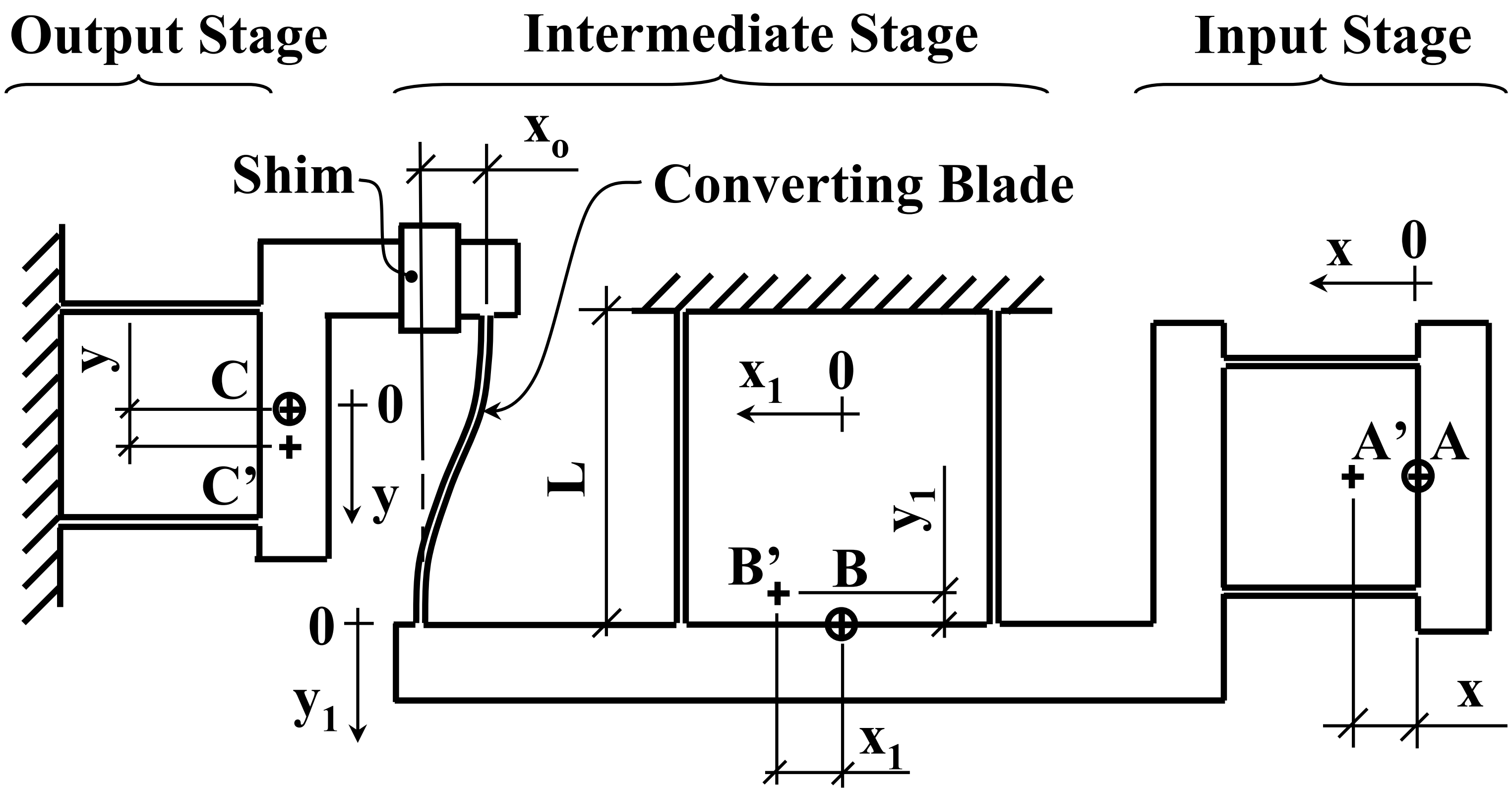
$$x_2 = x_1 / 1000$$

[M.P. Koster, Constructieprincipes, 1996]

Nanoconverter : « *Converting μm into nanometers* »



Nanoconverter : working principle



$$y_1 = -3x_1^2/(5L) \qquad x_1 \cong x$$

$$y = \frac{3(x+x_0)^2}{5L} - \frac{3x^2}{5L} = \frac{6x_0}{5L}x + \frac{3x_0^2}{5L}$$

$\Rightarrow$

Reduction factor:

$$\boxed{i = \frac{x}{y} = \frac{5L}{6x_0}}$$

[Henein, S. (2006), European Patent EP06021785, Device for converting a first motion into a second motion responsive to said first motion under a demagnification scale, Holder: Paul Scherrer Institut]

