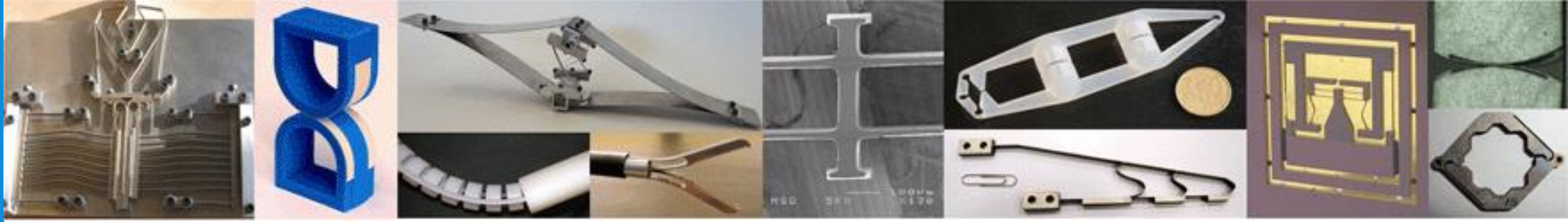
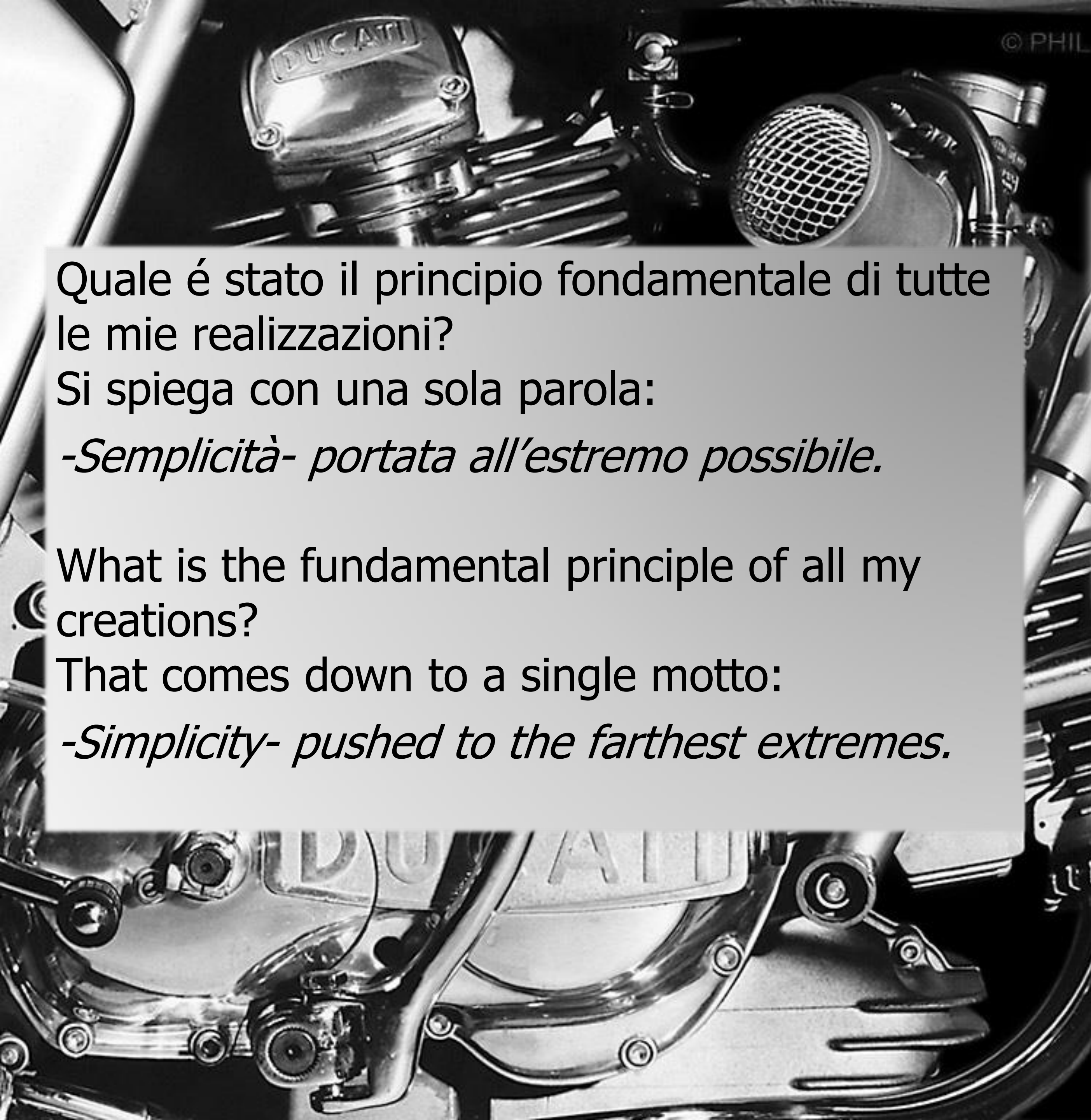


2016 Kinematics Summer School

Static Balancing of Compliant Mechanisms (SBCM)

Just Herder


SUPERSPORT 750
DUCATI



Quale é stato il principio fondamentale di tutte le mie realizzazioni?
Si spiega con una sola parola:

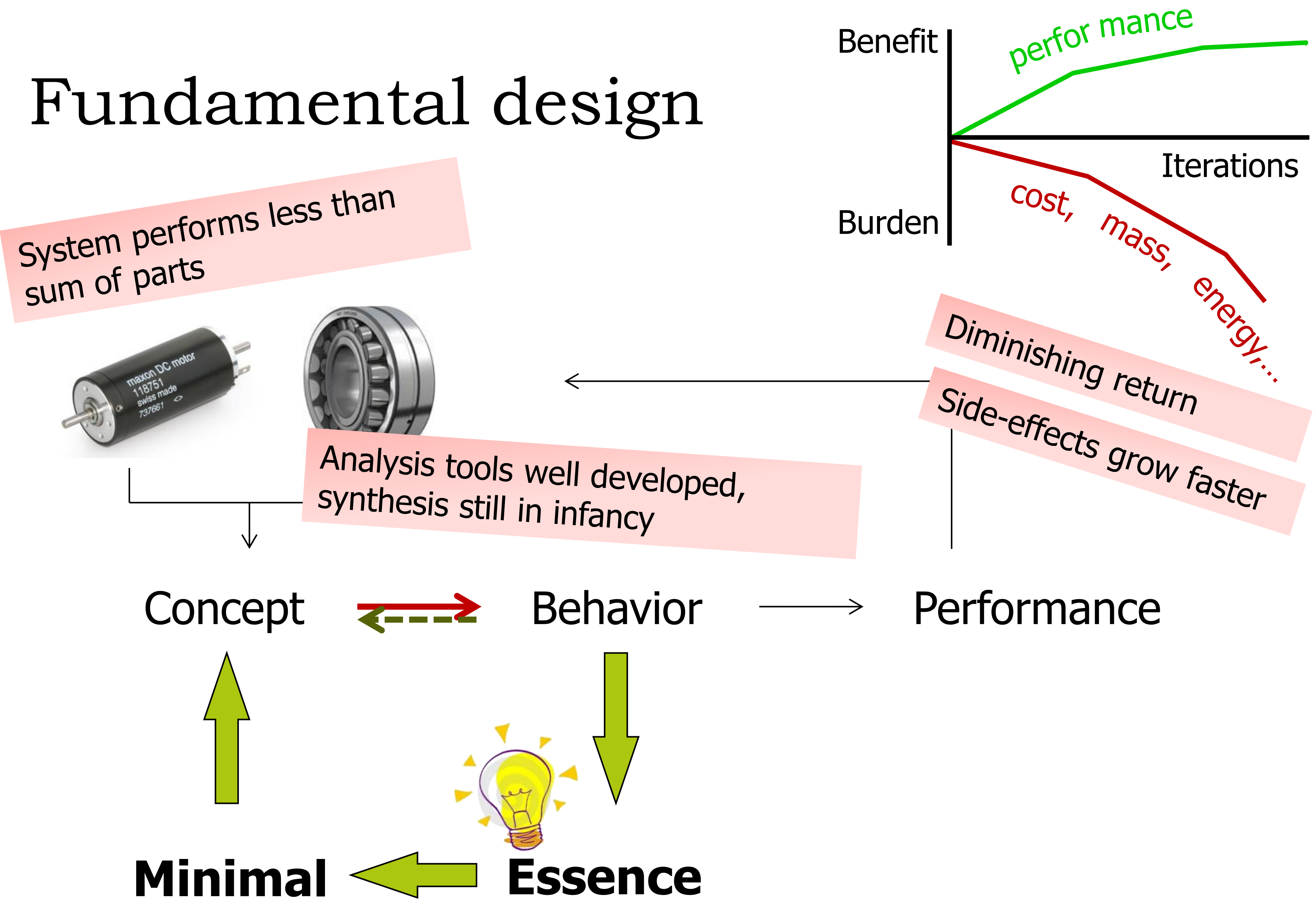
-Semplicità- portata all'estremo possibile.

What is the fundamental principle of all my creations?
That comes down to a single motto:

-Simplicity- pushed to the farthest extremes.

Ing. Fabio Taglioni

Fundamental design



Benefit

perfor mance

Iterations

Burden

cost, mass, energy,...

System performs less than sum of parts

Diminishing return

Side-effects grow faster

Analysis tools well developed, synthesis still in infancy

Concept

Behavior

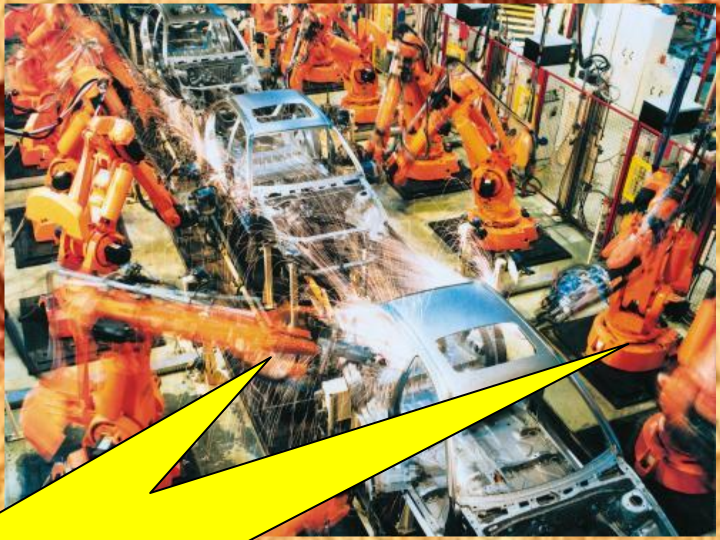
Performance

Minimal

Essence

Skelton, Slocum, Cool and others

Earliest mechanisms



Doing the wrong thing better and better...

Cave paintings in Valltorta Gorge, Spain, 20,000 BC
Kuka Robotics, TAG Heuer

Quiz

Strength and stiffness…
CM toolbox contains…
(add one..)

Ever designed a linkage mechanism?

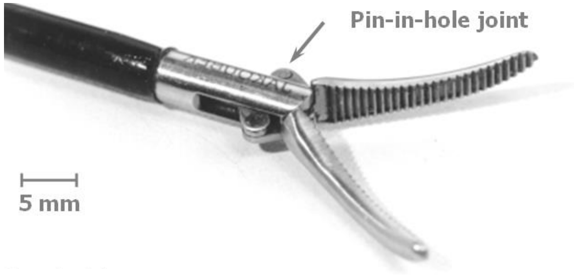
Ever designed a compliant mechanism?

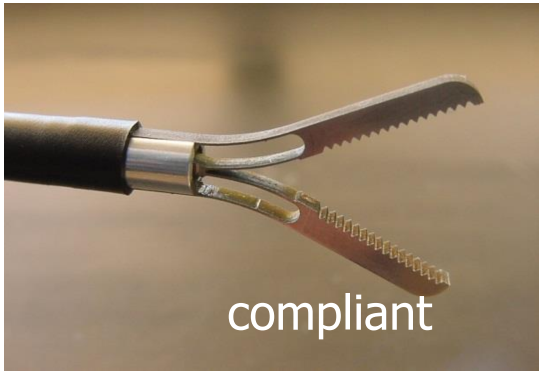
Advantages compliant mechanisms?

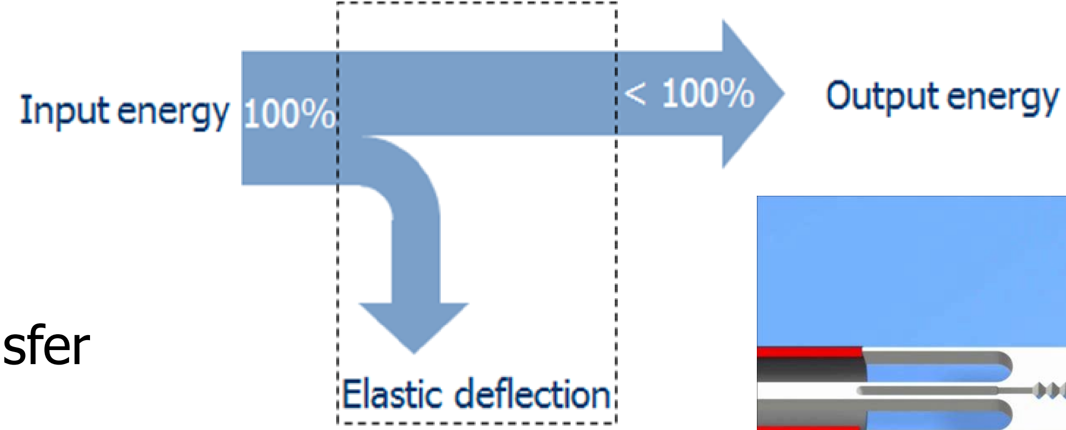
Disadvantages compliant mechanisms?

Compliant mechanisms

- Inherently soft and slender
- Low mass
- No assembly
- No friction or backlash
- No lubrication (clean, vacuum)
- Down-scalable
- …





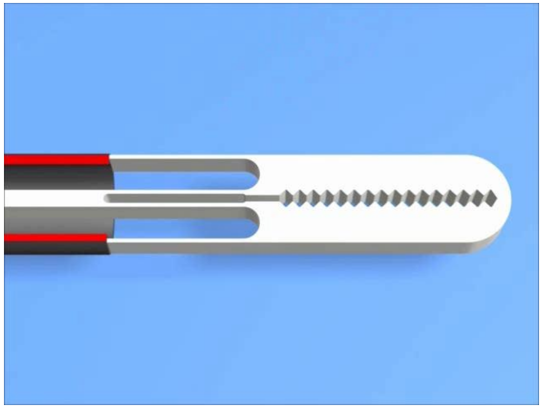


But

- Poor efficiency
- Poor force transfer

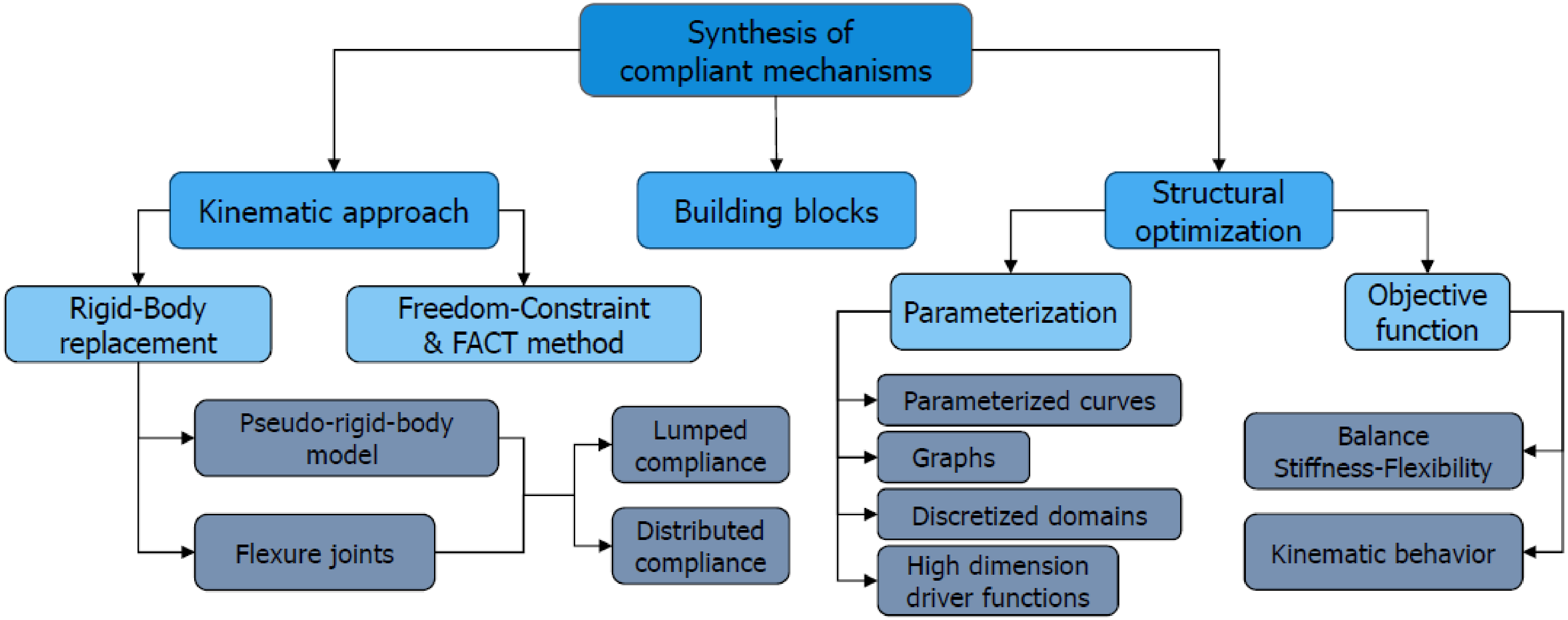
$Hooke's\ law: \sigma = E\varepsilon$

$Stiffness: F = kx$



Today

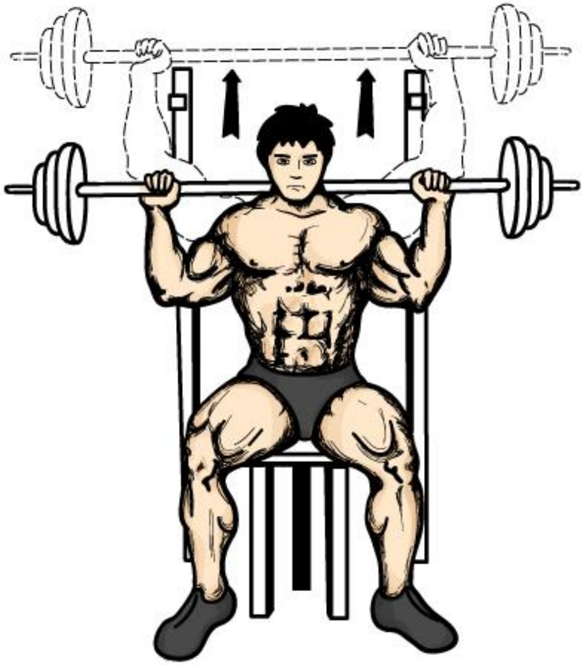
- Static balancing
- Static balancing of compliant mechanisms
- Mainly rigid body replacement



Gallego Sanchez JA, Herder JL (2009) Synthesis methods in compliant mechanisms: an overview, *2009 ASME IDETC*, 2009, San Diego, California, Paper number DETC2009-86845

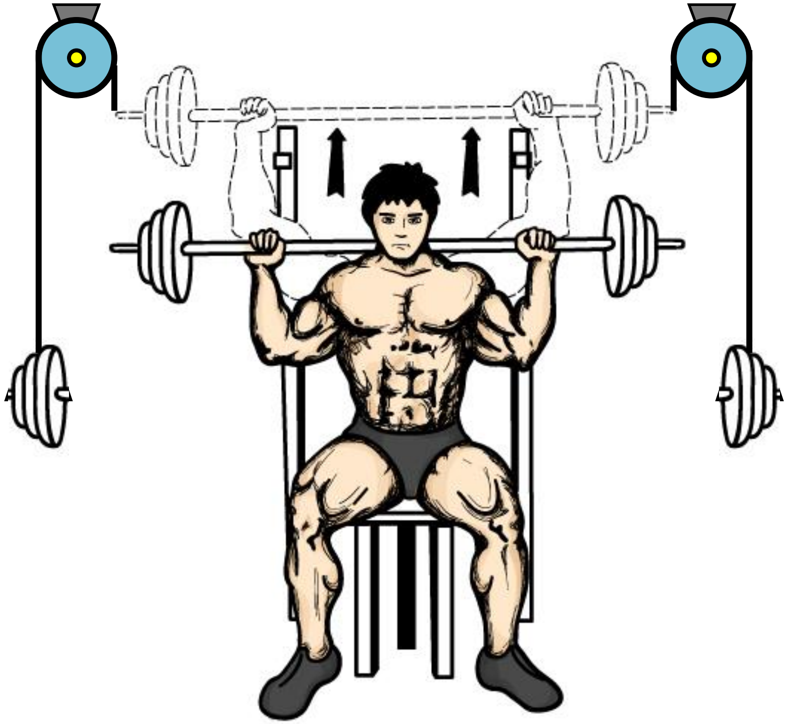
Weight lifting

- Requires doing work…



Weight lifting

- Requires doing work… or does it not?