Nanoconverter : key characteristics

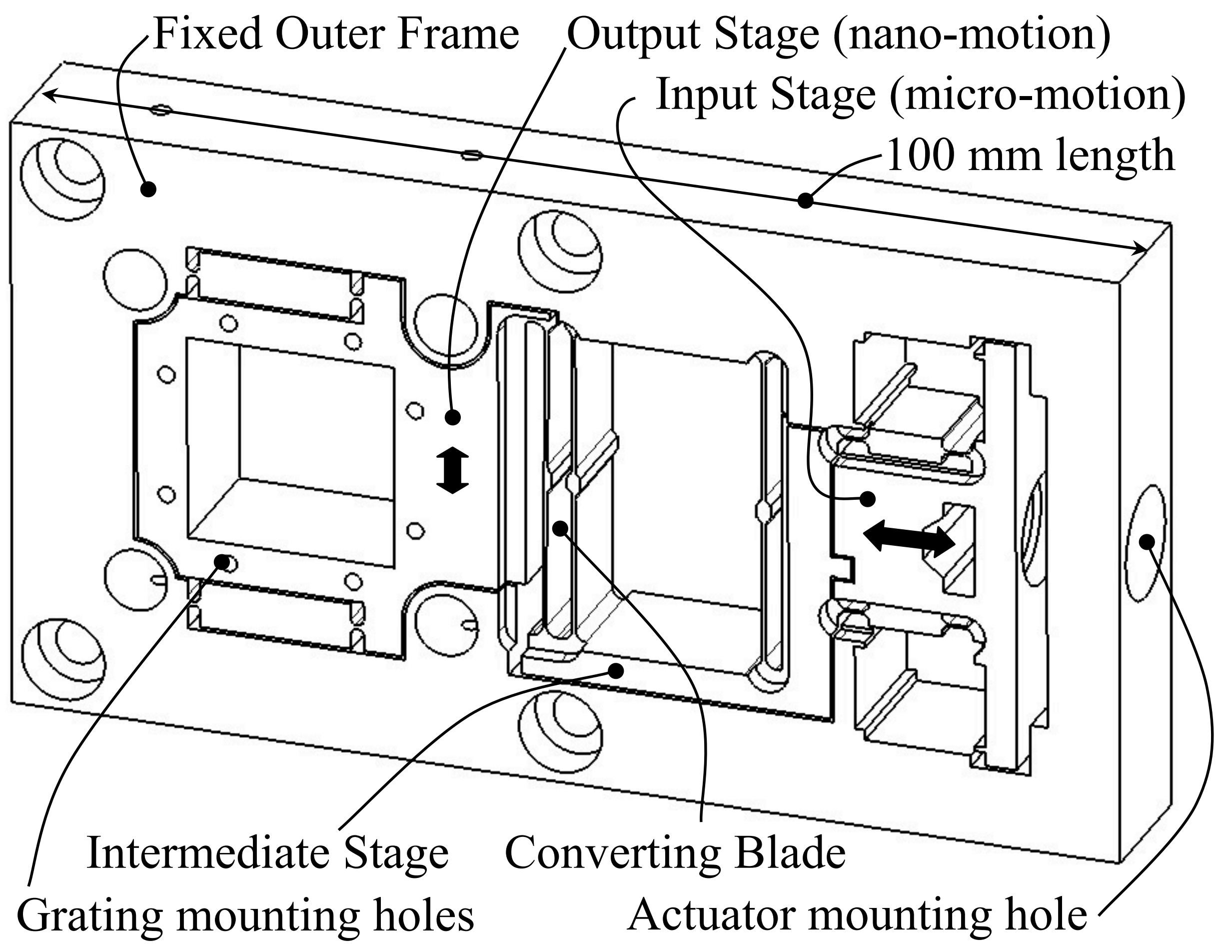
Main blades
Lenght: 30 mm
Thickness: 0.35 mm
Width: 10 mm

Offset: 0.25 mm

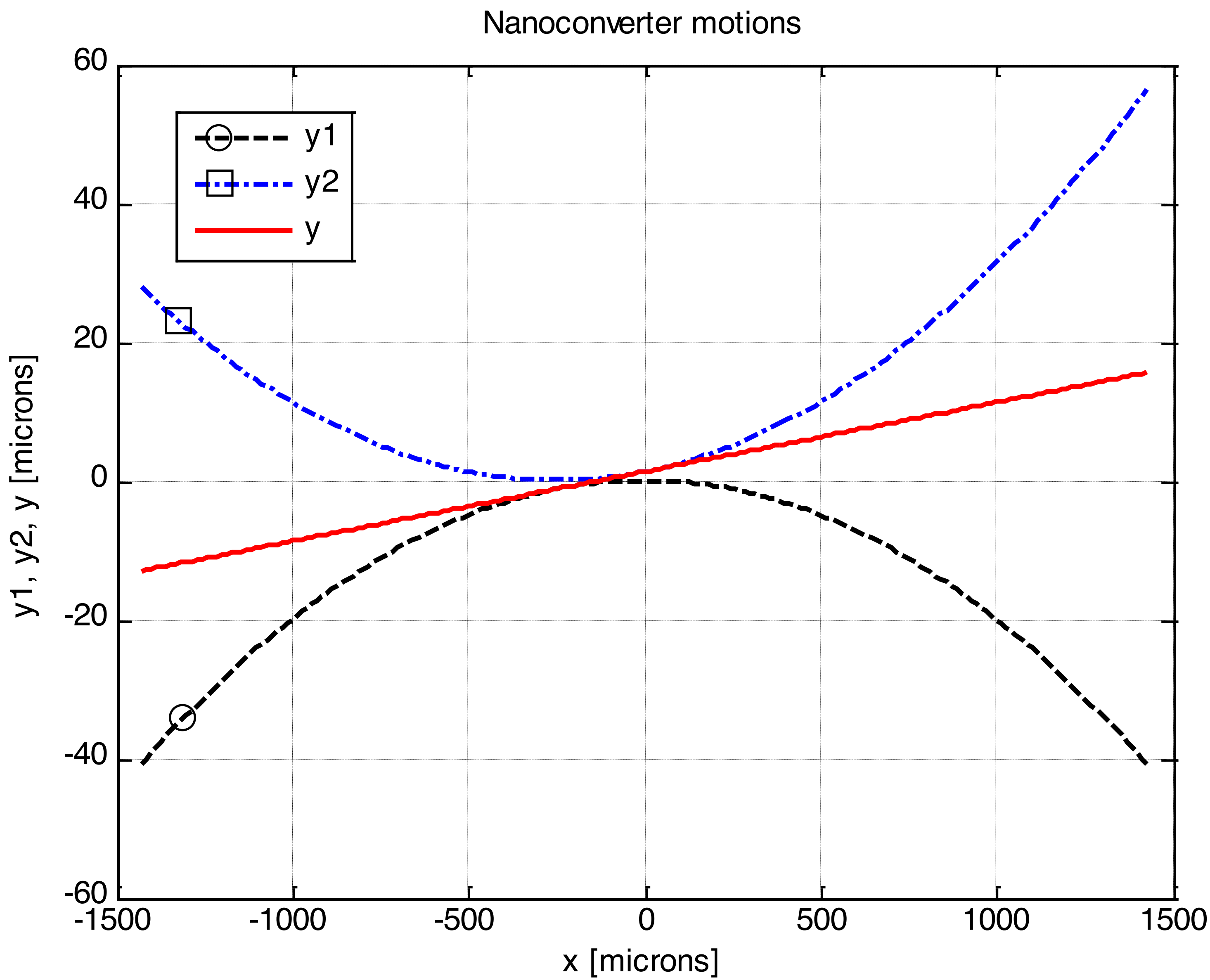
Reduction factor: 100

Material : Stainless Steel
Böhler W720

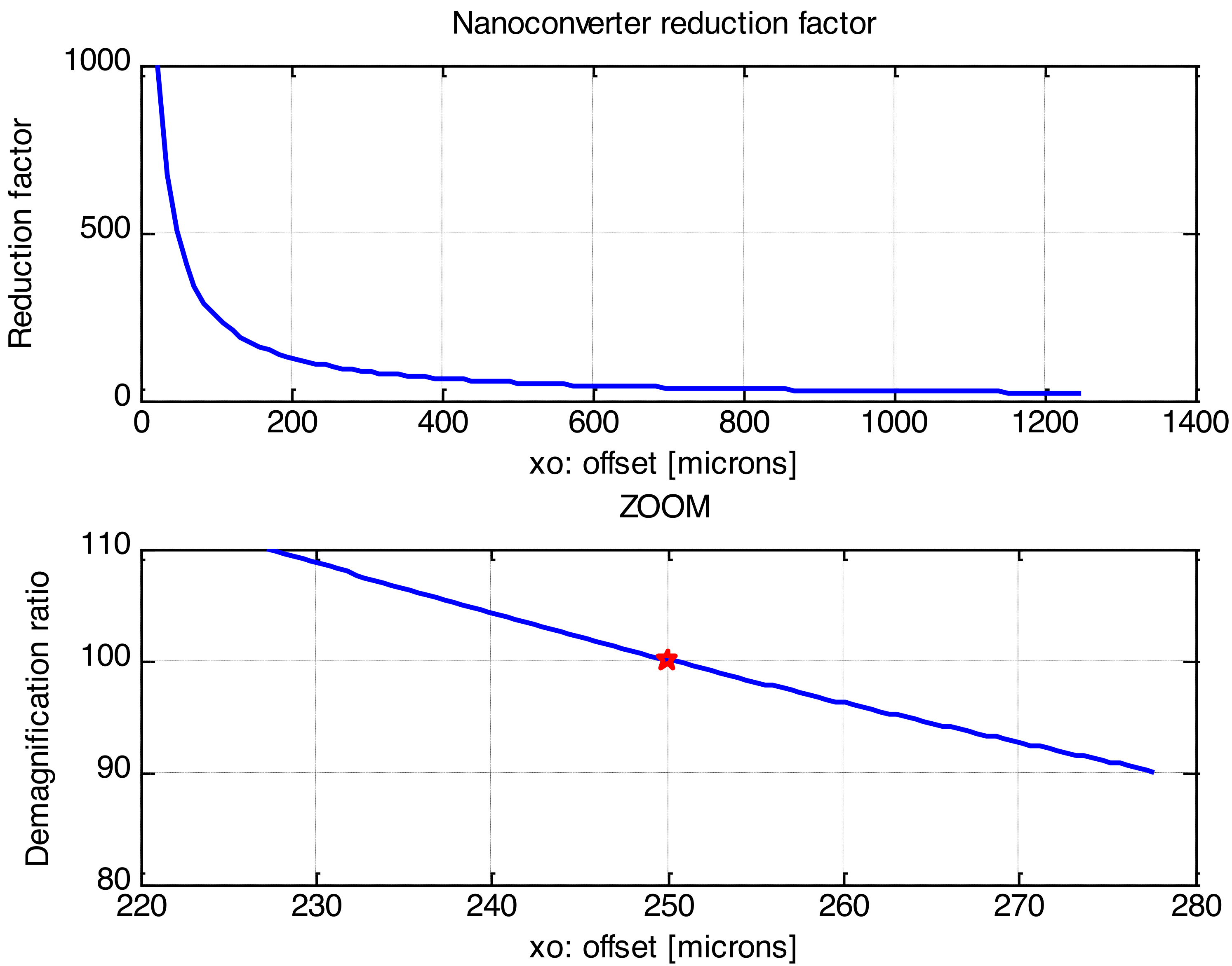
Manufacturing: Wire-EDM
(Monolithical)