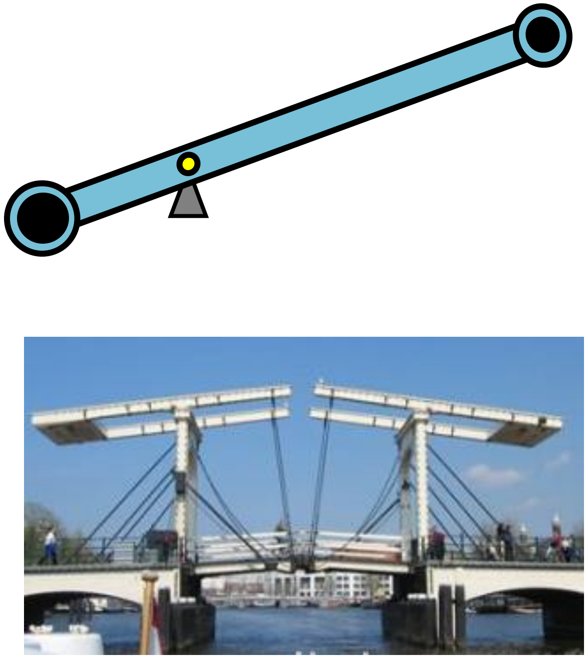


Draw bridge

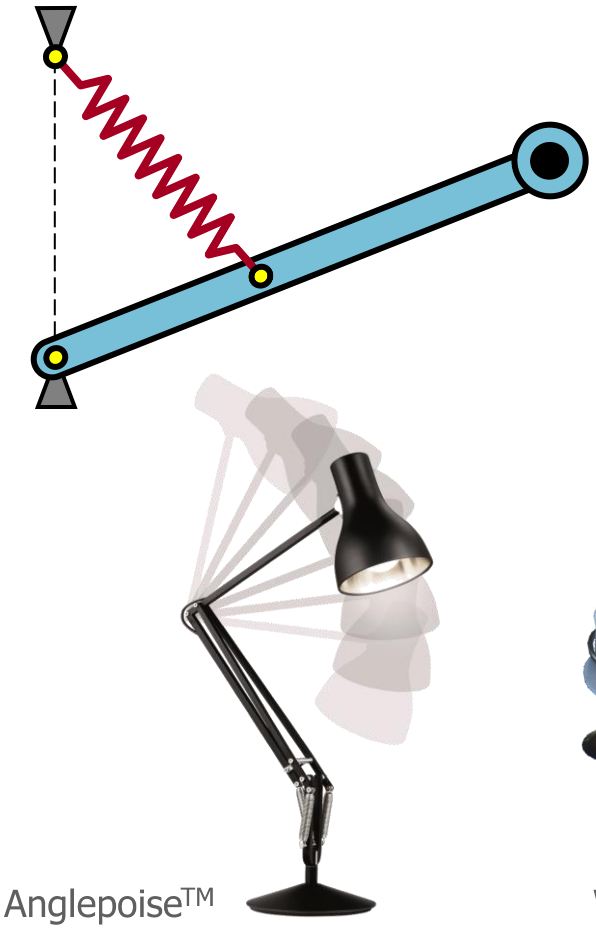
Draw bridge

Static Balancing

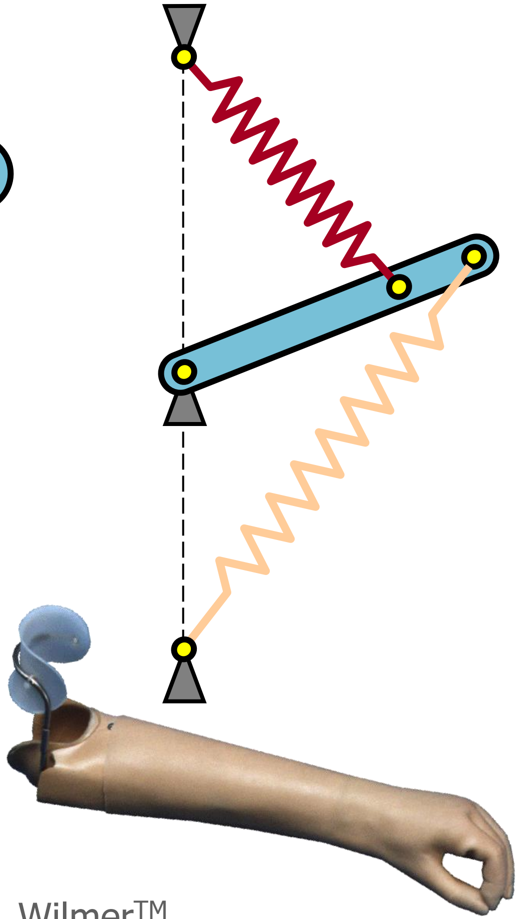
All conservative forces can be cancelled out!



Meager Bridge (Amsterdam)



Anglepoise™

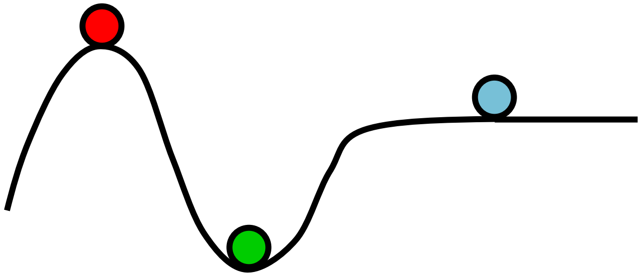


Wilmer™

Static Balancing

All conservative forces can be cancelled out!

- Continuous equilibrium
- Constant potential energy
- Neutral stability

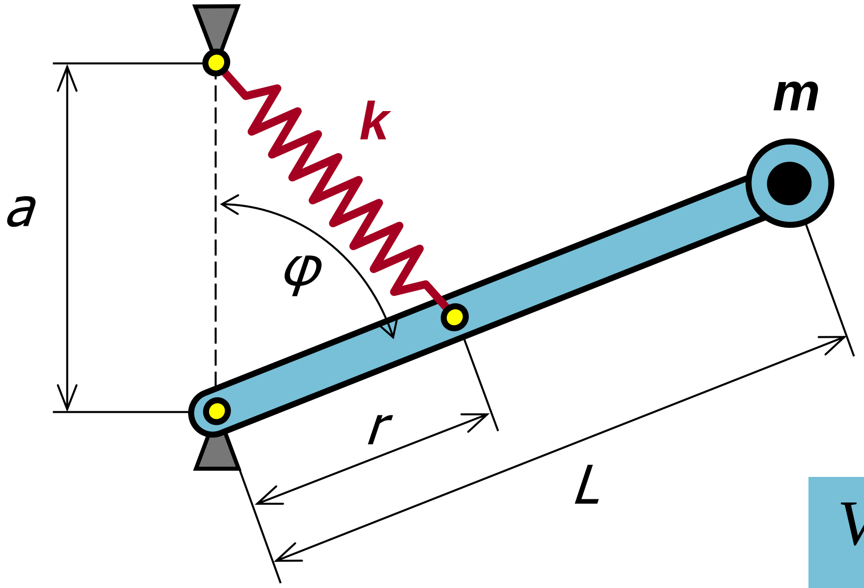


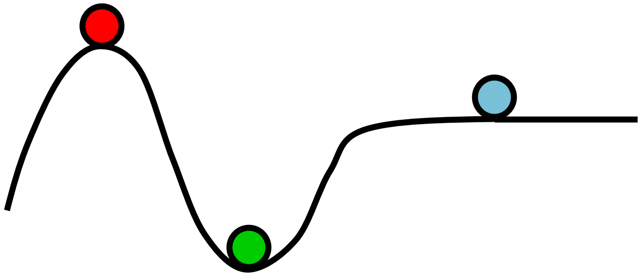
Meager Bridge (Amsterdam)

Anglepoise™

Wilmer™

Constant potential energy





Assuming zero-free-length (ZFL) springs:

$$\bar{F} = k\bar{\ell}$$

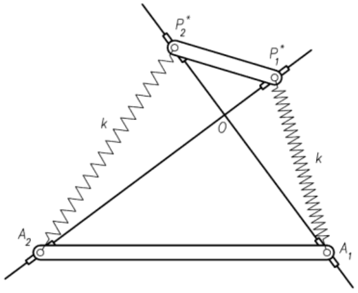
$$V_m = mgL\cos\varphi$$

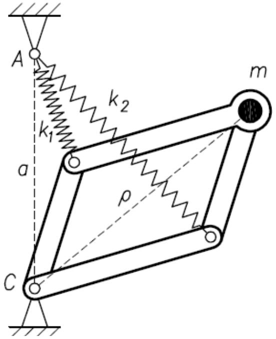
$$V_s = \tfrac{1}{2}k\ell^2 = \tfrac{1}{2}k\left(a^2 + r^2\right) - kar\cos\varphi$$

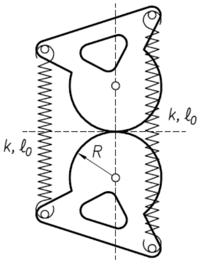
$$V_{tot} = cnst + \left(mgL - kar\right)\cos\varphi$$

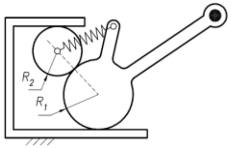
$$Condition: \boxed{mgL = kar}$$

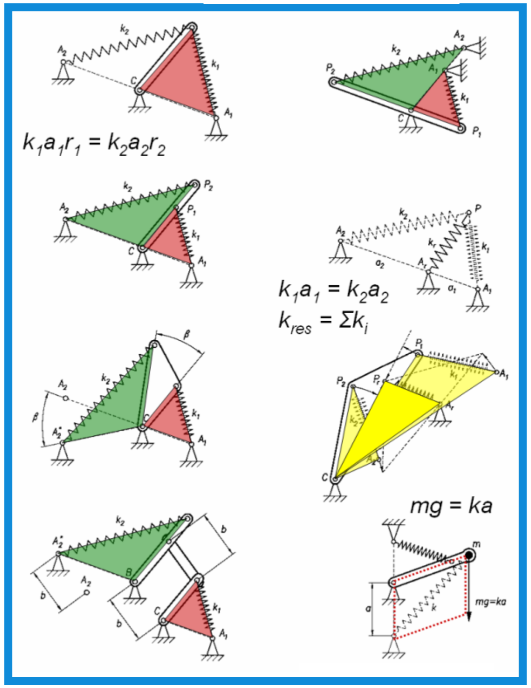
Conceptual design, framework

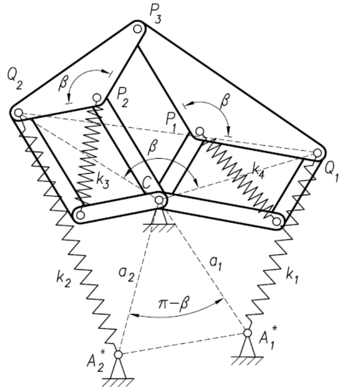


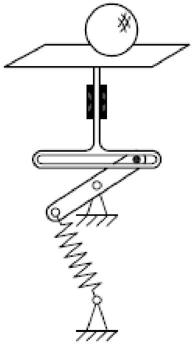


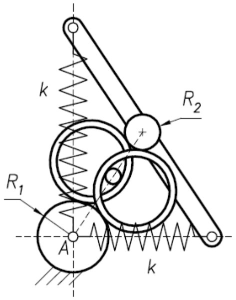


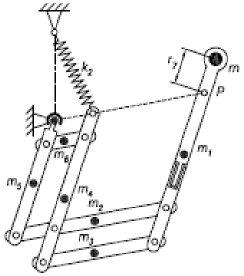


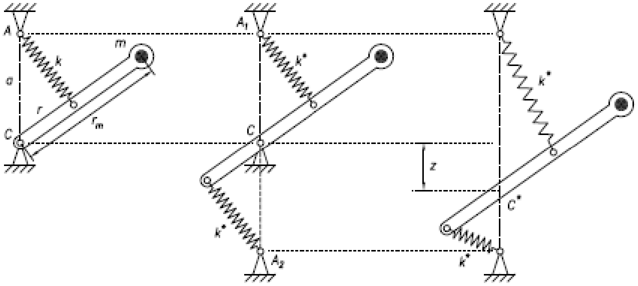


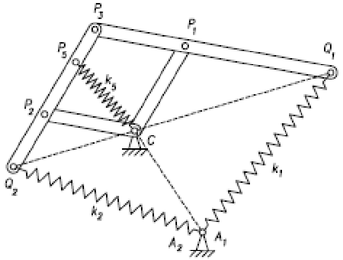


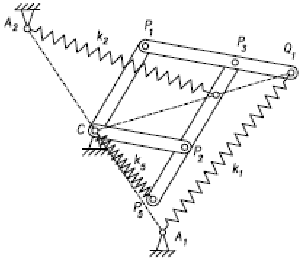


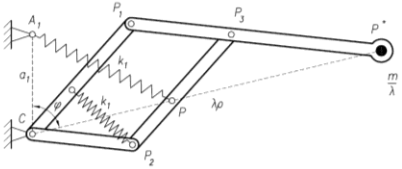




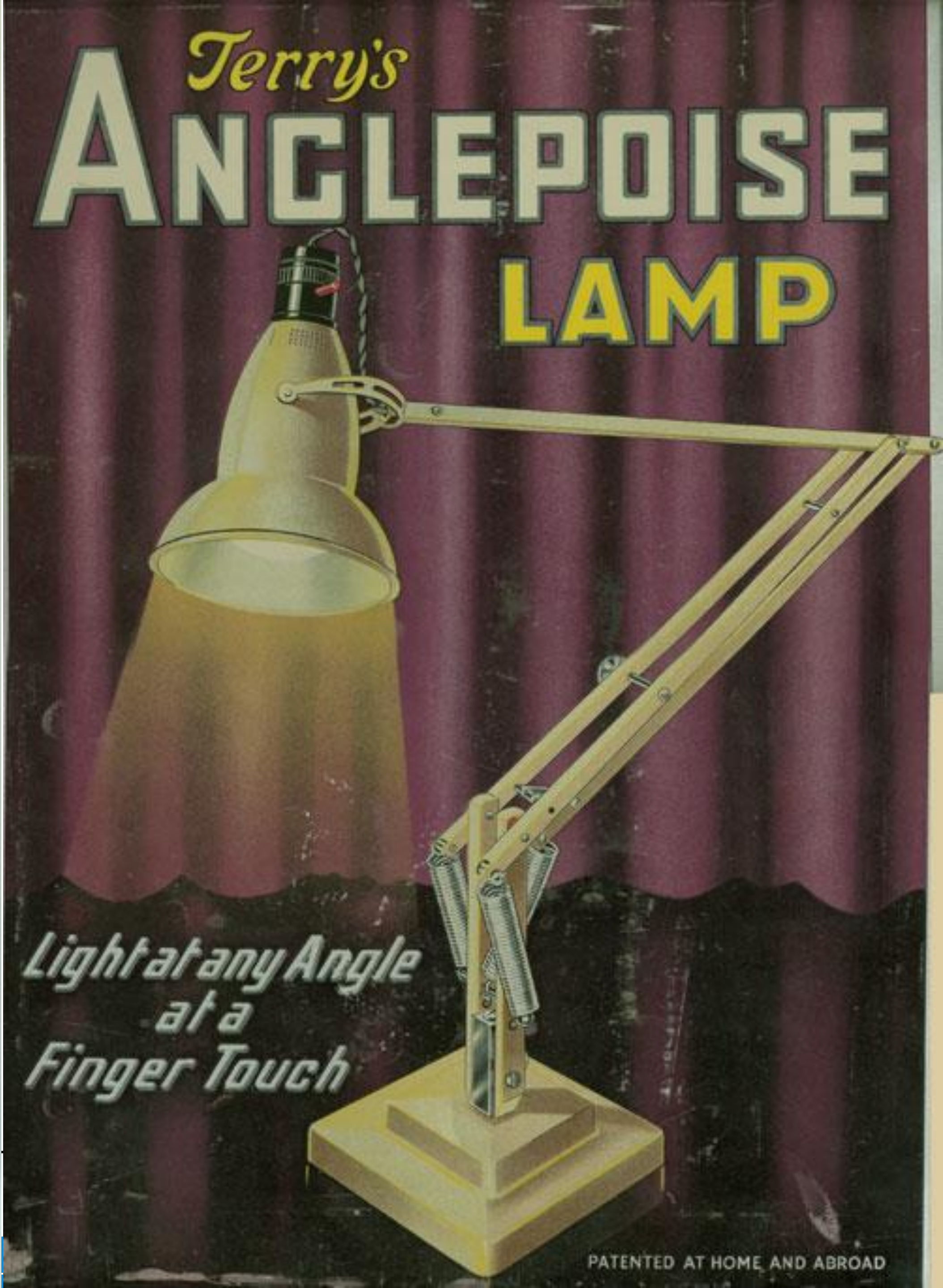




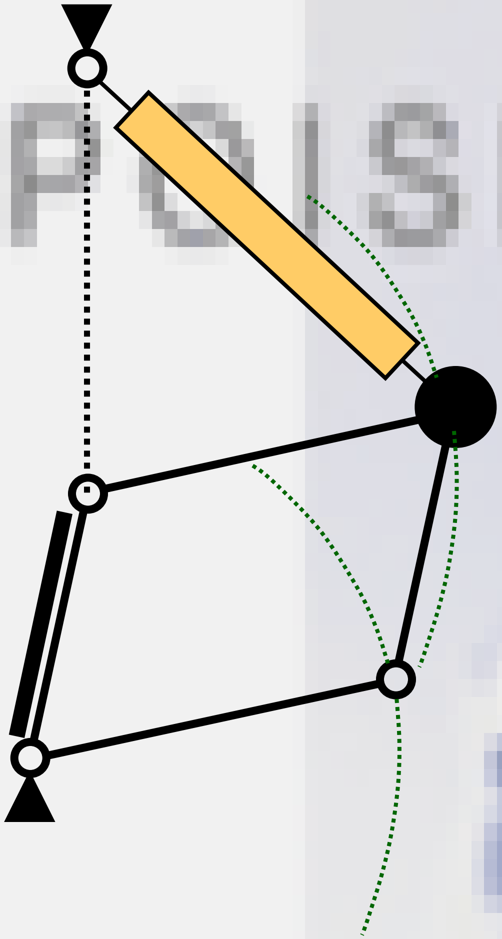




Herder JL (2001) *Energy-free Systems; Theory, conception and design of statically balanced spring mechanisms,* Ph.D. Thesis, Delft University of Technology, ISBN 90-370-0192-0 (http://repository.tudelft.nl/ search: Herder energy-free), DOI: 10.13140/RG.2.1.3942.8966.


Terry's
ANGLEPOISE
LAMP
Light at any Angle at a Finger Touch
PATENTED AT HOME AND ABROAD

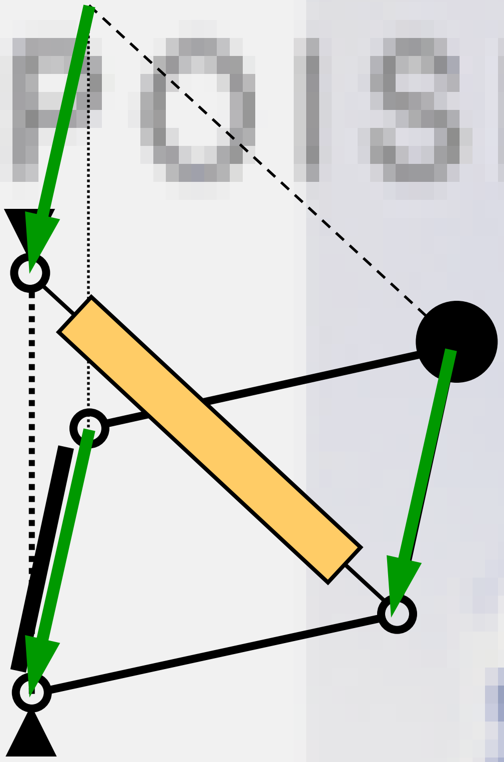
ANGLEPOISE®



$mgL_1=r_1k_1a_1$

Superposition:

first degree of freedom



Modification:

shift of spring element

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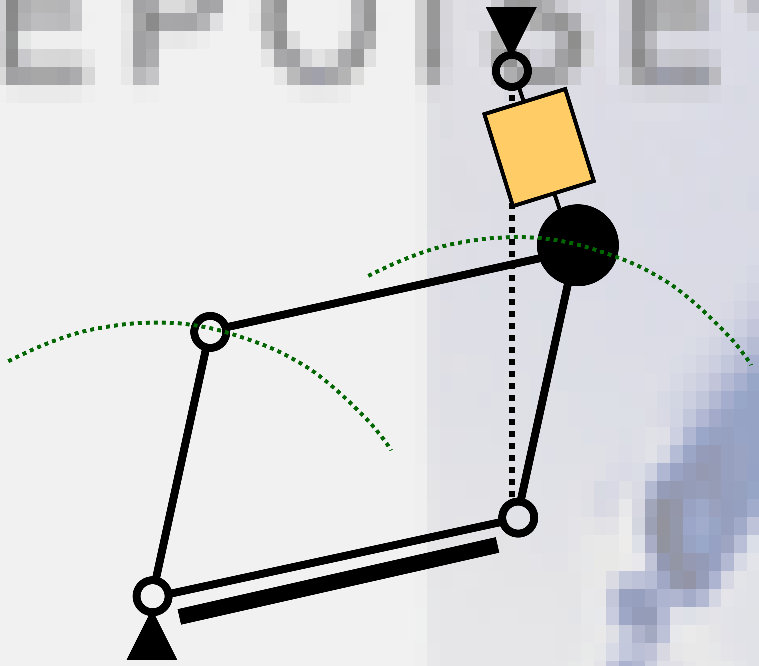

$mgL_2=r_2k_2a_2$

Superposition:

second degree of freedom

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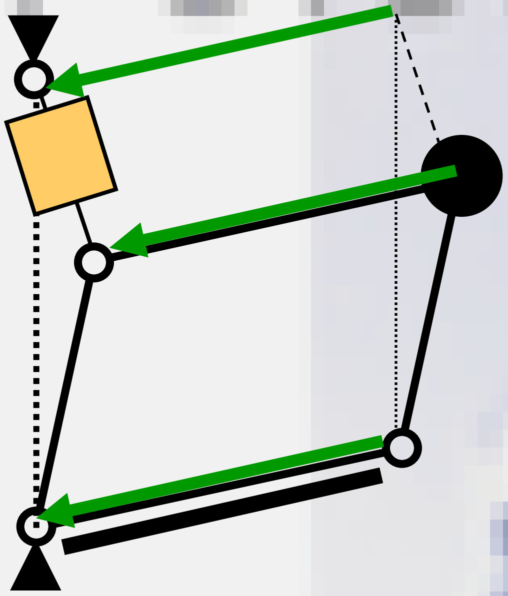
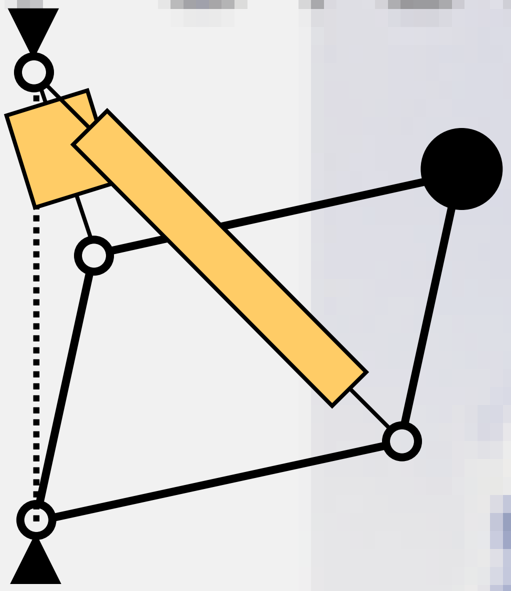