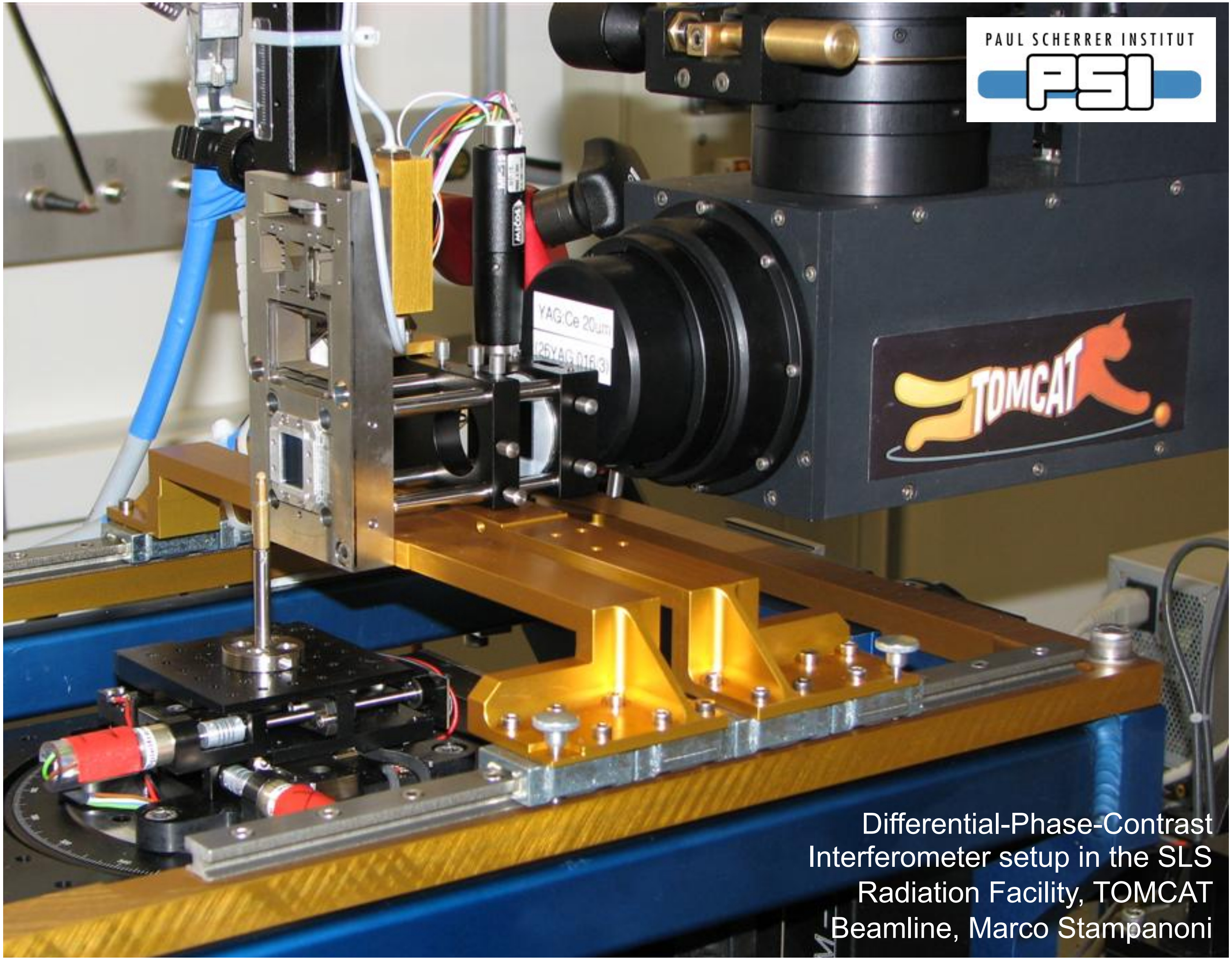
Nanoconverter : differential linear conversion



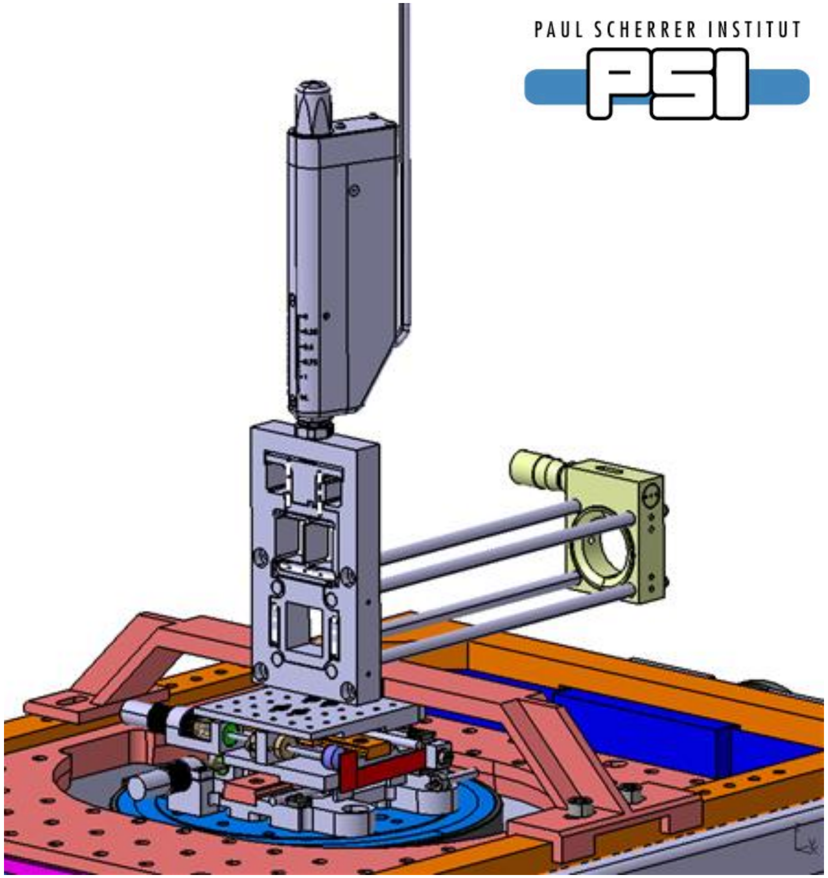
Reduction factor as a function of the offset (e.g. for L=30 mm)