Modification:

shift of spring element

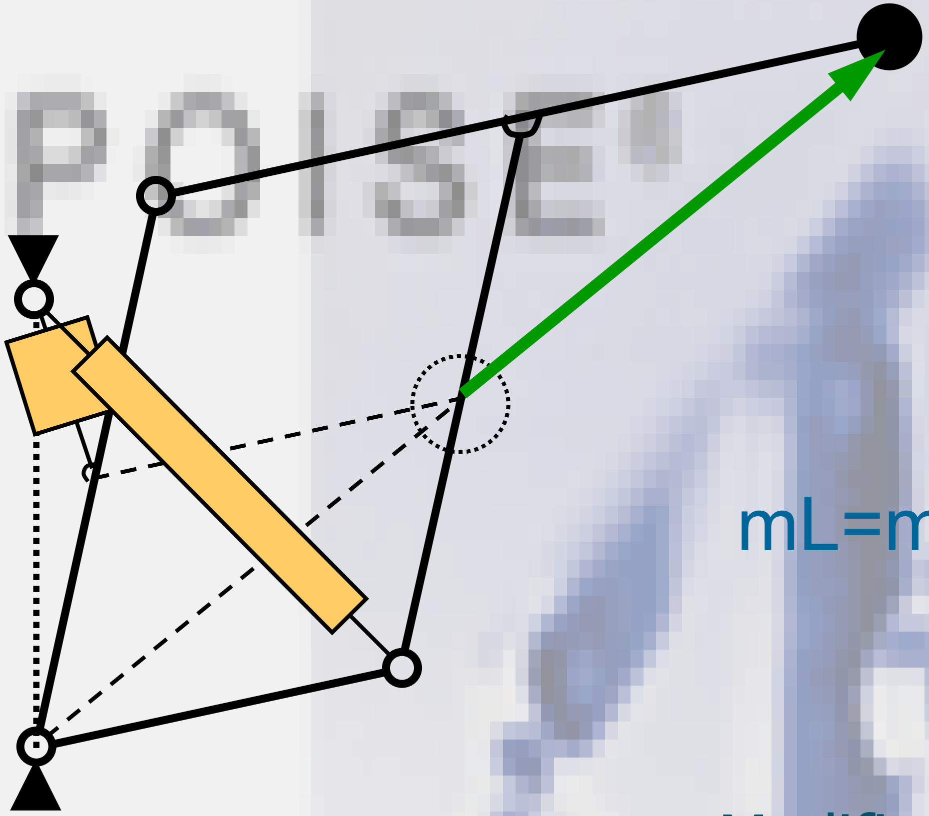


$mgL_1=r_1k_1a_1$

$mgL_2=r_2k_2a_2$

Superposition:

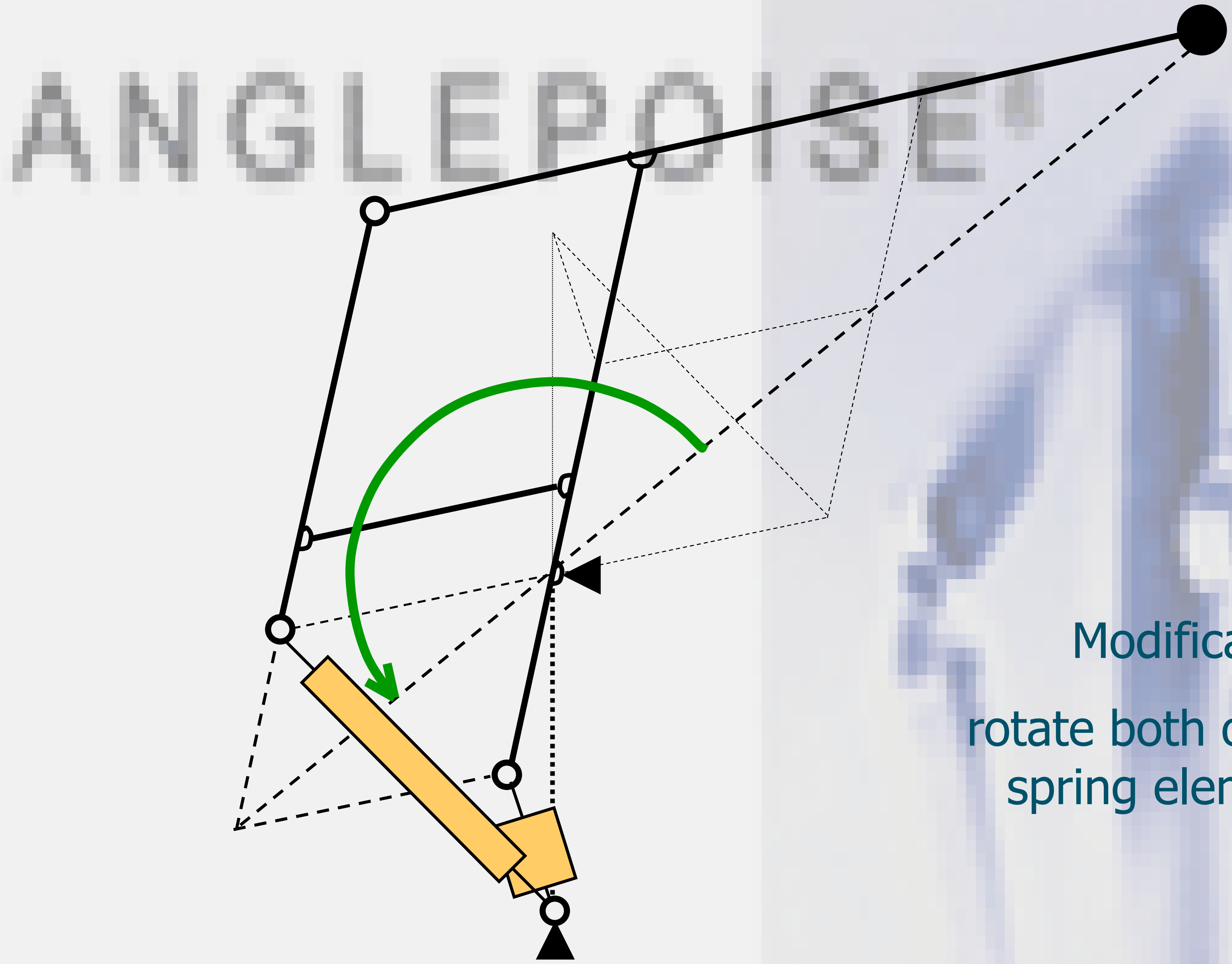
combination of the two degrees of freedom



mL=m’L’

Modification:

elongate lever while reducing mass



Modification:

rotate both of the spring elements

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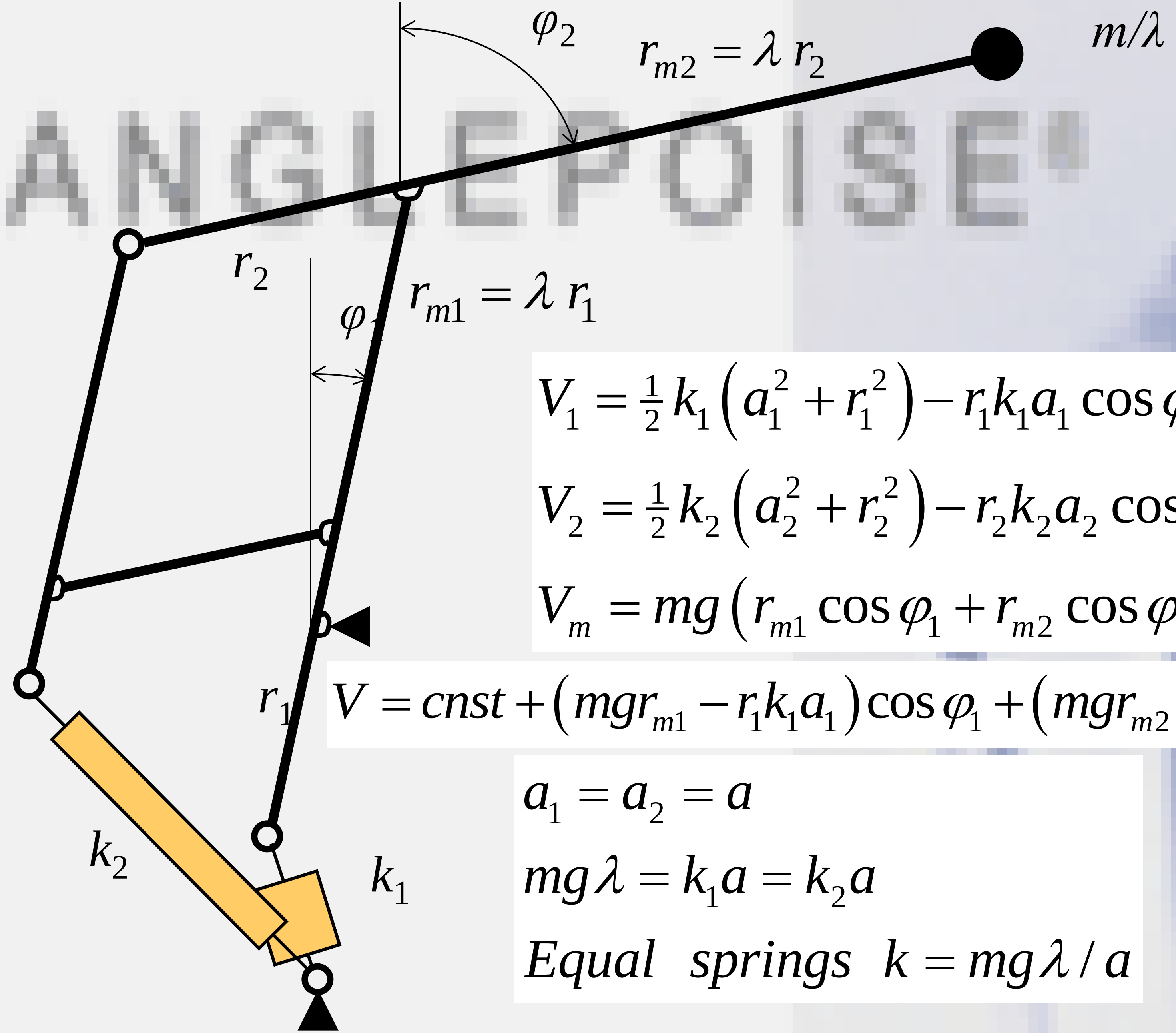
Carwardine

(1935)



$$V_1 = \tfrac{1}{2} k_1 \left(a_1^2 + r_1^2\right) - r_1 k_1 a_1 \cos\varphi_1$$

$$V_2 = \tfrac{1}{2} k_2 \left(a_2^2 + r_2^2\right) - r_2 k_2 a_2 \cos\varphi_2$$

$$V_m = mg\left(r_{m1}\cos\varphi_1 + r_{m2}\cos\varphi_2\right)$$

$$V = cnst + \left(mgr_{m1} - r_1 k_1 a_1\right)\cos\varphi_1 + \left(mgr_{m2} - r_2 k_2 a_2\right)\cos\varphi_2$$

$$a_1 = a_2 = a$$

$$mg\lambda = k_1 a = k_2 a$$

$$Equal \quad springs \quad k = mg\lambda / a$$

John Terry and several lamp generations

ANGLEPOISE®

ANGLEPOISE®

Type 3

www.anglepoise.com

Past work: Armon mobile arm support

MICROGRAVITY
PRODUCTS

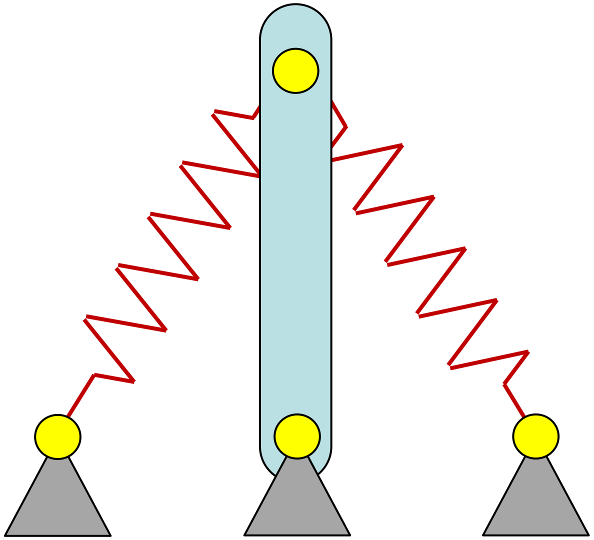
2001: MSc projects
2003: MGP established
2010: 150 units produced

Herder JL, Vrijlandt N, Antonides T, Cloosterman M, Mastenbroek PL (2006) Principle and design of a mobile arm support for people with muscular weakness, *Journal of Rehabilitation Research and Development,* 43(5)591-604 (DOI: 10.1682/JRRD.2006.05.0044).

Zero-gravity force environment

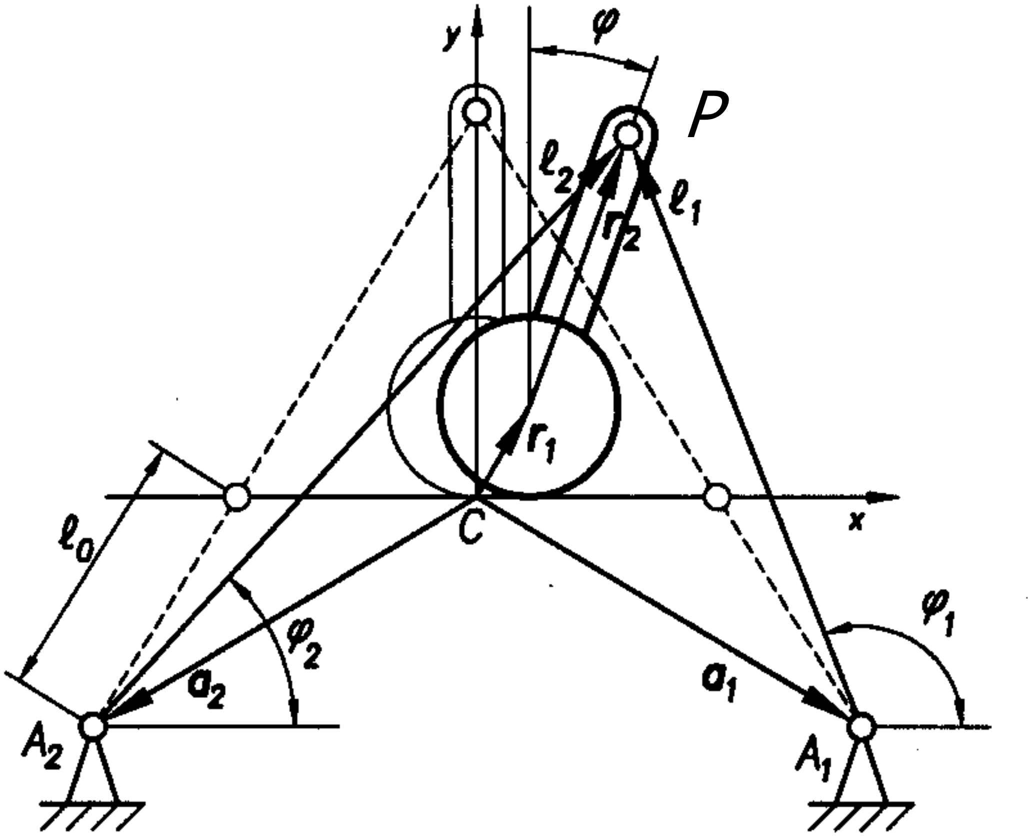
André Kuipers at ISS

Extended vector loop closure



1. Start with ZFL solution

Extended vector loop closure



1. Start with ZFL solution
2. Replace ZFL by normal springs (ℓ_0)
3. Apply rolling contact joint (optional)
4. Extend vector loop with energy eq.:

$$a_1 + \ell_1 = r_1 + r_3$$

$$a_2 + \ell_2 = r_1 + r_3$$

$$V_1 + V_2 = K$$

In this case two loops, one for each spring

Herder JL (2001) *Energy-free Systems; Theory, conception and design of statically balanced spring mechanisms,* Ph.D. Thesis, Delft University of Technology, ISBN 90-370-0192-0 (http://repository.tudelft.nl/ search: Herder energy-free), DOI: 10.13140/RG.2.1.3942.8966.

Extended vector loop closure

$$0 = A_x + R\varphi_i + r_2 \sin\varphi_i + \ell_{1,i} \cos\varphi_{1,i}$$

$$0 = A_y + R + r_2 \cos\varphi_i - \ell_{1,i} \sin\varphi_{1,i}$$

$$0 = -A_x - R\varphi_i - r_2 \sin\varphi_i + \ell_{2,i} \cos\varphi_{2,i}$$

$$0 = A_y + R + r_2 \cos\varphi_i - \ell_{2,i} \sin\varphi_{2,i}$$

$$0 = \tfrac{1}{2}k\left(\ell_{1,i} - \ell_{01}\right)^2 + \tfrac{1}{2}k\left(\ell_{2,i} - \ell_{02}\right)^2 - K$$

$$a_1 + \ell_1 = r_1 + r_3$$

$$a_2 + \ell_2 = r_1 + r_3$$

$$V_1 + V_2 = K$$

Extended vector loop closure

$$0 = A_x + R\varphi_i + r_2 \sin\varphi_i + \ell_{1,i} \cos\varphi_{1,i}$$

$$0 = A_y + R + r_2 \cos\varphi_i - \ell_{1,i} \sin\varphi_{1,i}$$

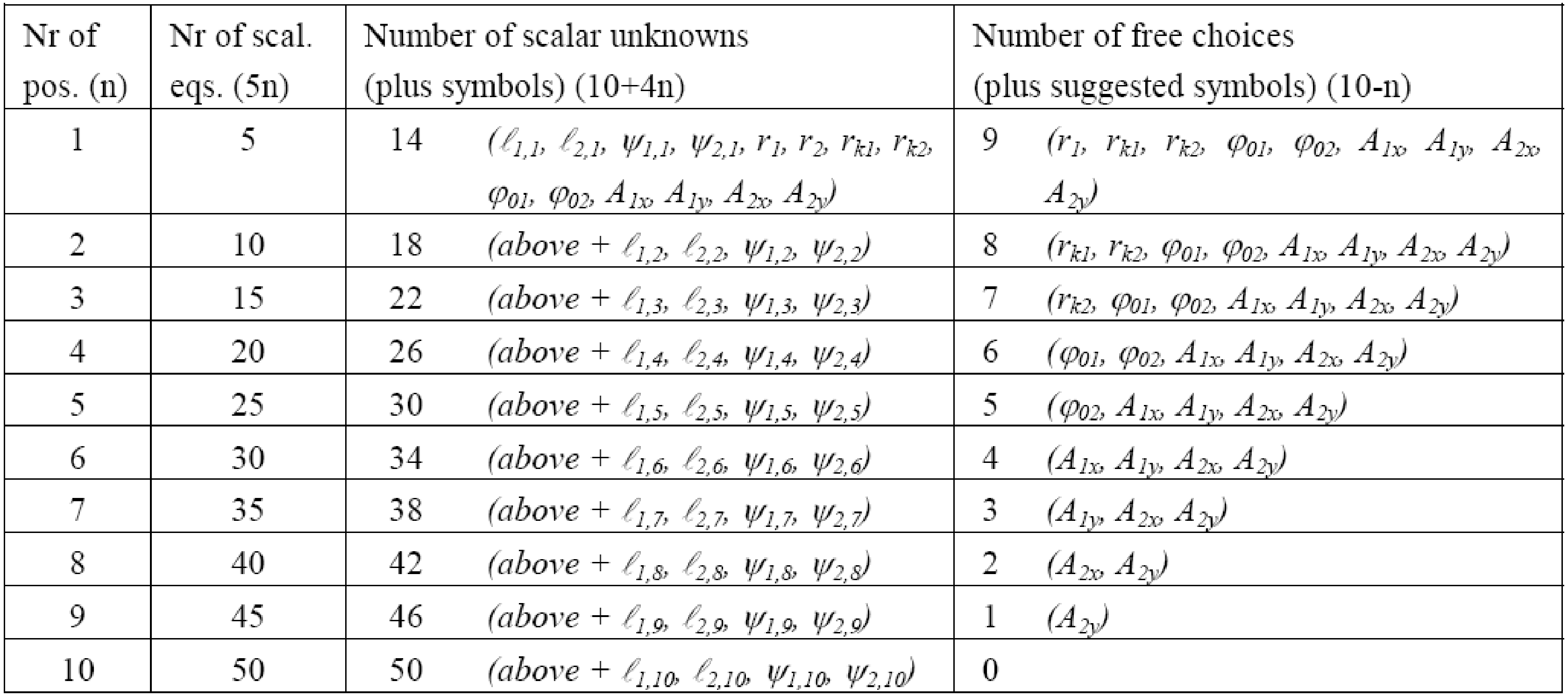
$$0 = -A_x - R\varphi_i - r_2 \sin\varphi_i + \ell_{2,i} \cos\varphi_{2,i}$$

$$0 = A_y + R + r_2 \cos\varphi_i - \ell_{2,i} \sin\varphi_{2,i}$$

$$0 = \tfrac{1}{2} k\left(\ell_{1,i} - \ell_{01}\right)^2 + \tfrac{1}{2} k\left(\ell_{2,i} - \ell_{02}\right)^2 - K$$