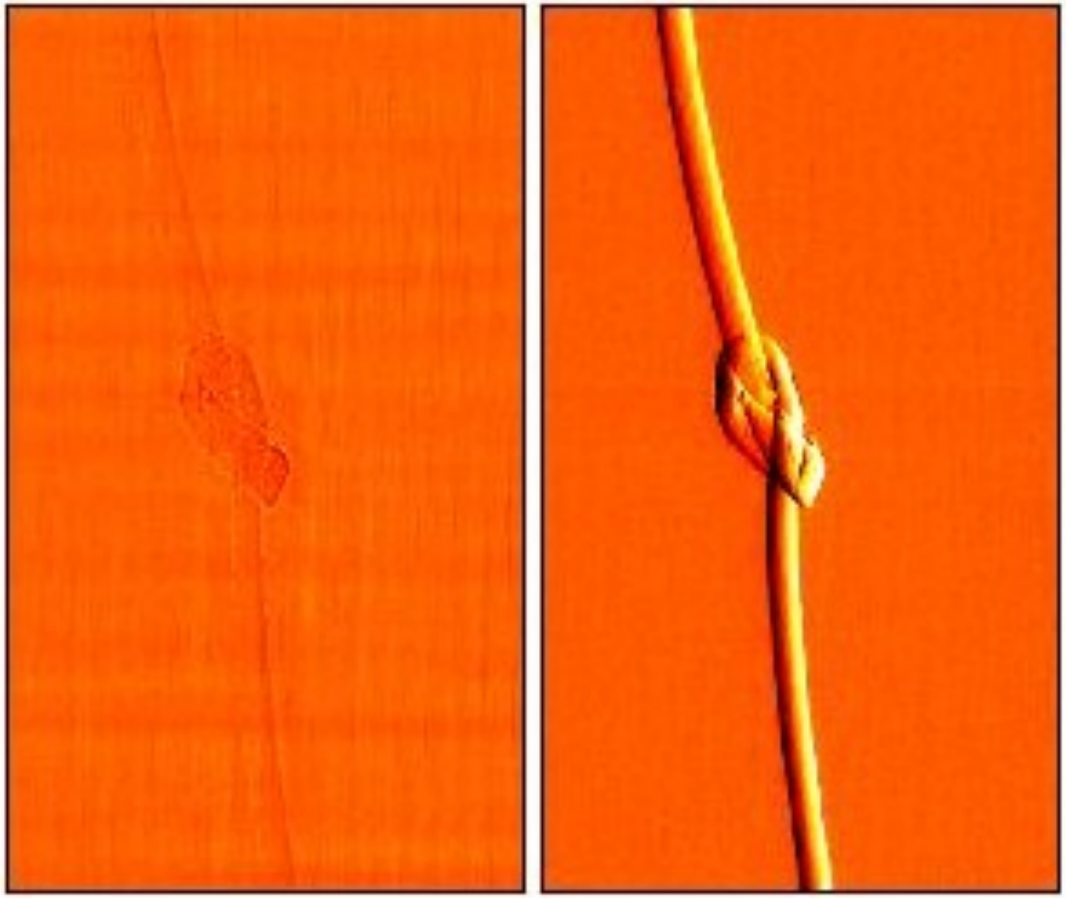
Differential Phase Contrast setup



Application: Differential Phase Contrast (DPC) Interferomtery



Differential-Phase-Contrast Setup



Phase gradient image (right) of a human hair with knot compared to classical absorption image (left)

Trends in synchrotron-based tomographic imaging: the SLS experience, M. Stampanoni et al., Proceedings of SPIE, Vol. 6318, Developments in X-Ray Tomography V, Ulrich Bonse, Editor, 2006

Nanoconverter : conclusions

Key advantages

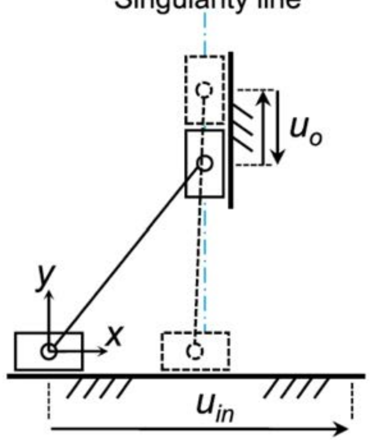
- Wide range of reduction factor achievable: typically 20 to 1000
- Linear conversion (reduction factor fixed over the full motion range)
- Planar design (2D), monolihtically manufacturable by EDM, Laser, Etching...etc

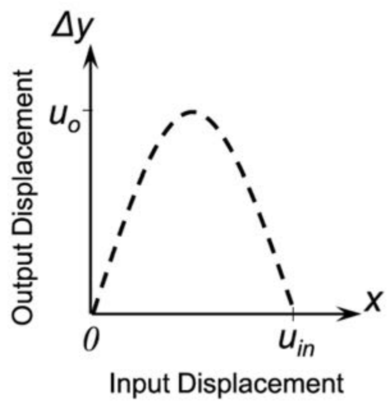
[Henein S. (2006), Device for converting a first motion into a second motion responsive to said first motion under a demagnification scale, Patent EP06021785, Holder: Paul Scherrer Institut]

[Henein, S. et al. (2007), The Nanoconverter: a novel flexure-based mechanism to convert microns into nanometers, Proc. of the 7th EUSPEN International Conference, Bremen]

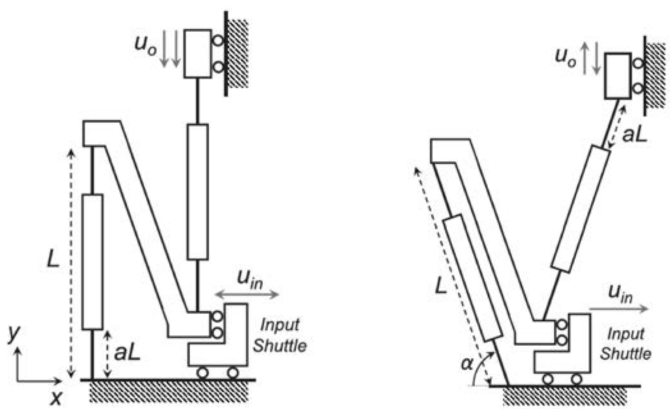
Frequency quadrupler

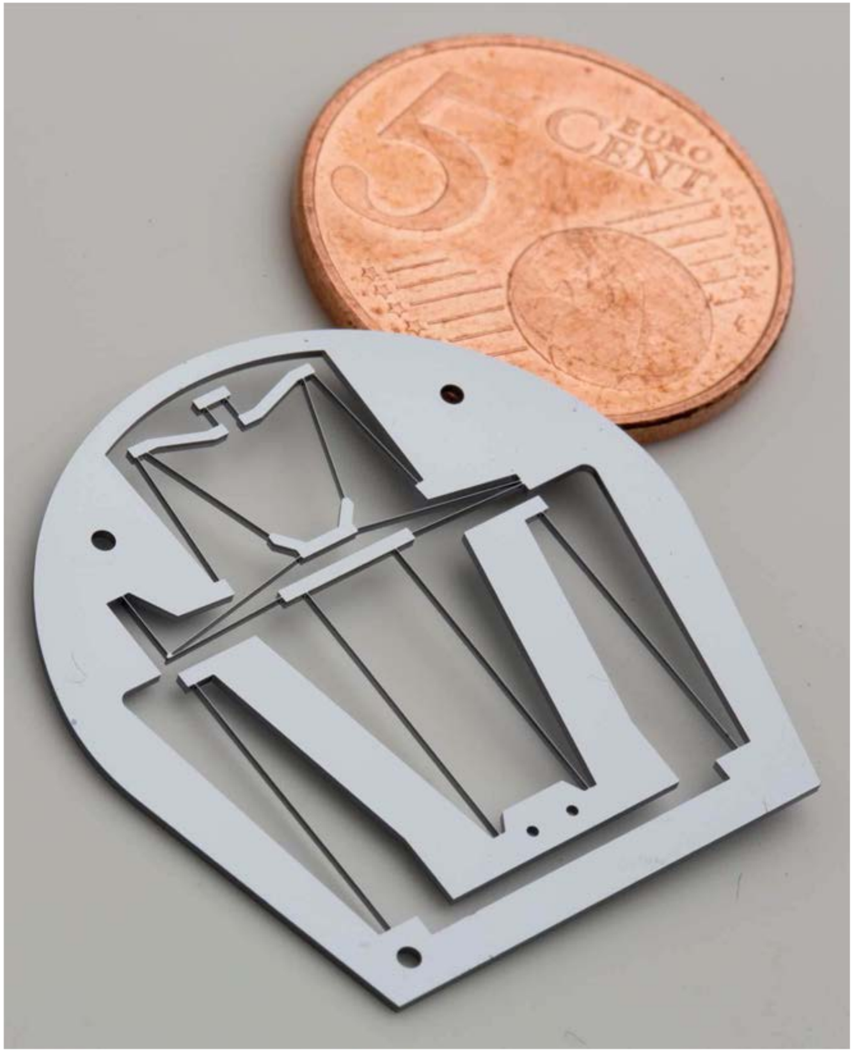
Frequency doubling using parasitic motion