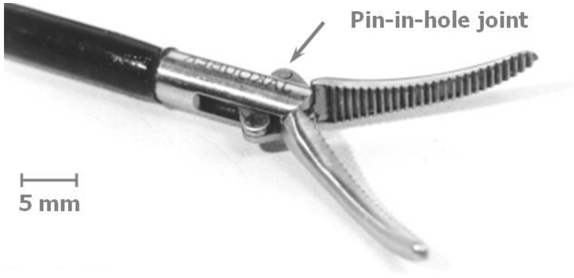
1. Assume springs are preselected, then k, ℓ_{01} and ℓ_{02} are known.
2. Also preselect energy level K
3. Then **5n** equations and **10** (r_1, r_2, r_{k1}, r_{k2}, φ_{01}, φ_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y}) + **4n** (ℓ_1, ℓ_2, ψ_1, ψ_2) unknowns.
4. From 5n=10+4n we find at most 10 precision points

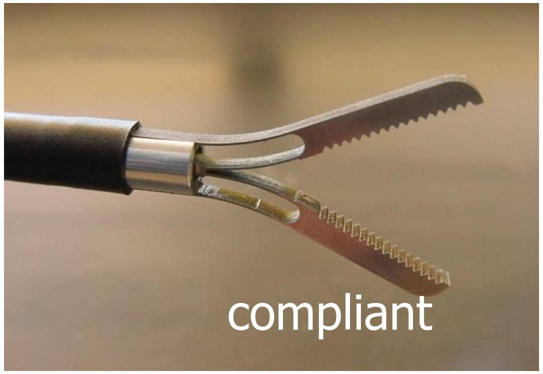
Extended vector loop closure



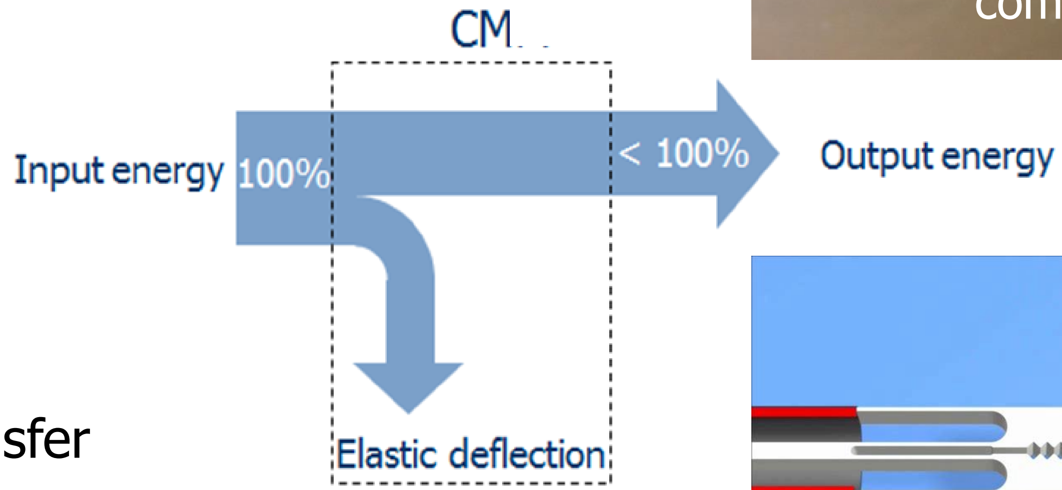
Nr of pos. (n)	Nr of scal. eqs. (5n)	Number of scalar unknowns (plus symbols) (10+4n)		Number of free choices (plus suggested symbols) (10-n)	
1	5	14	$(\ell_{1,1}, \ell_{2,1}, \psi_{1,1}, \psi_{2,1}, r_1, r_2, r_{k1}, r_{k2}, \varphi_{01}, \varphi_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y})$	9	$(r_1, r_{k1}, r_{k2}, \varphi_{01}, \varphi_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y})$
2	10	18	$(above + \ell_{1,2}, \ell_{2,2}, \psi_{1,2}, \psi_{2,2})$	8	$(r_{k1}, r_{k2}, \varphi_{01}, \varphi_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y})$
3	15	22	$(above + \ell_{1,3}, \ell_{2,3}, \psi_{1,3}, \psi_{2,3})$	7	$(r_{k2}, \varphi_{01}, \varphi_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y})$
4	20	26	$(above + \ell_{1,4}, \ell_{2,4}, \psi_{1,4}, \psi_{2,4})$	6	$(\varphi_{01}, \varphi_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y})$
5	25	30	$(above + \ell_{1,5}, \ell_{2,5}, \psi_{1,5}, \psi_{2,5})$	5	$(\varphi_{02}, A_{1x}, A_{1y}, A_{2x}, A_{2y})$
6	30	34	$(above + \ell_{1,6}, \ell_{2,6}, \psi_{1,6}, \psi_{2,6})$	4	$(A_{1x}, A_{1y}, A_{2x}, A_{2y})$
7	35	38	$(above + \ell_{1,7}, \ell_{2,7}, \psi_{1,7}, \psi_{2,7})$	3	(A_{1y}, A_{2x}, A_{2y})
8	40	42	$(above + \ell_{1,8}, \ell_{2,8}, \psi_{1,8}, \psi_{2,8})$	2	(A_{2x}, A_{2y})
9	45	46	$(above + \ell_{1,9}, \ell_{2,9}, \psi_{1,9}, \psi_{2,9})$	1	(A_{2y})
10	50	50	$(above + \ell_{1,10}, \ell_{2,10}, \psi_{1,10}, \psi_{2,10})$	0	

Compliant mechanisms





Monolithic
- No friction or backlash
- No lubrication
- No assembly



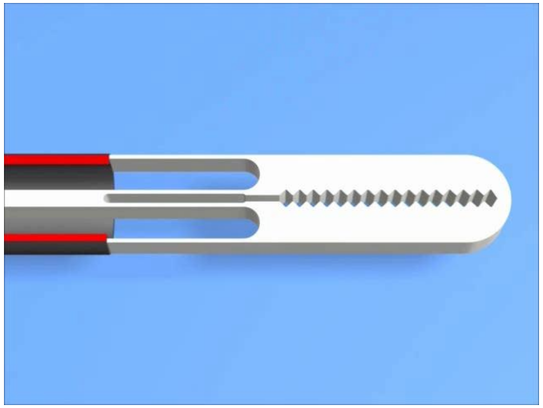
CM

Input energy 100%

< 100% Output energy

Elastic deflection

But
- Poor efficiency
- Poor force transfer

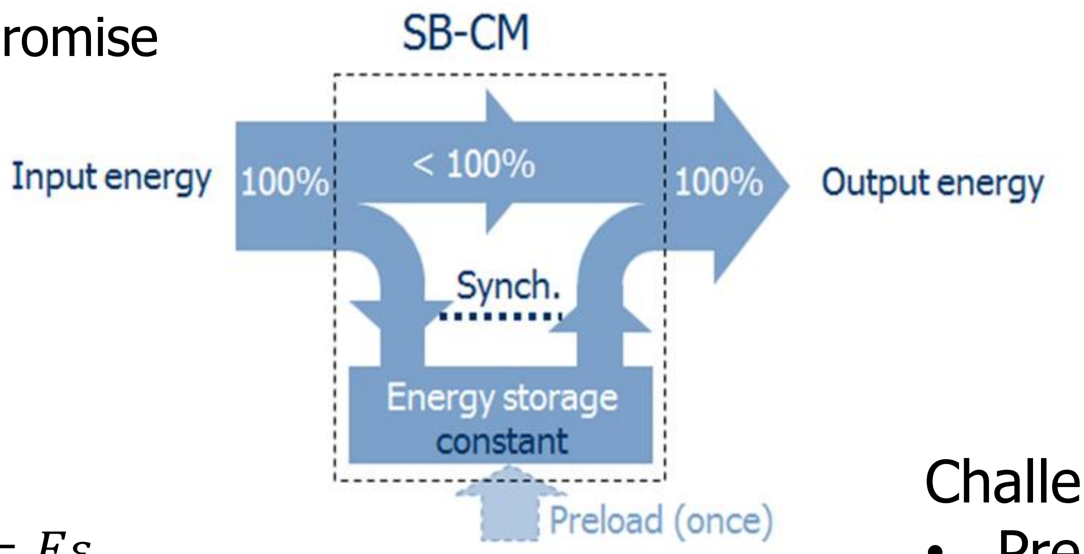


Static Balancing of Compliant Mech.

NWO stw "VIDI"

- Energy not dissipated > Balancing
- Best of both worlds!
- No longer compromise

SB-CM



Challenges:

- Preload
- Tuning

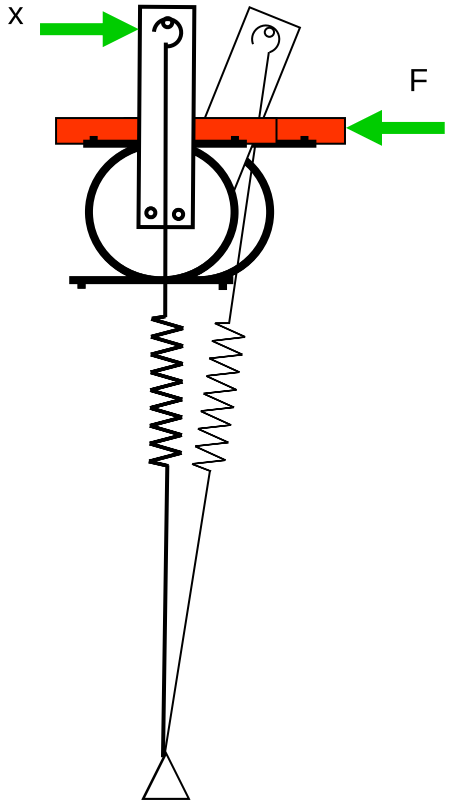
$Hooke's\ law: \sigma = E\varepsilon$

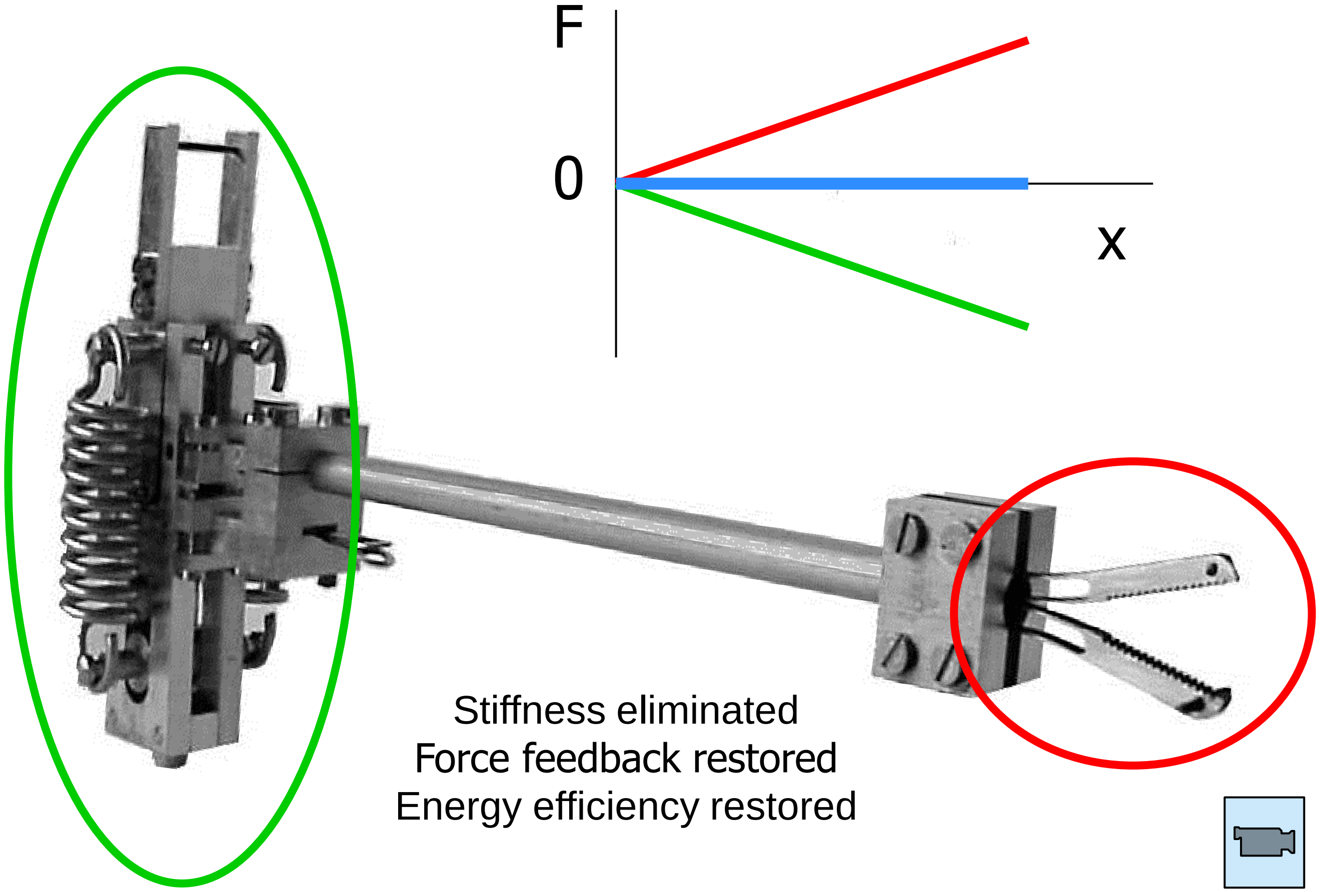
$Stiffness: F = kx$ ⇒ Zero stiffness

Stiffness is not a material property

Static Balancing of Compliant Mech.

"VIDI"

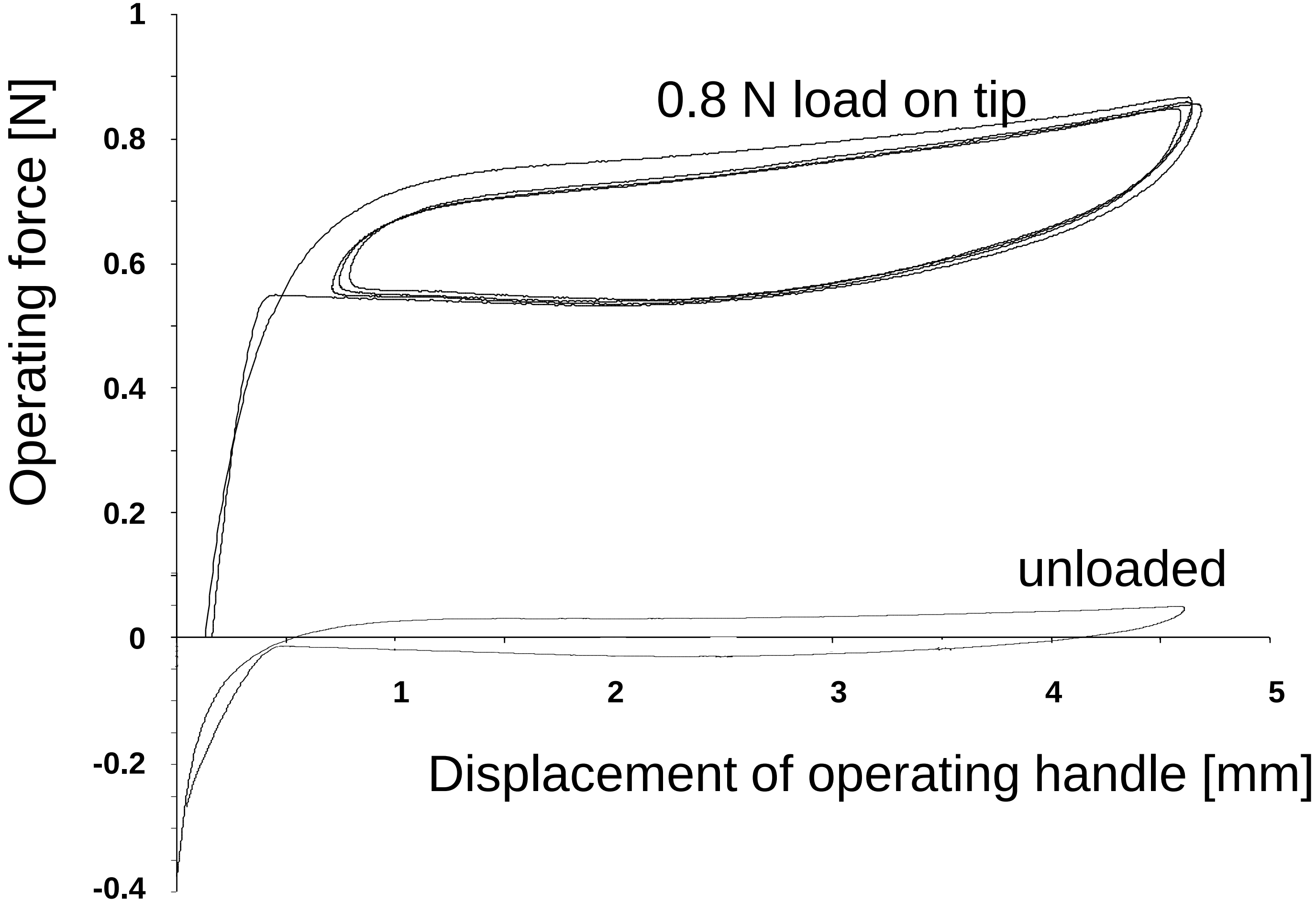




Stiffness eliminated
Force feedback restored
Energy efficiency restored

Herder JL, Berg FPA van den (2000) Statically balanced compliant mechanisms (SBCM's), an example and prospects, *ASME DETC* Sept 10-13, Baltimore, Maryland, DETC2000/MECH-14144.

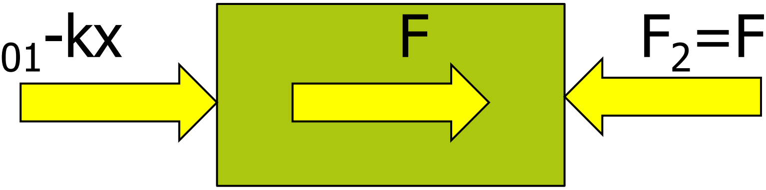
Rolling contact forceps



Herder JL, Berg FPA van den (2000) Statically balanced compliant mechanisms (SBCM's), an example and prospects, *ASME DETC* Sept 10-13, Baltimore, Maryland, DETC2000/MECH-14144.

Does an opposite spring provide static balance?

No they don't, in fact they double the stiffness



$F_1=F_{01}-kx$

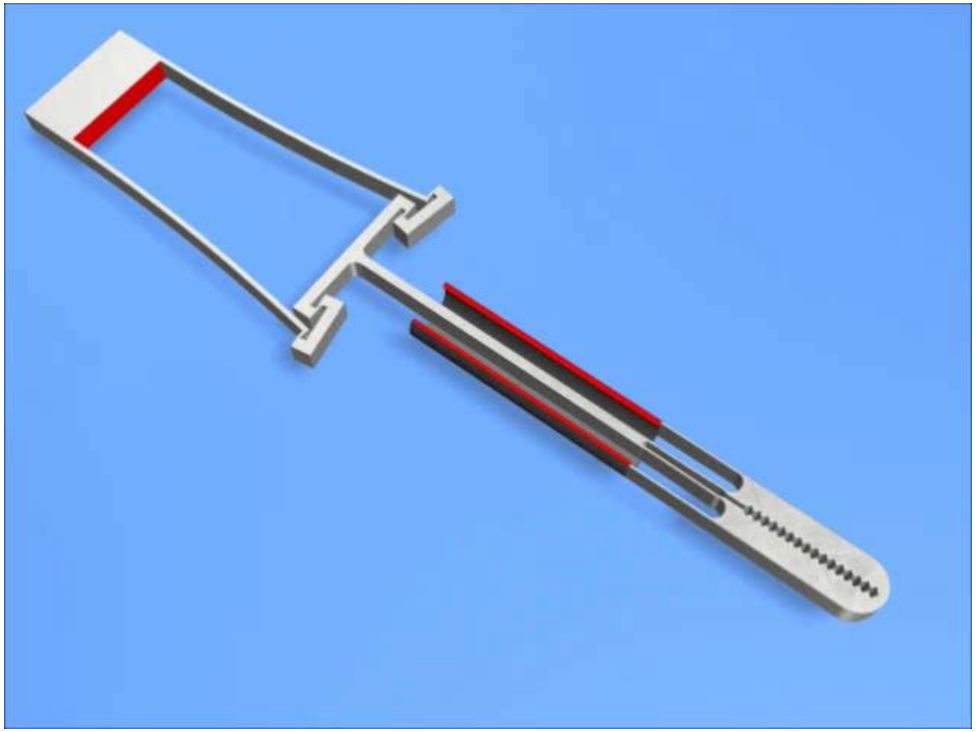
F

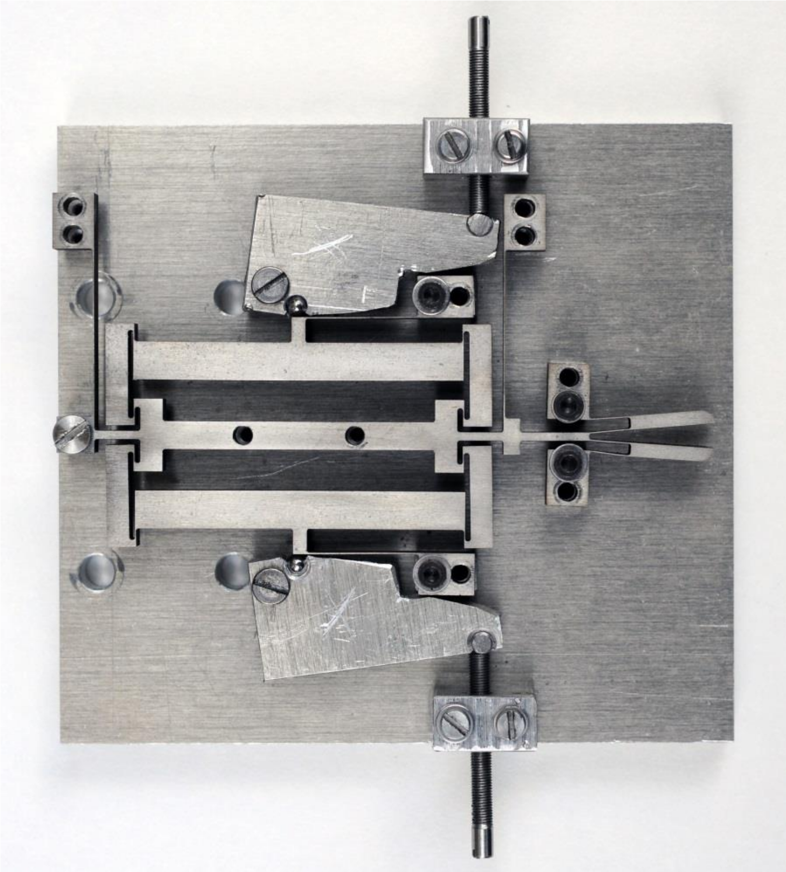
$F_2=F_{02}+kx$

$$F + F_{01}-kx = F_{02}+kx$$

Preload drops out, F = 2kx, so stiffness doubled

Static Balancing of Compliant Mech.

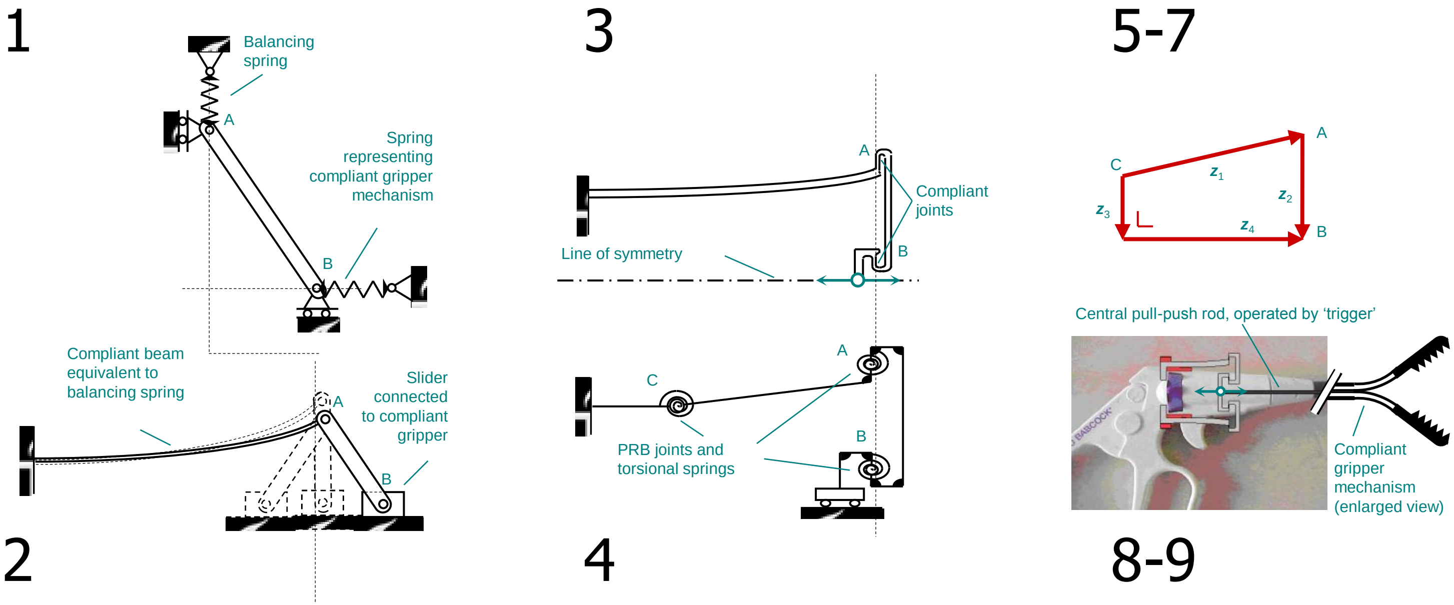




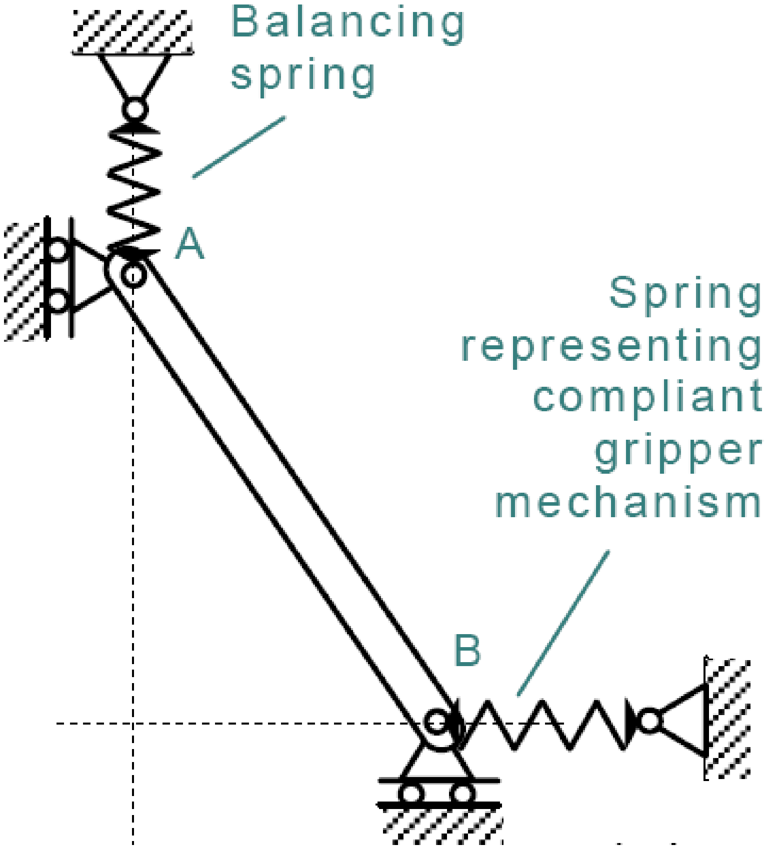
TU Delft

Lamers AJ, Gallego Sanchez JA, Herder JL (2015) Design of a Statically Balanced Fully Compliant Grasper, *Mechanism and Machine Theory* **92**:230-239 (DOI: 10.1016/j.mechmachtheory.2015.05.014, IF 1.66).

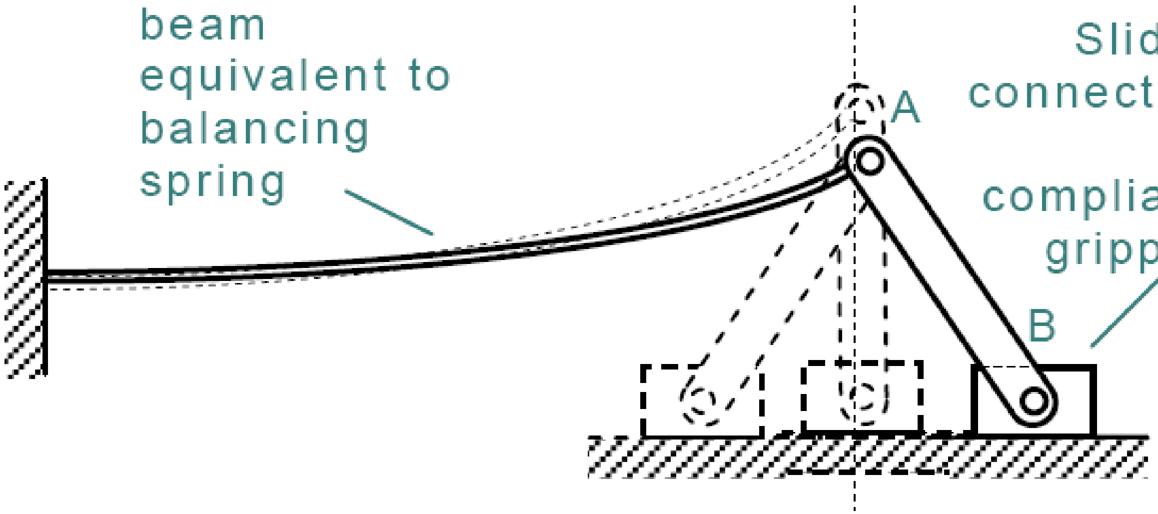
Design steps



Step 1: Known rigid-link SB mech.



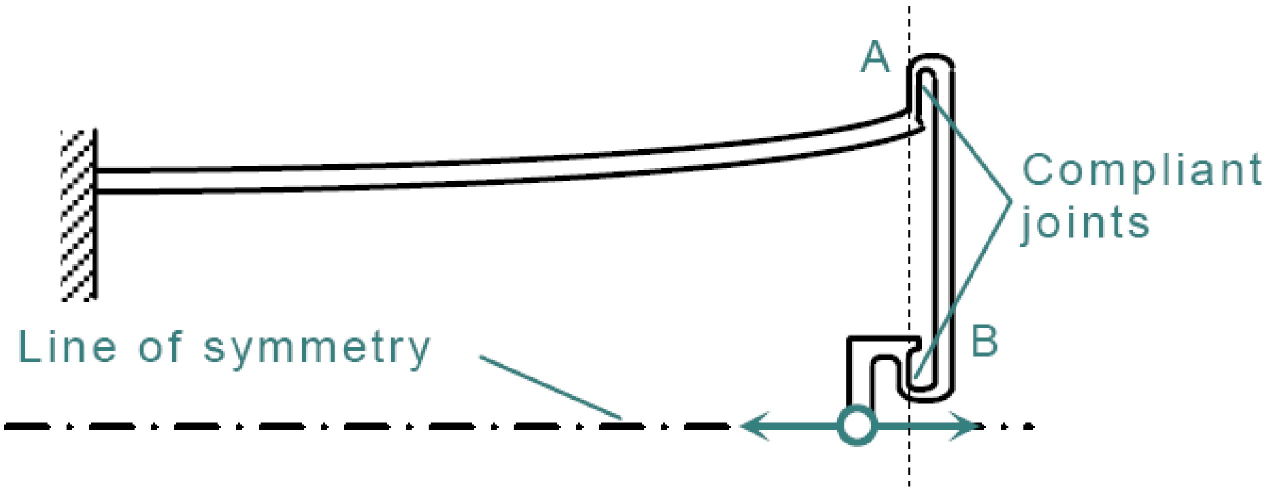
Step 2: Replace spring by CM



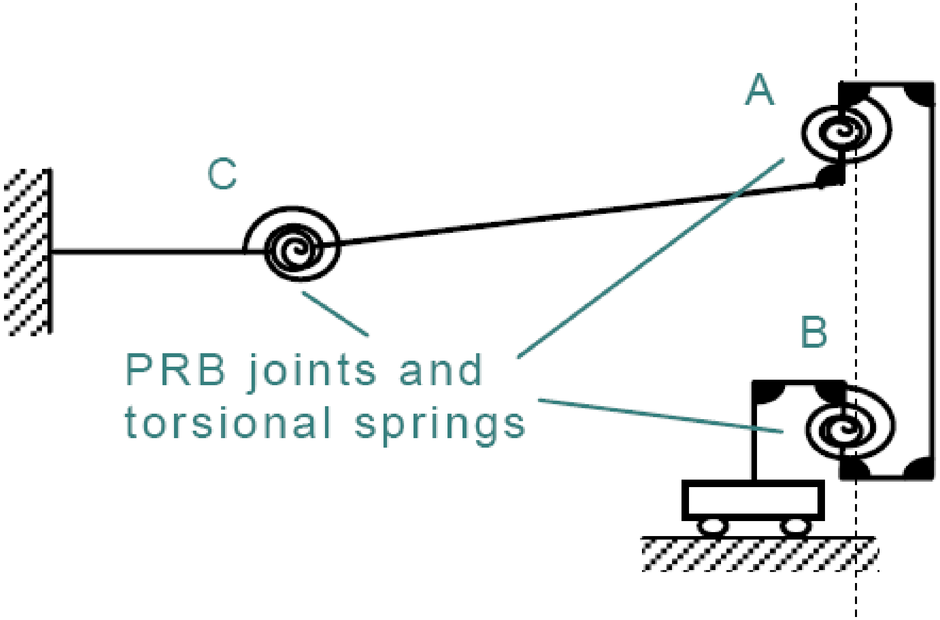
Compliant beam equivalent to balancing spring