Flexure implementation

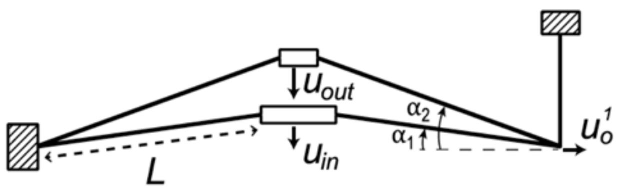


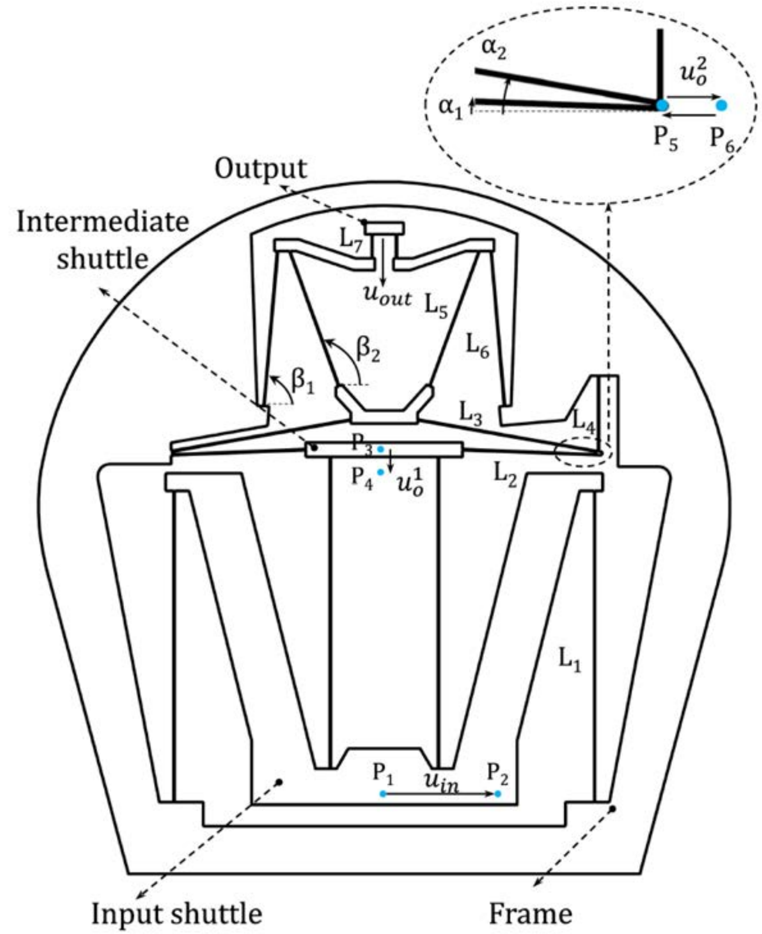


Machekposhti, D. F., Herder, J. L., Sémon, G., & Tolou, N. (2018). A Compliant Micro Frequency Quadrupler Transmission Utilizing Singularity. Journal of Microelectromechanical Systems, 27(3), 506–512

Frequency quadrupler

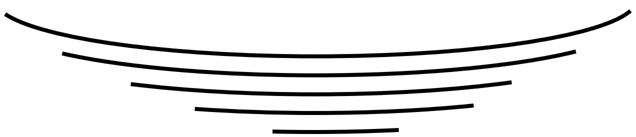
Combination with stroke amplifier





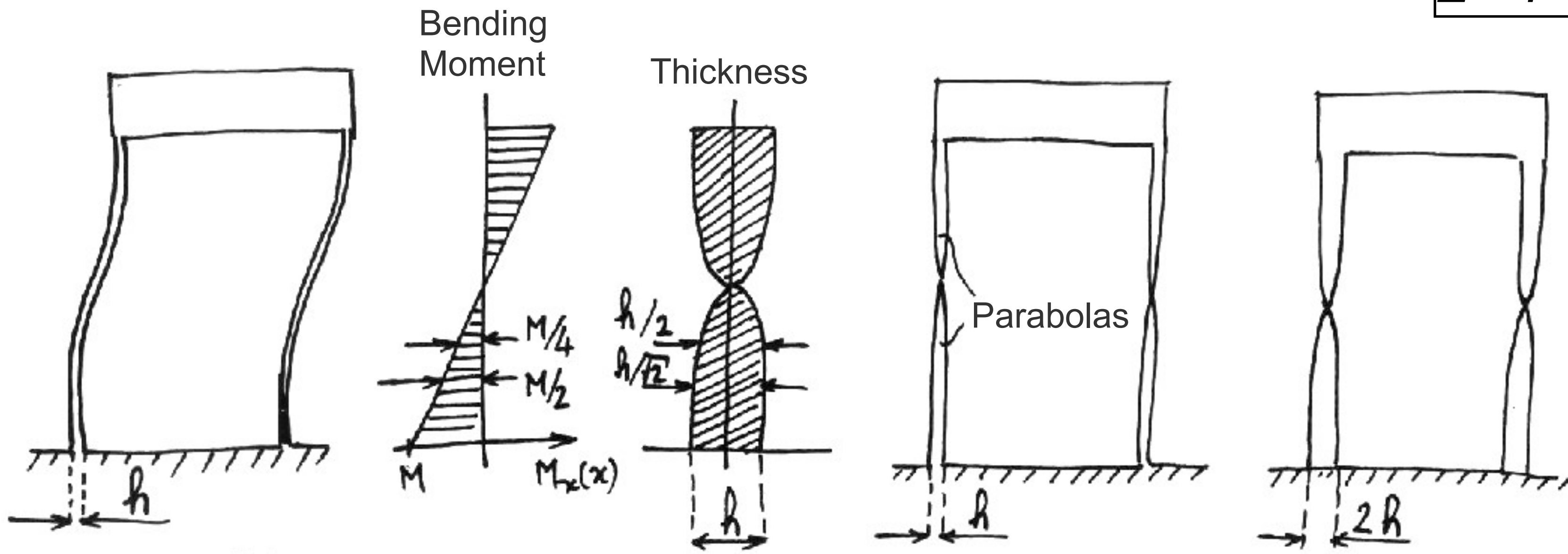
Machekposhti, D. F., Herder, J. L., Sémon, G., & Tolou, N. (2018). A Compliant Micro Frequency Quadrupler Transmission Utilizing Singularity. Journal of Microelectromechanical Systems, 27(3), 506–512