Slider connected to compliant gripper **(not shown)**

Step 3: Replace joints by CM

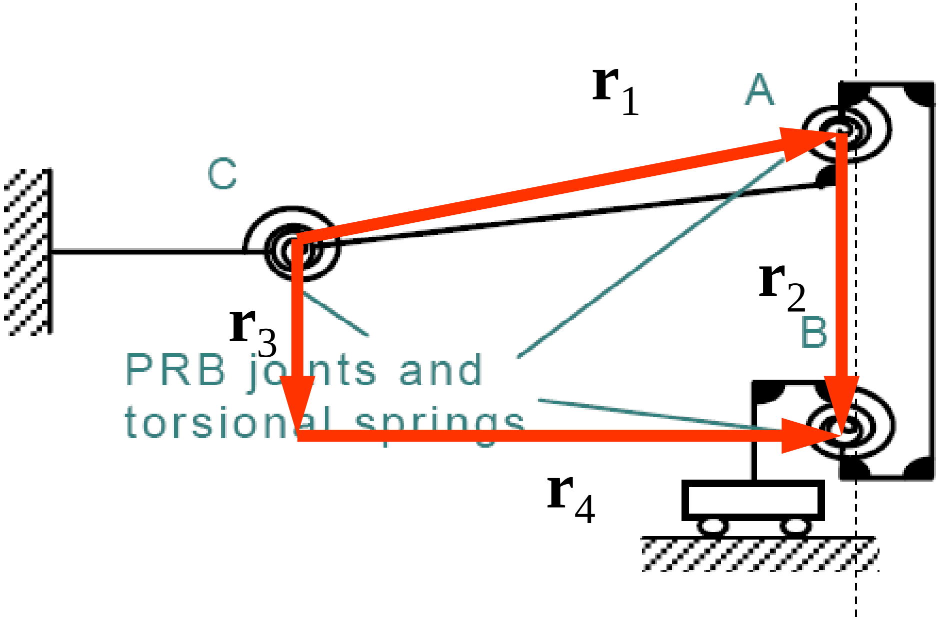


Step 4: PRB modeling



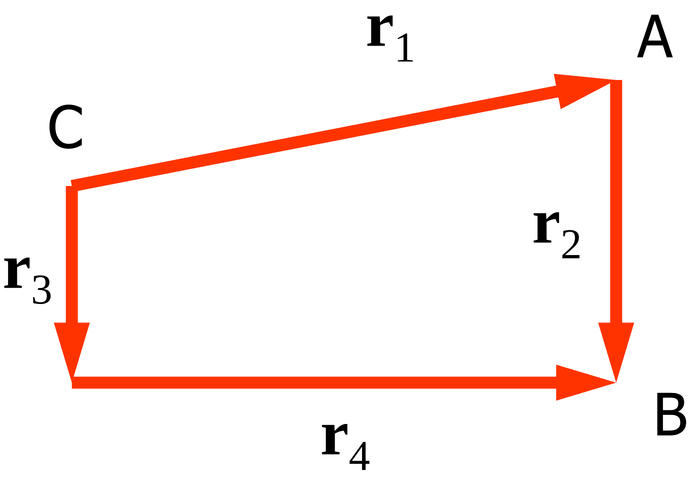
Few parameters, e.g. k_A, k_B, k_C, λ_c

Step 5: Kinematics, loop closure



Few parameters, e.g. k_A, k_B, k_C, λ_c

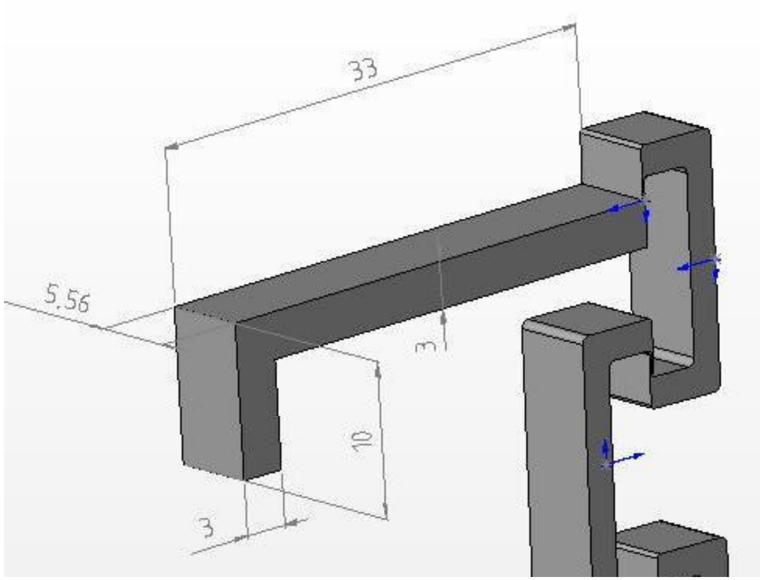
Step 5: Kinematics, loop closure$^+$

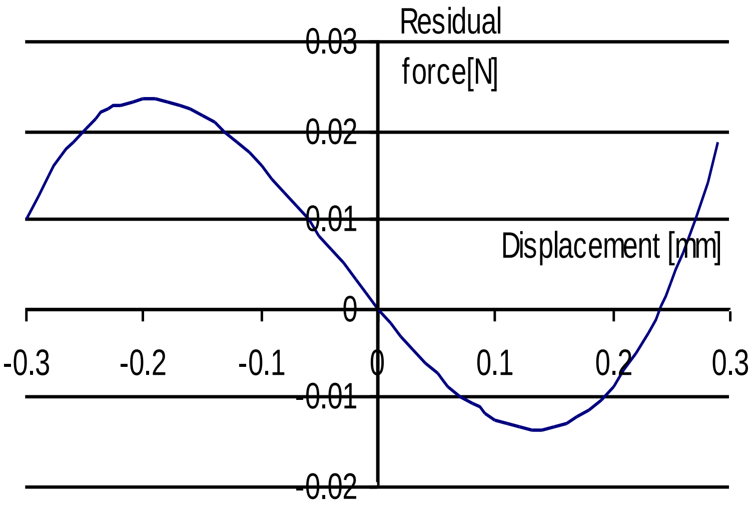


$$\boldsymbol{r}_1 + \boldsymbol{r}_2 = \boldsymbol{r}_3 + \boldsymbol{r}_4$$

$$V_A + V_B + V_C + V_{\text{gripper}} = \mathit{Constant}.$$

Step 6: Dimensioning the CM

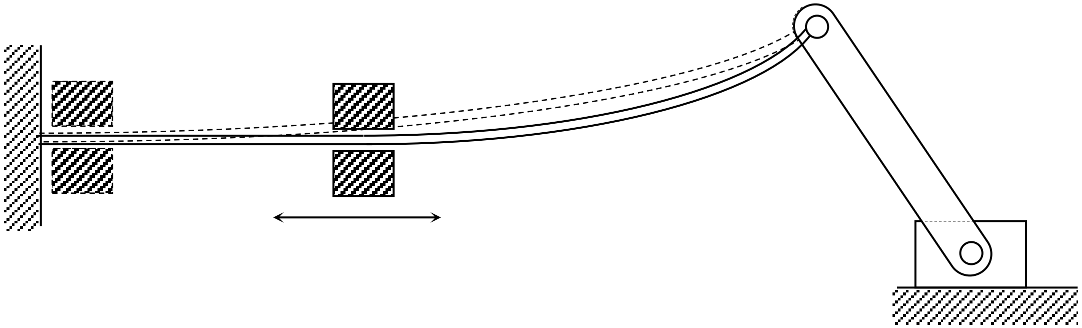




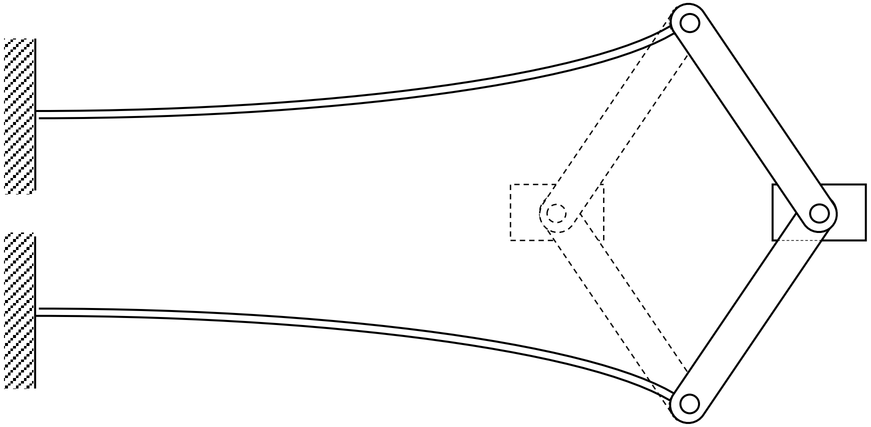
Aaron Stapel, 2004

Step 7: Instrument design

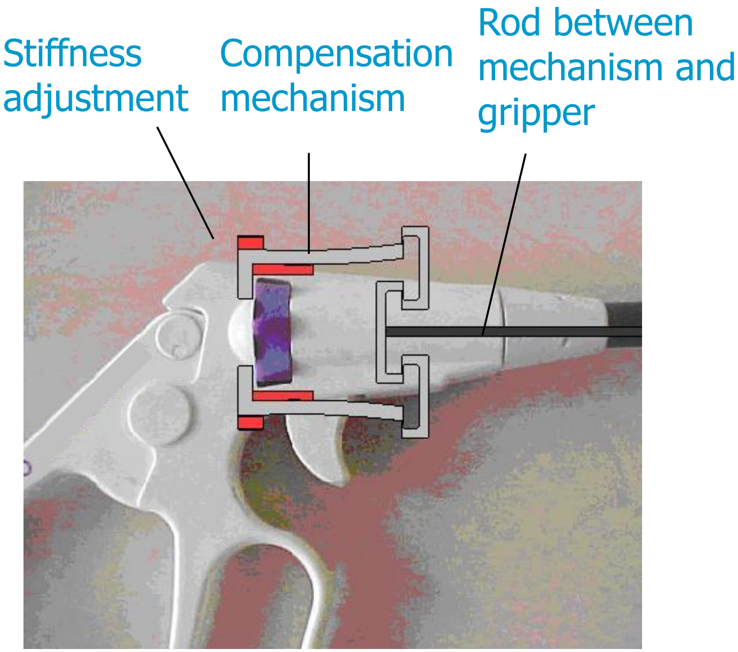
Stiffness adjustment

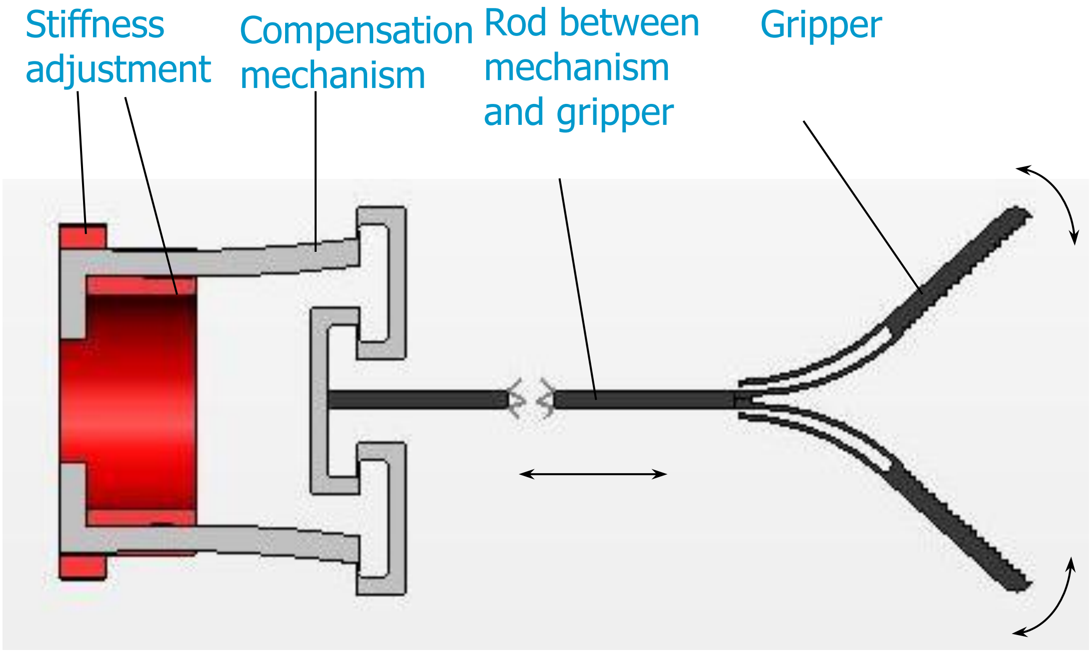


Symmetric arrangement

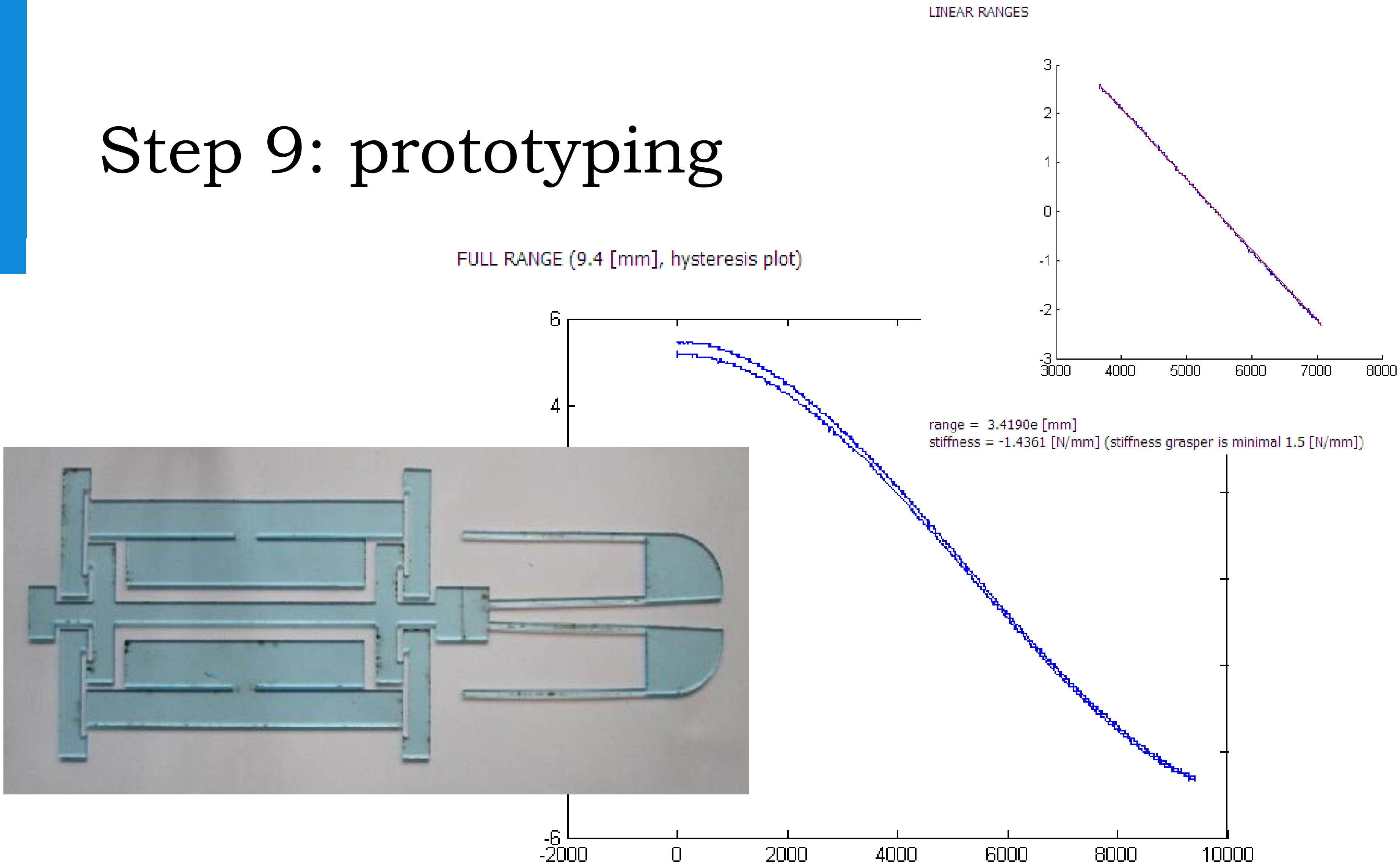


Step 8: Detailed design



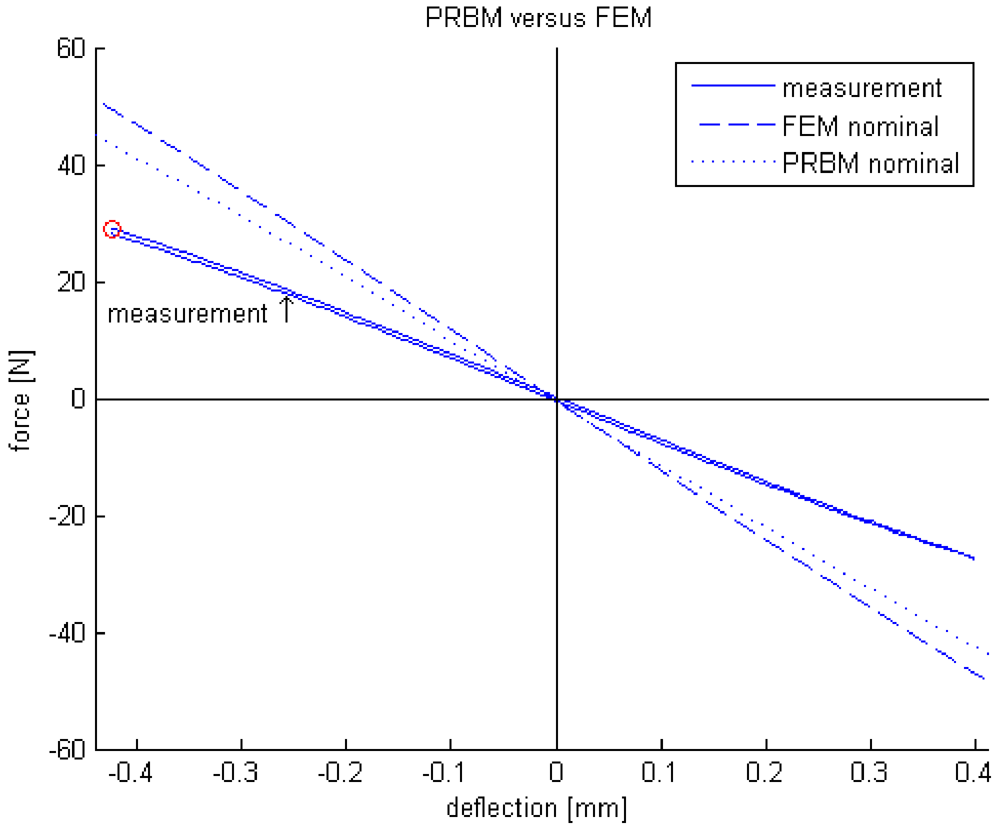


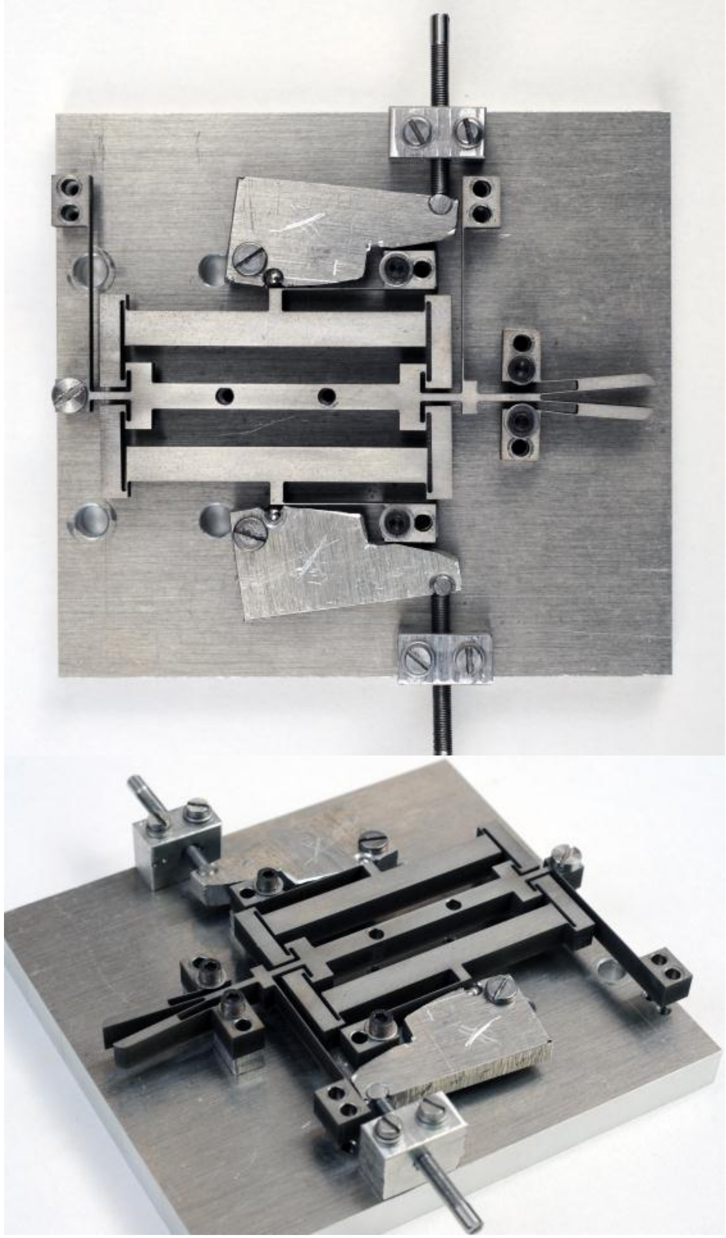
Step 9: prototyping



range = 3.4190e [mm]
stiffness = -1.4361 [N/mm] (stiffness grasper is minimal 1.5 [N/mm])

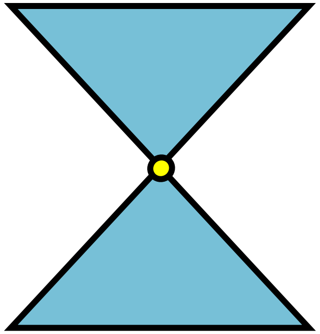
Step 9: prototyping

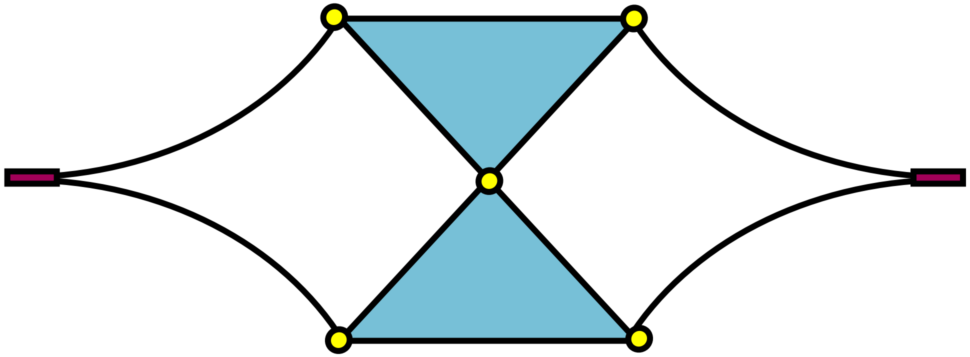


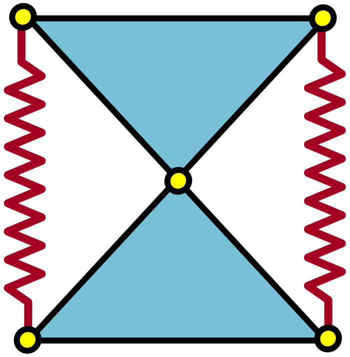


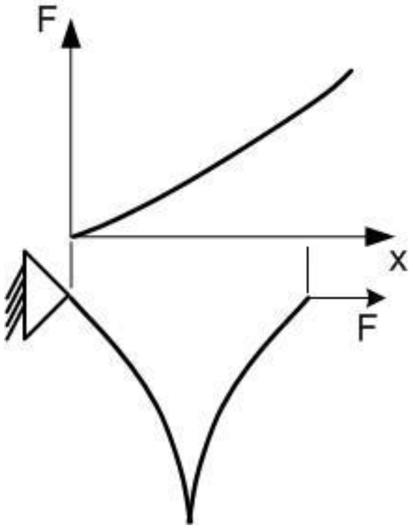
Toon Lamers, 2012

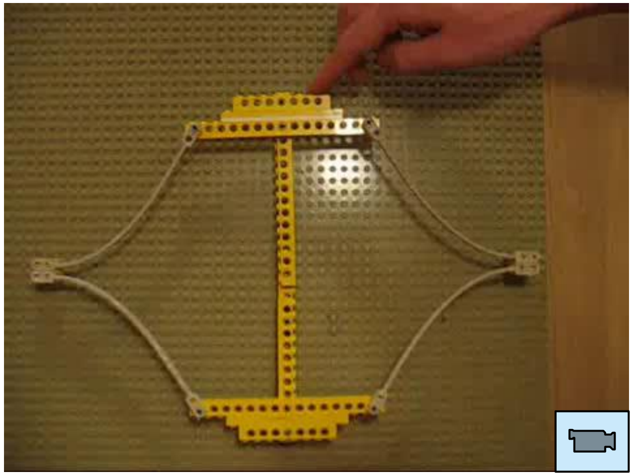
Zero stiffness joint



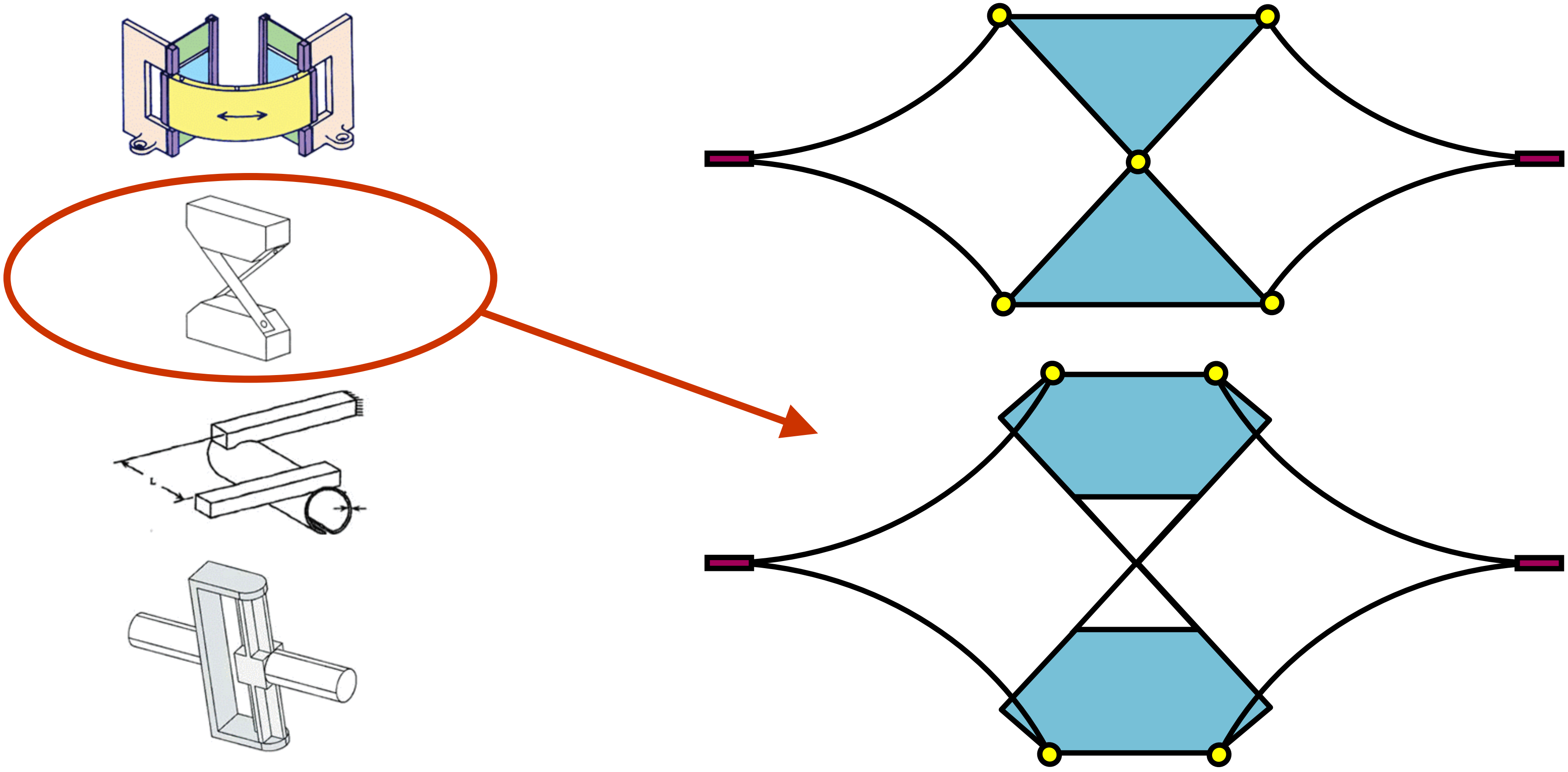




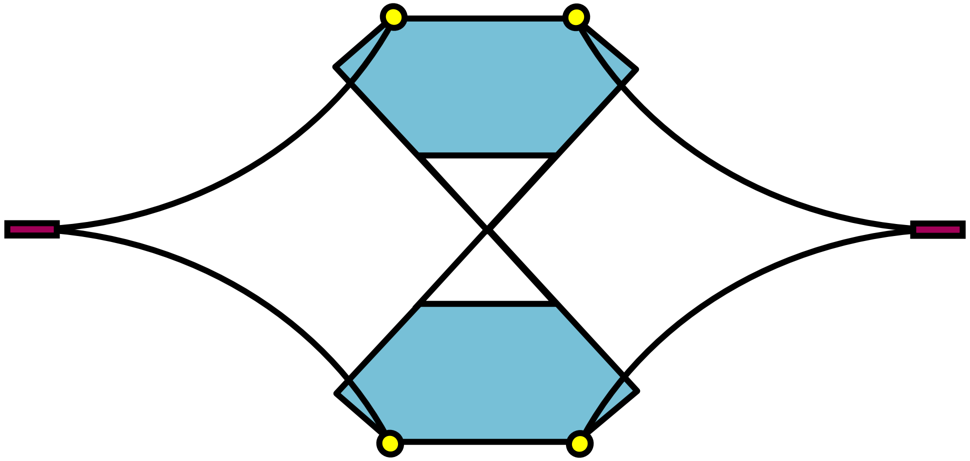


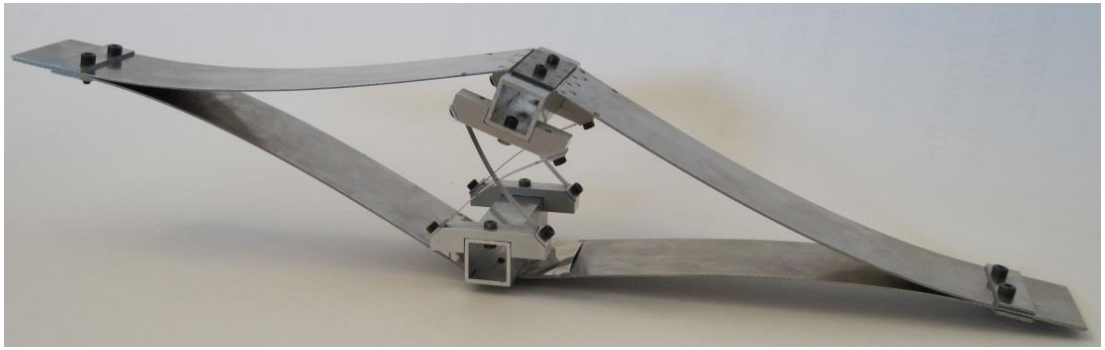


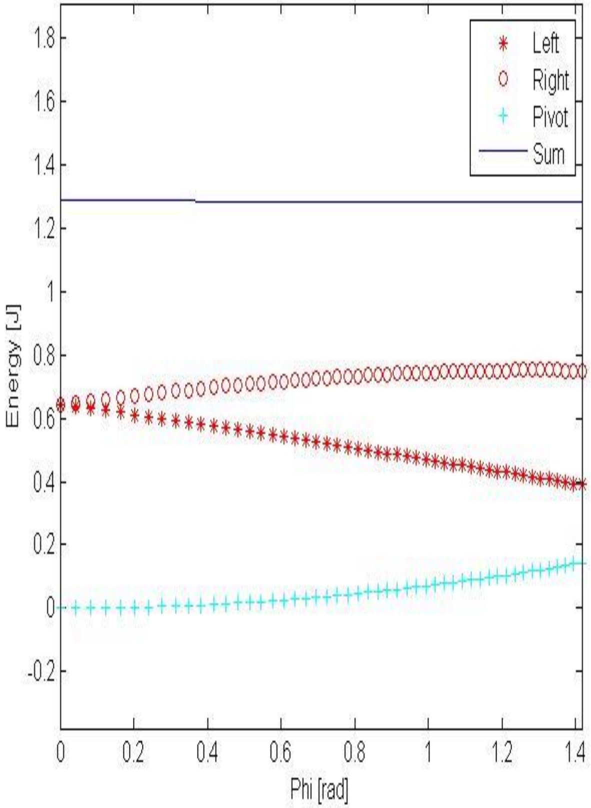
Zero stiffness joint



Zero stiffness joint

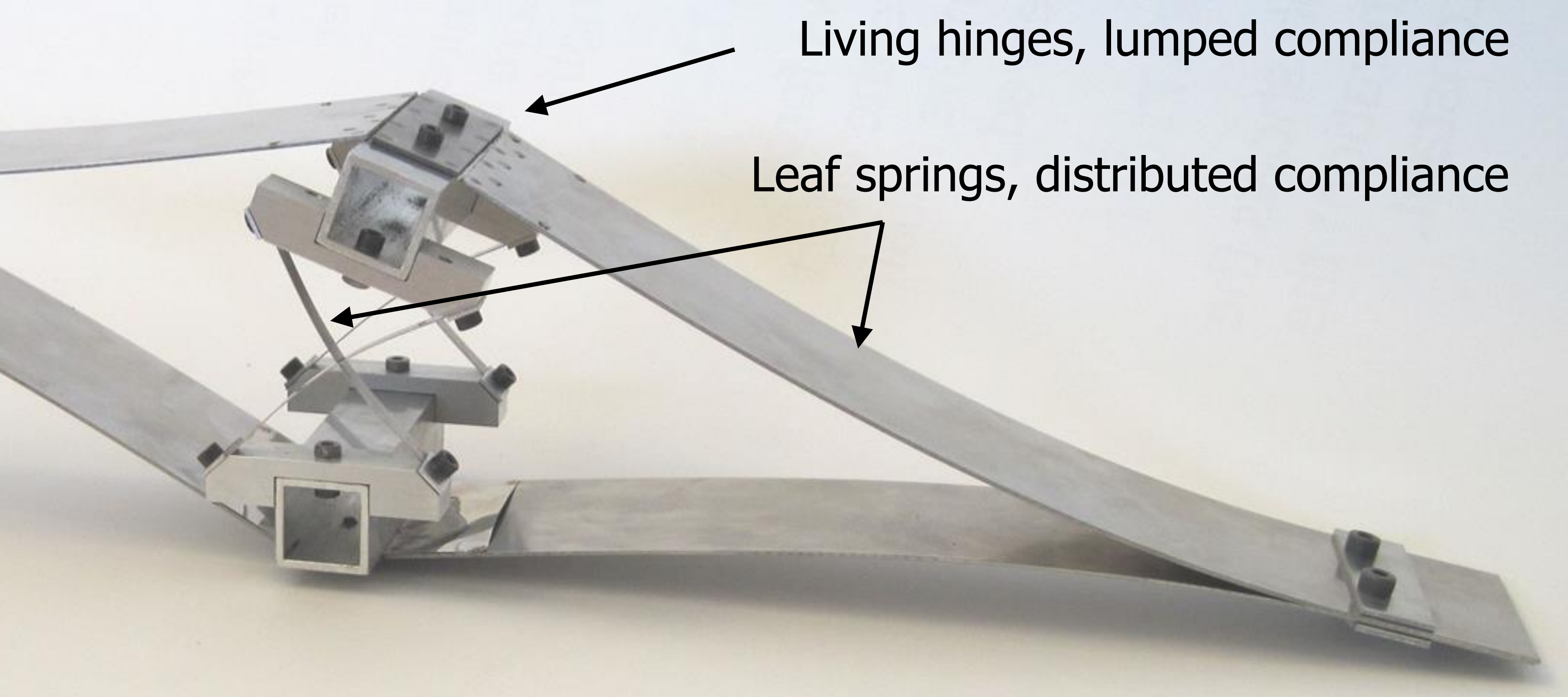






Morsch F, Herder JL (2010) Design of a generic zero stiffness compliant joint, *2010 ASME IDETC*, August 15-18, 2010, Montreal, Canada, Paper number DETC2010-28351.

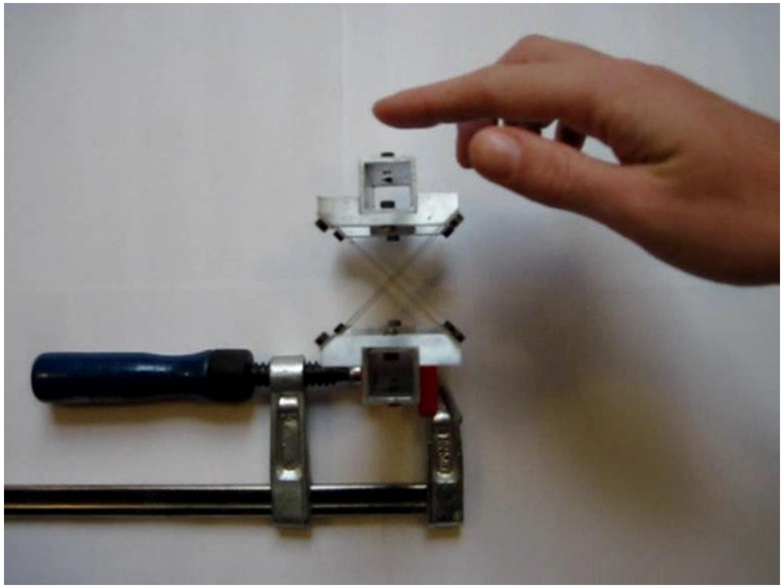
Zero stiffness joint

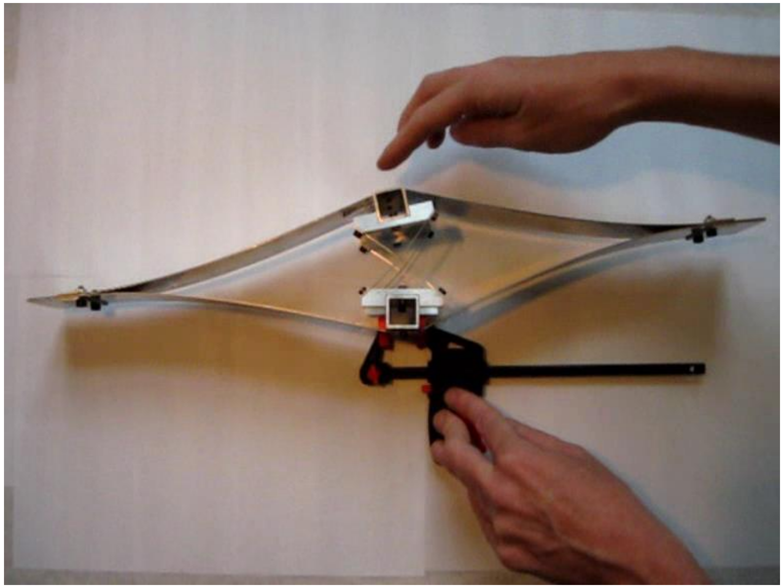


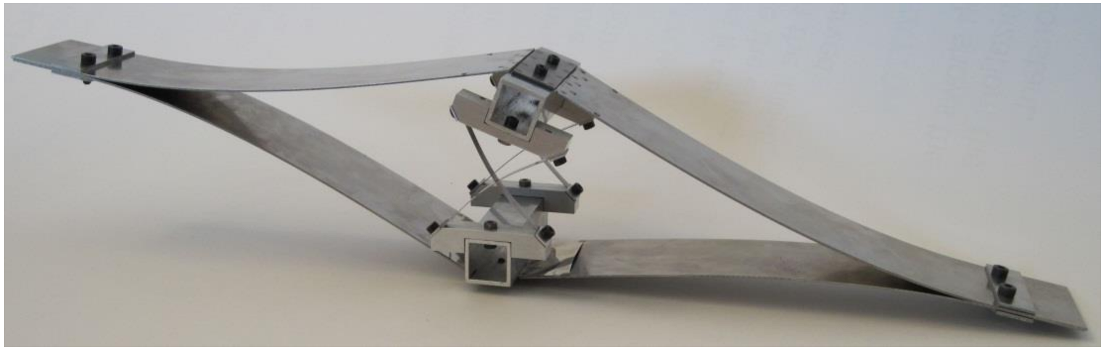
Living hinges, lumped compliance

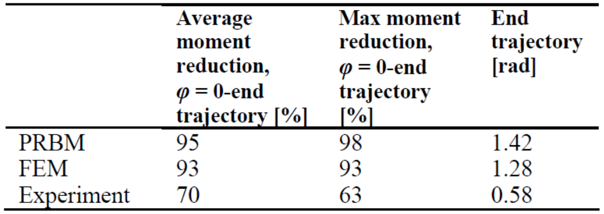
Leaf springs, distributed compliance

(Near) zero stiffness joint





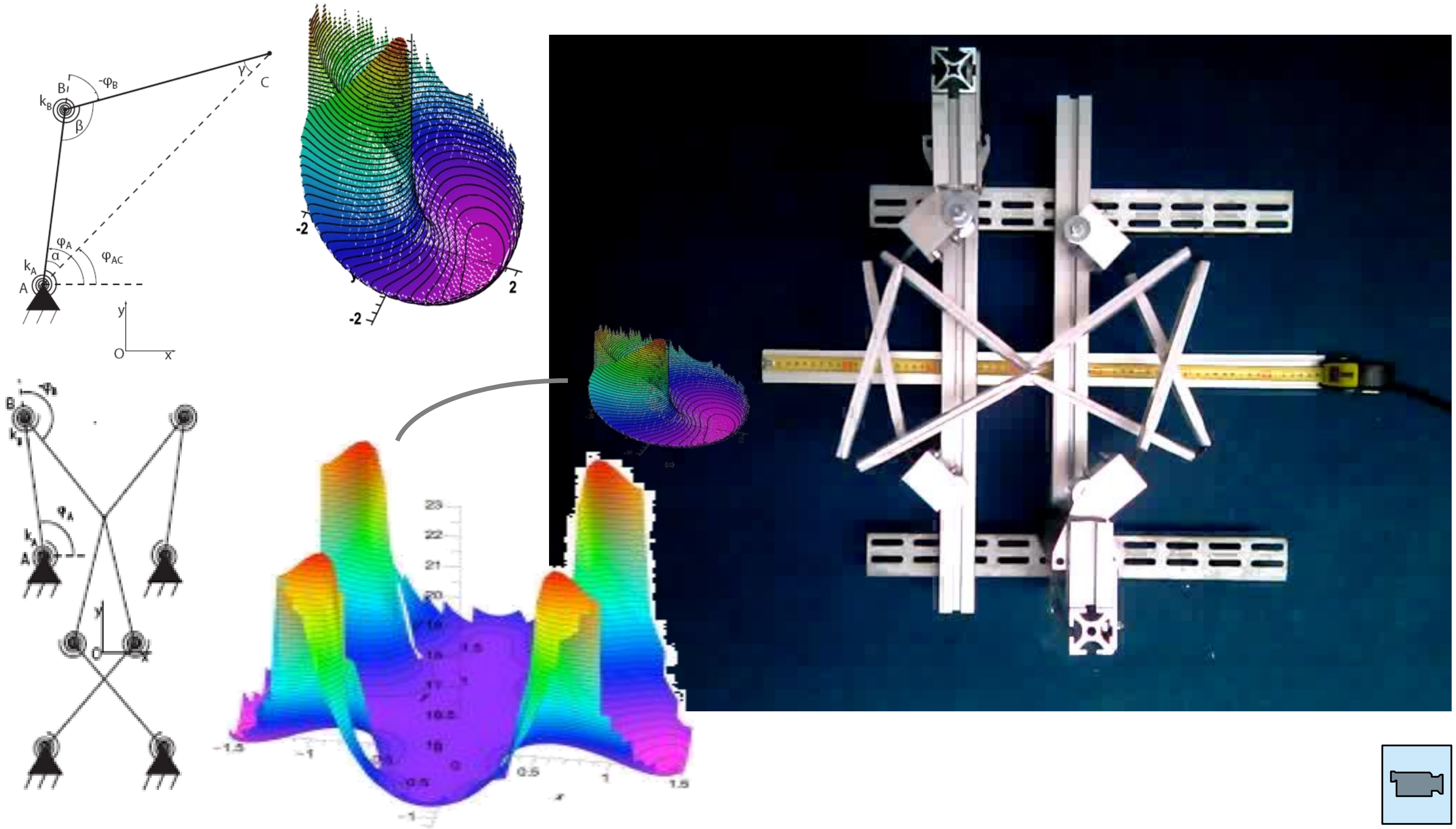




	Average moment reduction, φ = 0-end trajectory [%]	Max moment reduction, φ = 0-end trajectory [%]	End trajectory [rad]
PRBM	95	98	1.42
FEM	93	93	1.28
Experiment	70	63	0.58

Morsch F, Herder JL (2010) Design of a generic zero stiffness compliant joint, *2010 ASME IDETC*, August 15-18, 2010, Montreal, Canada, Paper number DETC2010-28351.

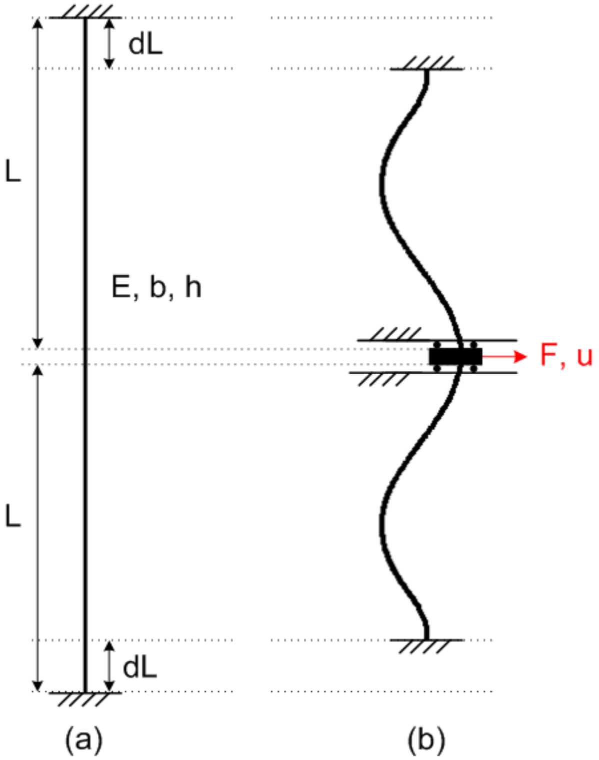
Straight-line self-guiding SBCM

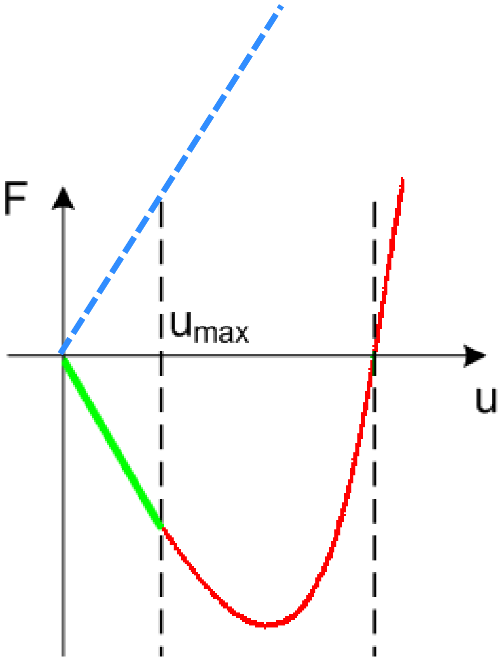


Rosenberg EJ, Radaelli G, Herder JL (2010) An energy approach to a 2DoF complaint parallel mechanism with self-guiding statically-balanced straight-line behavior, *2010 ASME IDETC*, Paper nr DETC2010-28447.

Static Balancing of Compliant Mech.

“VIDI”





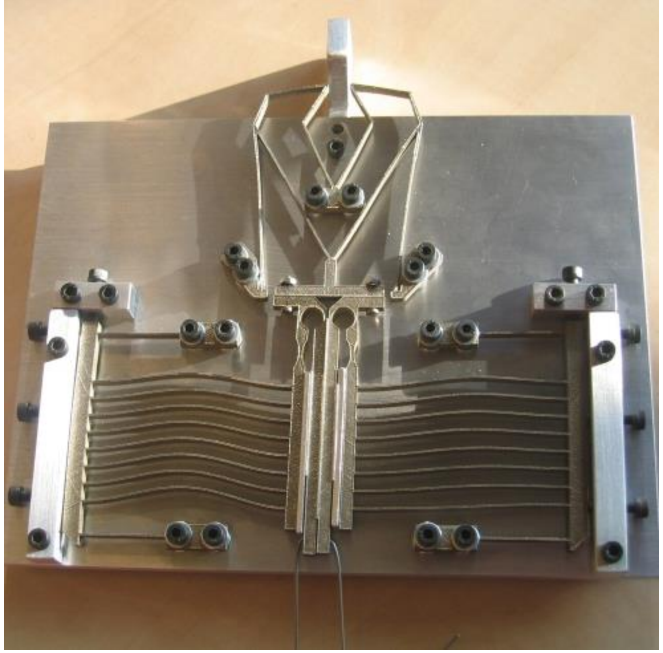
Static Balancing of Compliant Mech.

“VIDI”

Statically balanced gripper

Karin Hoetmer, Charles Kim,
Geoffrey Woo, Just Herder
2009

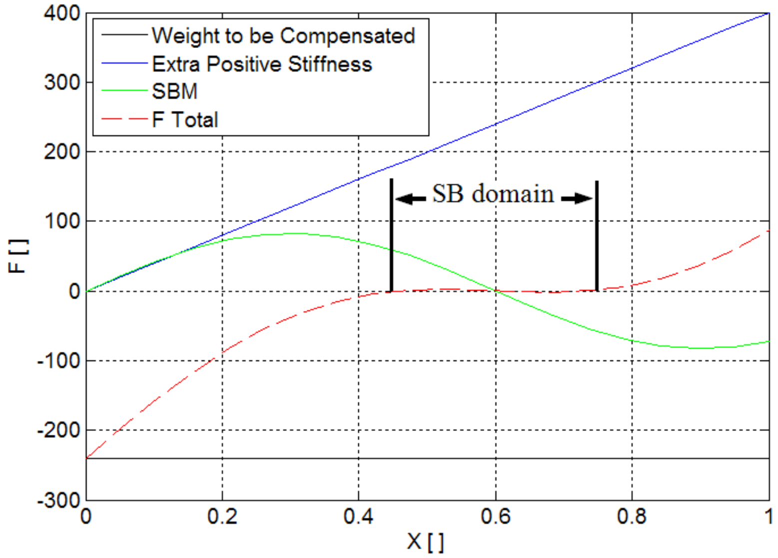
Delft University of Technology
Bucknell University

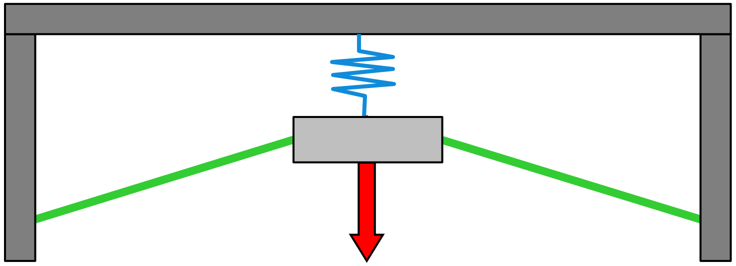


Hoetmer K, Woo G, Kim C, Herder JL (2010) Negative stiffness building blocks for statically balanced compliant mechanisms: design and testing, *ASME J of Mech and Rob*, 2(4)041007 (DOI: 10.1115/1.4002247).