Elastic energy storage maximization

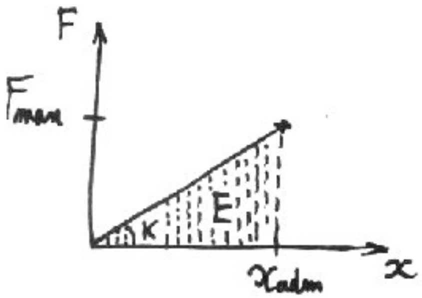


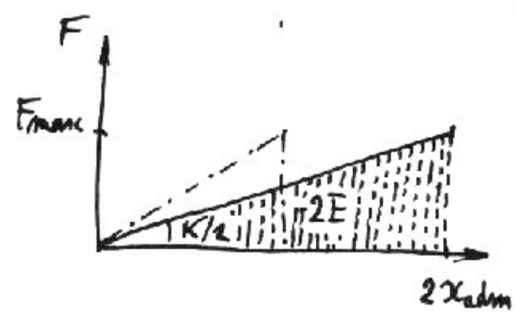
Parabolic blades

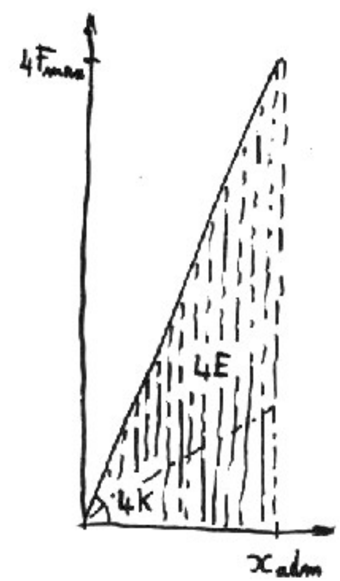
$$E = K x^2 / 2$$
$$E = F x / 2$$



Stroke	: x_{adm}	$2 \cdot x_{adm}$	x_{adm}
Stiffness	: K	$K/2$	$4K$
Force	: F_{max}	F_{max}	$4\,F_{max}$
Energy	: E $\left(E = \frac{1}{2} K x_{adm}^2 = \frac{1}{2} x_{adm} F_{max}\right)$	$2E$	$4E$

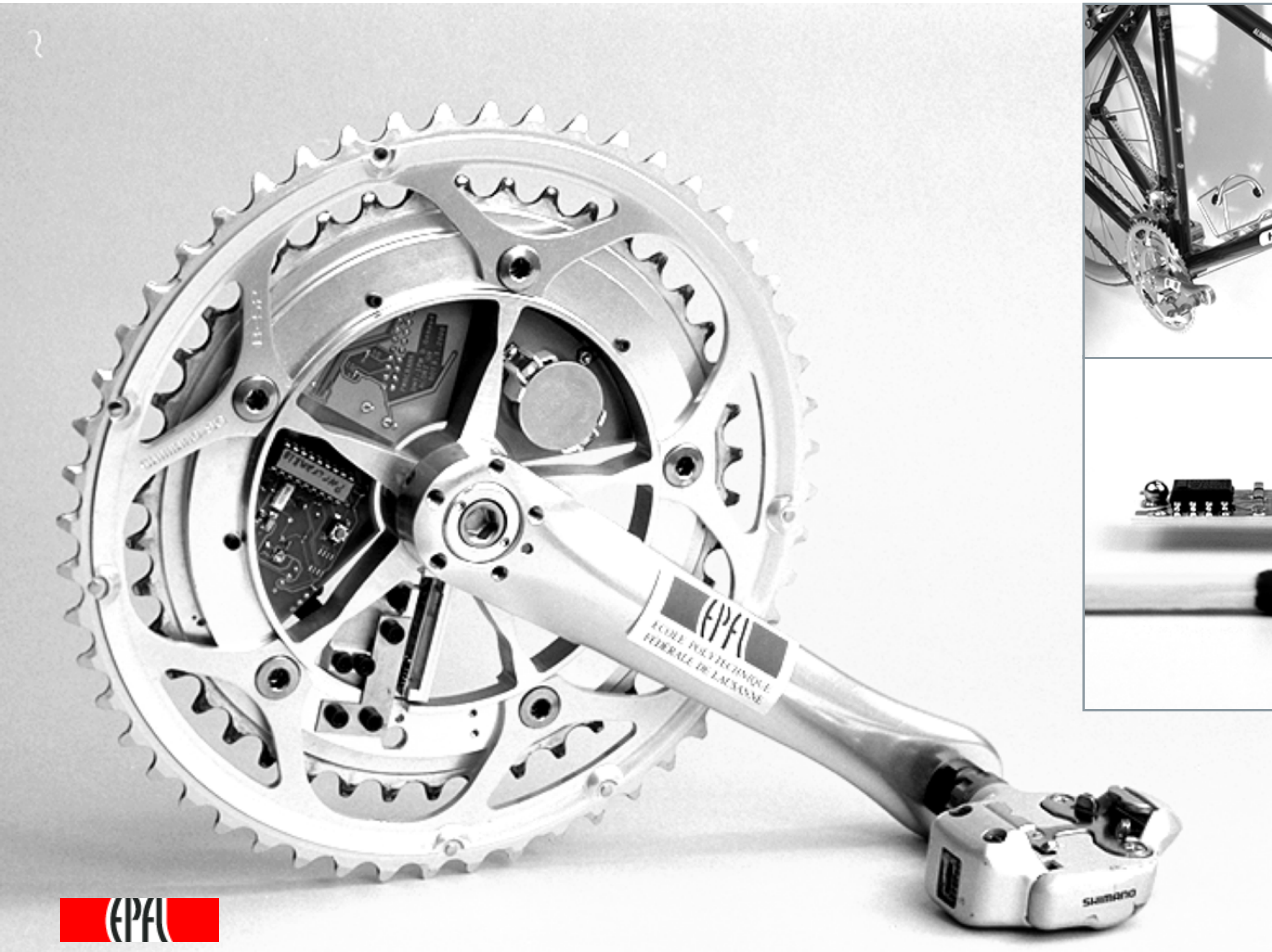






Elastic energy storage maximization

Example of a Power Counter for Bicycles



[S.Henein et al. (2000). Power Sensing Device, European Patent N° 001109196.6]

Structure optimized to get the **maximal angular stroke** for a **given torque**