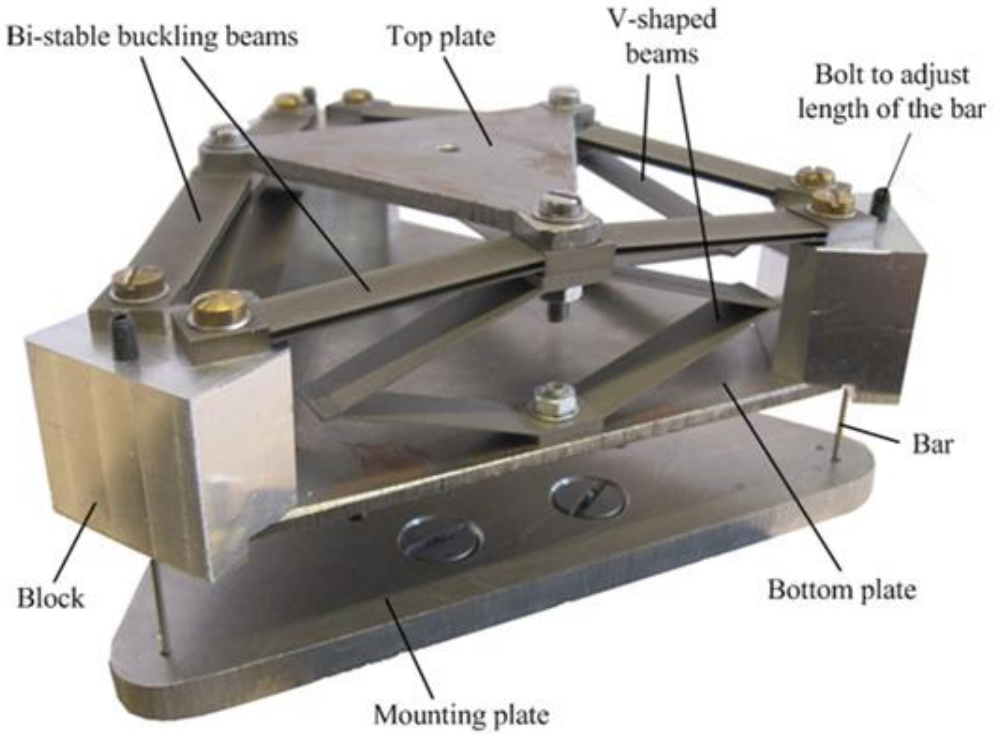
Constant force unit

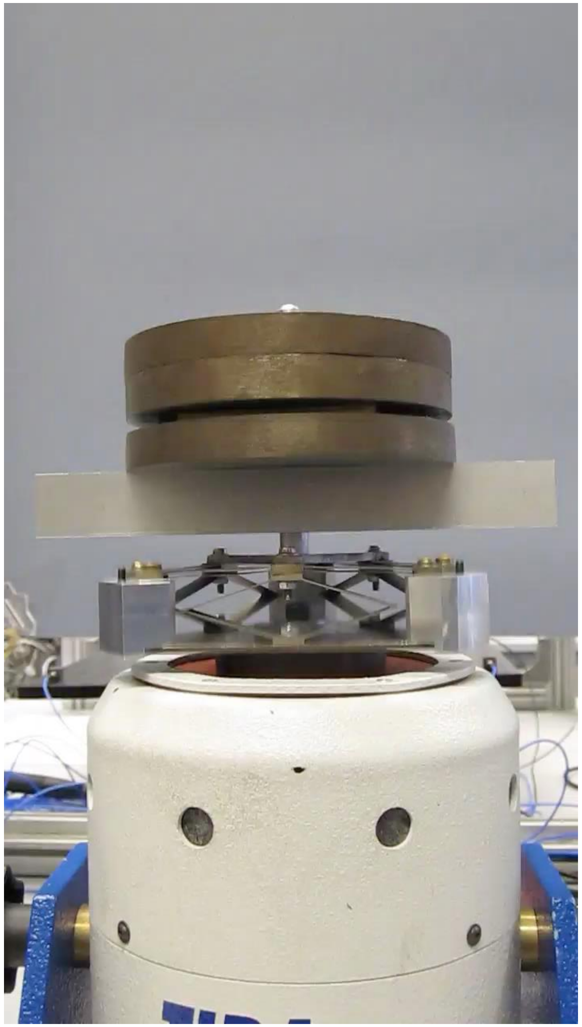
Force composition method





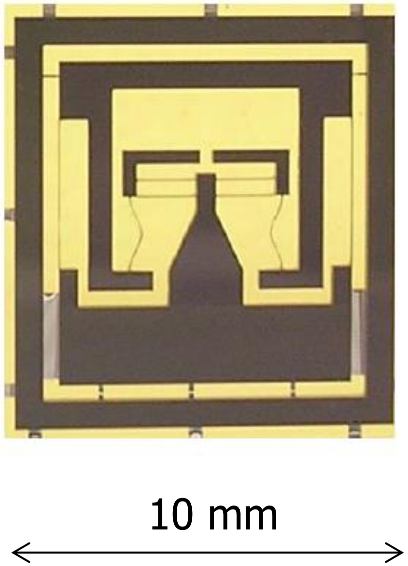
Vibration Isolator

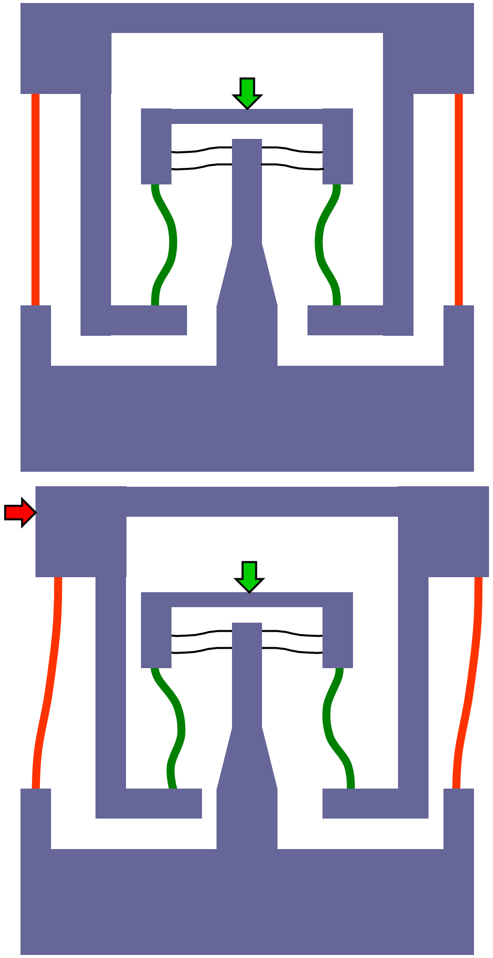


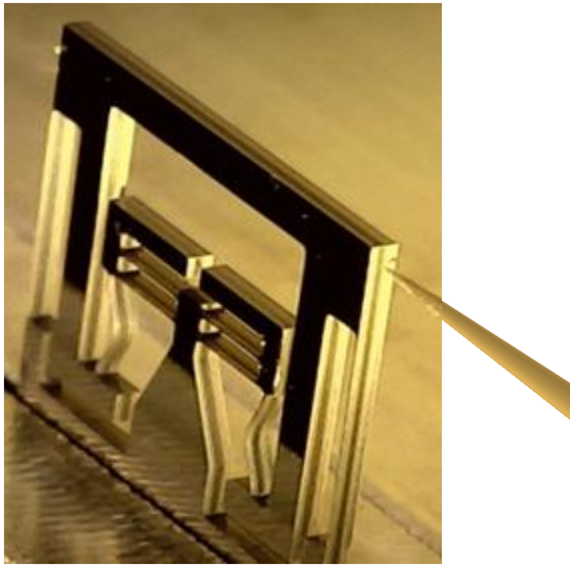


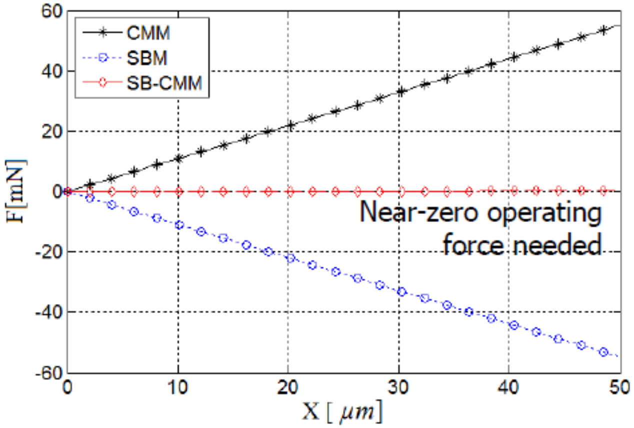
Dunning AG, Tolou N, Herder JL (2013) A Compact Low-Stiffness Six Degrees of Freedom Compliant Precision Stage, *Precision Engineering* 37(2)380-388 (http://dx.doi.org/10.1016/j.precisioneng.2012.10.007).

Statically balanced micromechanisms





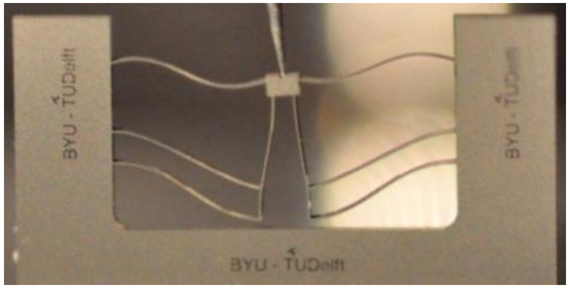


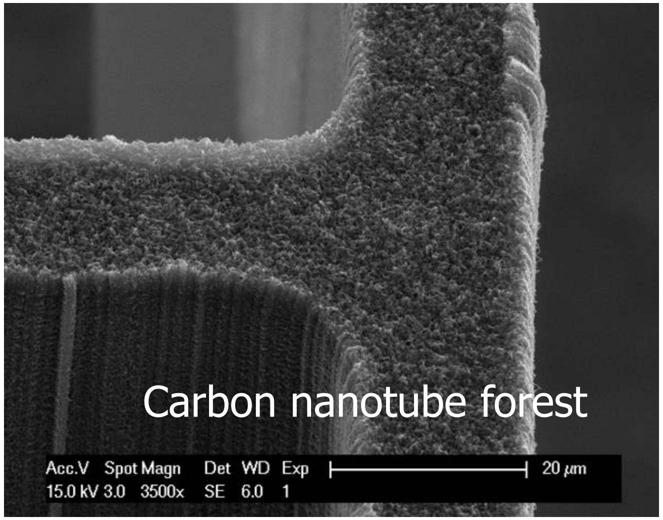


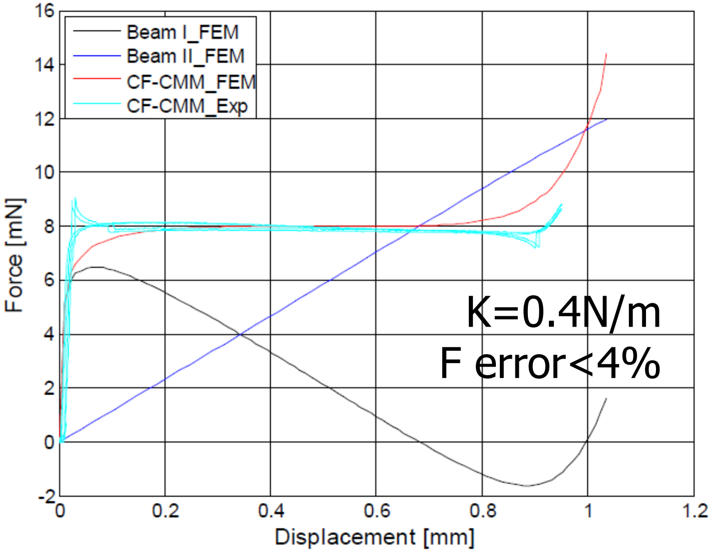
Near-zero operating force needed

Tolou N, Henneken VA, Herder JL (2010) Statically balanced compliant micro mechanisms (SB-MEMS): concepts and simulation, *2010 ASME IDETC,* August 15-18, 2010, Montreal, Paper DETC2010-28406.

Constant force



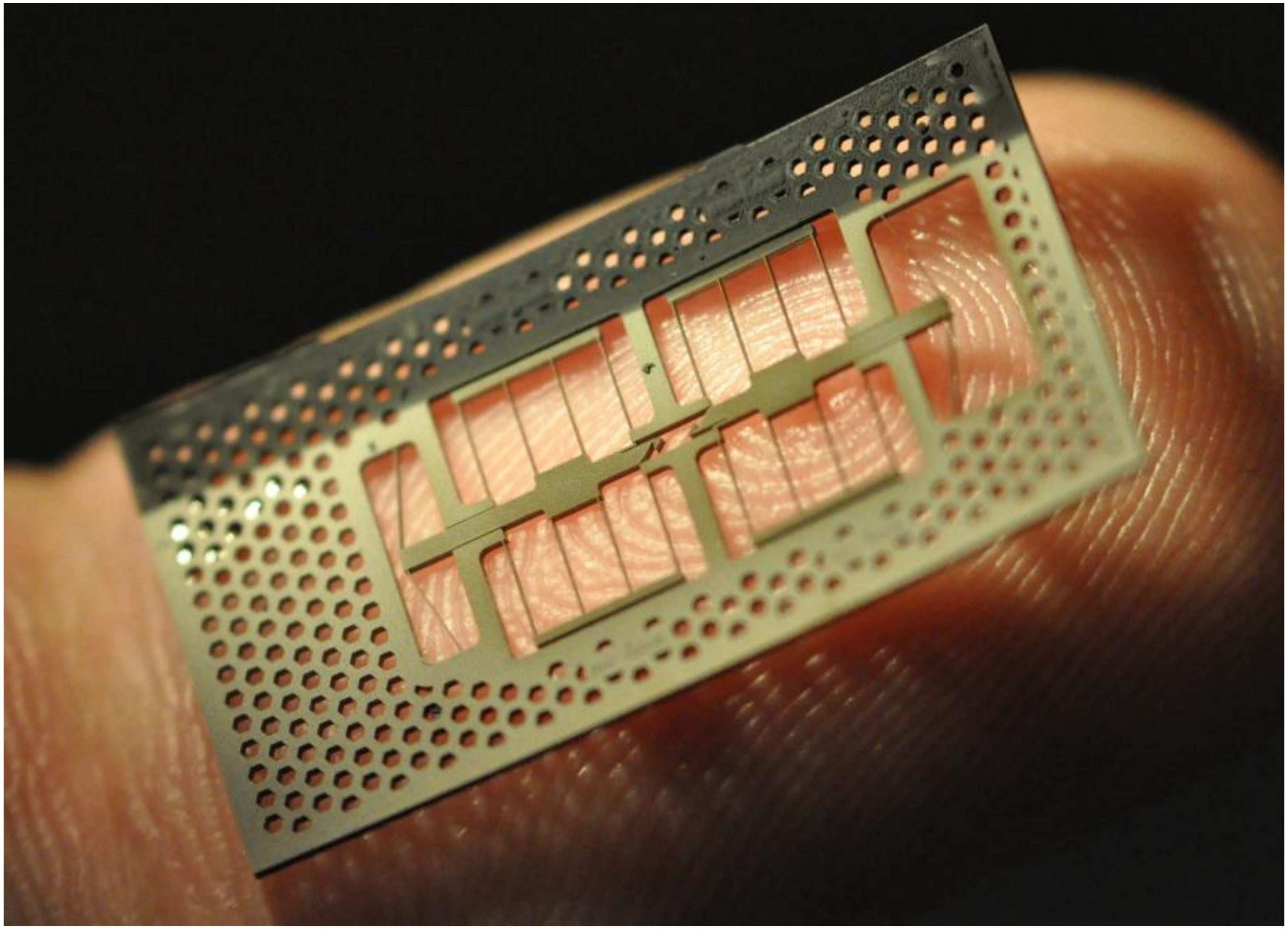




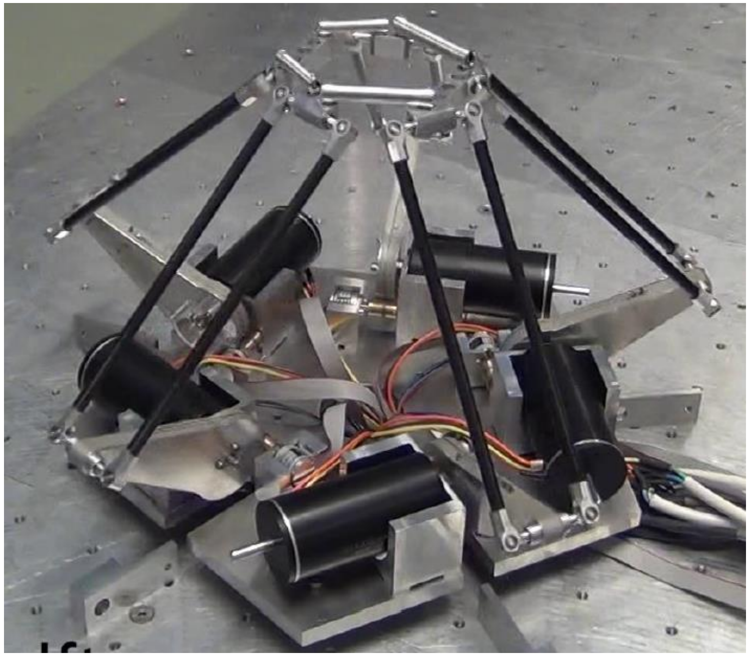
Preloading with ON/OFF switch

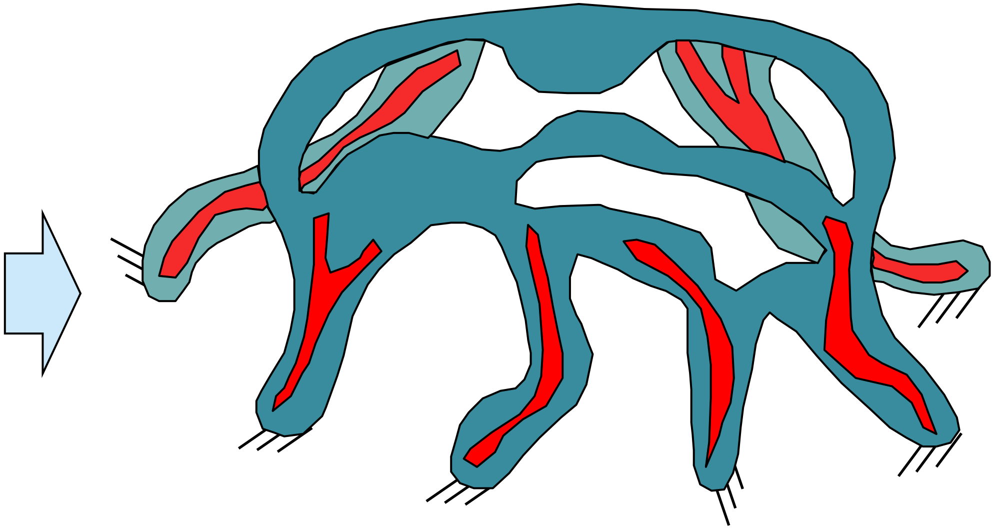
Pluimers PJ, Tolou N, Jensen BD, Howell LL, Herder JL (2012) A compliant on/off connection mechanism for preloading statically balanced compliant mechanisms, *ASME 2011 IDETC*, paper DETC2012-71509.

Towards zero force



Next next generation





Lambert P, Herder JL (2015) A Novel Parallel Haptic Device with 7 Degrees of Freedom, *World Haptics Conference 2015*, Chicago, p183-188 (DOI: 10.1109/WHC.2015.7177711).

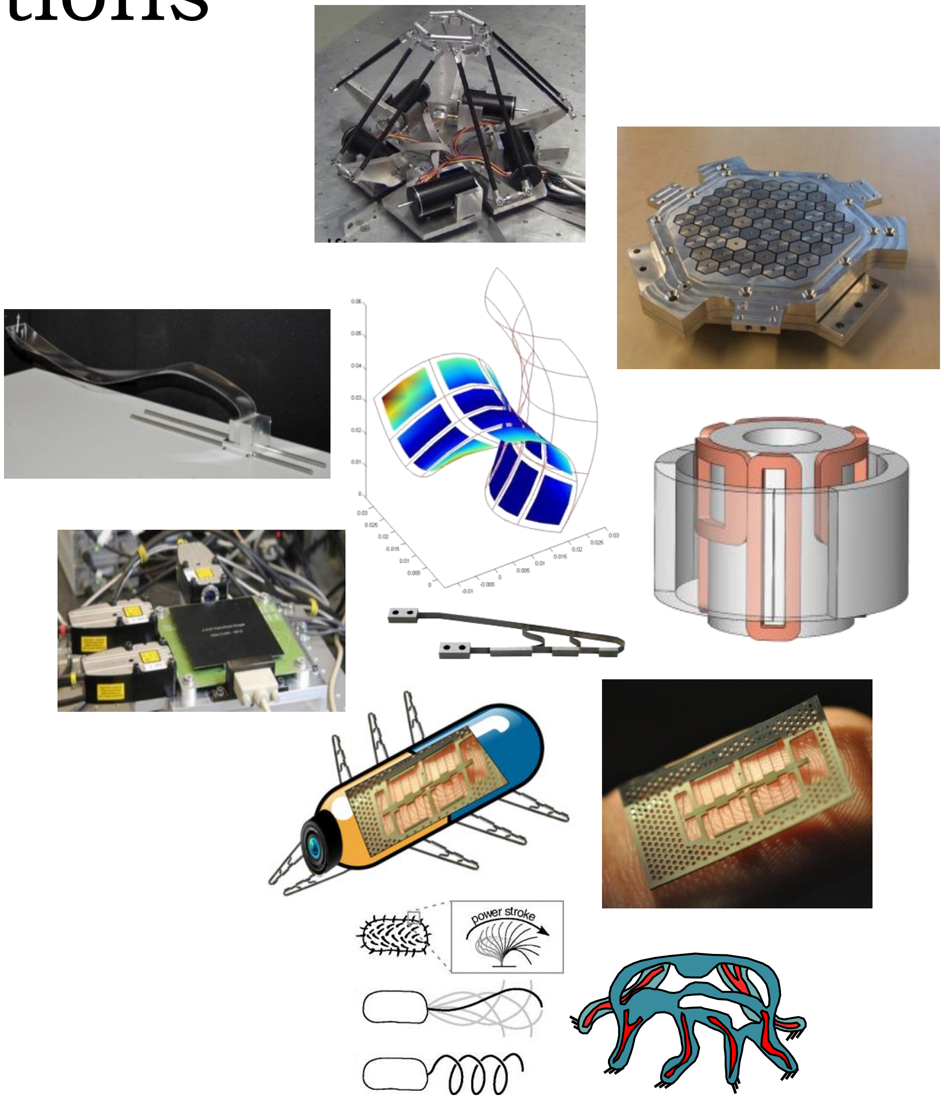
Research directions

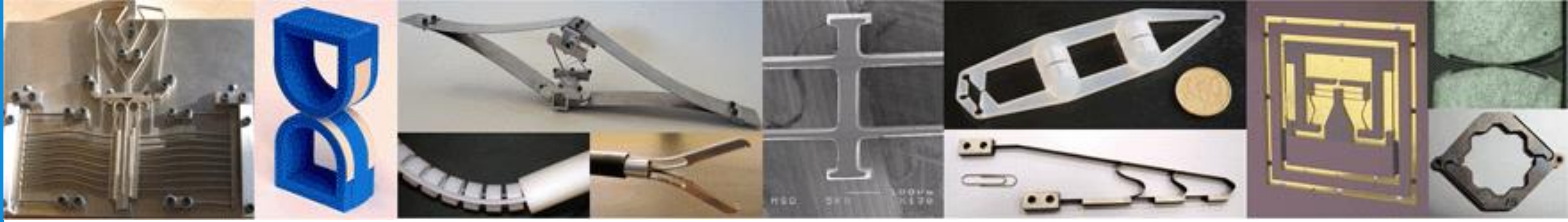
Large scale systems with special behavior

Large scale systems with micro/nano accuracy

Small scale systems with micro/nano features

Nano scale systems with nano accuracy





Strength and stiffness…
CM toolbox contains…
Stiffness is not…

Thank you!