iNaCoMM'25

IFToMM

7th International and 22nd National Conference on Machines and Mechanisms

Convention Center, IIT Hyderabad, December 7–10, 2025

Compliant mechanism in front of my office by Cees van der Geer

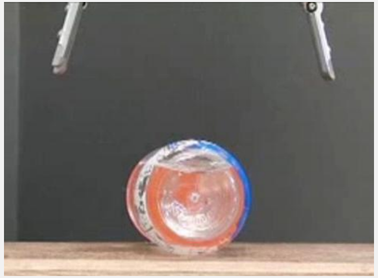
Precision
Compliant Mechanisms

Just Herder
Delft University of Technology

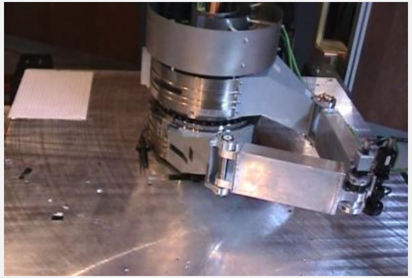
TU Delft

Compliant mechanism in front of my office by Cees van der Geer

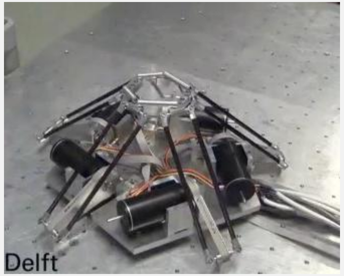
Remembrance of Prof. Ashok Midha
Characteristics of compliant mechanisms
Strategies to improve behavior
Trends and prospects



Underactuation
Mechanically adaptive grippers

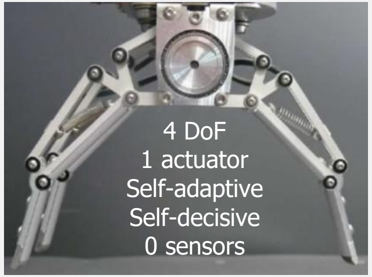


Dynamic balancing
Fast and accurate manipulators

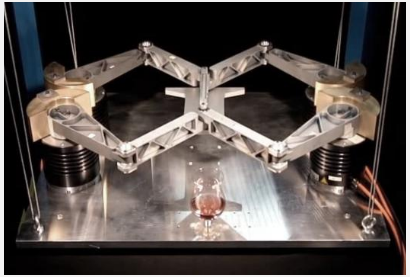


Parallel robotics
Light-weight and stiff

Static balancing
Adjustable spring mechanisms



Underactuation
Mechanically adaptive grippers



Dynamic balancing
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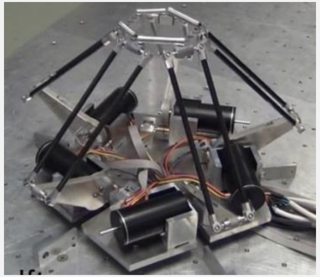

Parallel robotics
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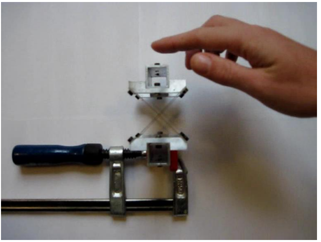
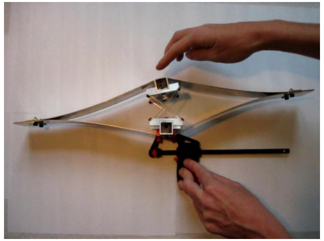
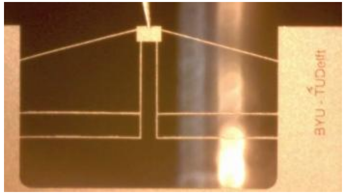
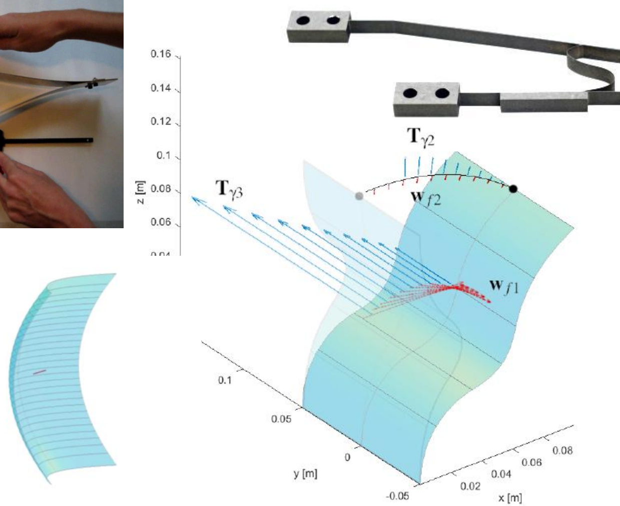
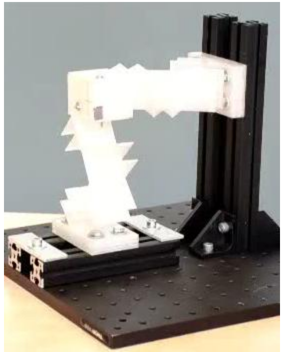



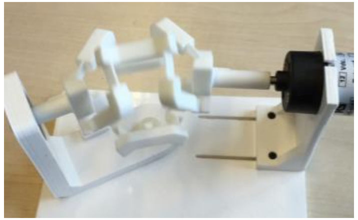
Compliant mechanisms
Precision motion and force transfer

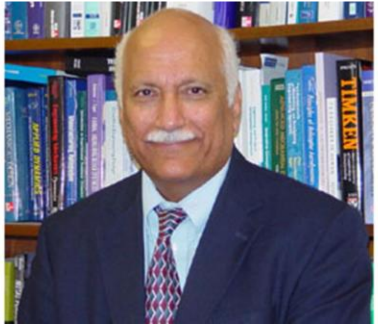






Shell mechanisms
Spatially curved flexures



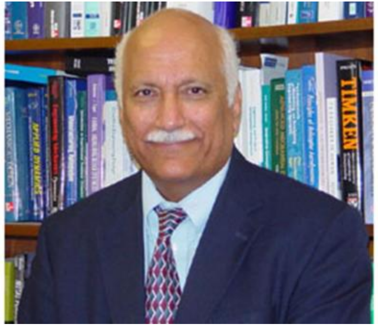


Prof. Ashok Midha

Prof. Ashok Midha
1946-2023

- B.Sc. National Institute of Technology in Jamshedpur in 1968
- M.Sc. 1970 and Ph.D. 1977 in Mechanical Engineering from the University of Minnesota
- Professor at Michigan Technological Institute, Pennsylvania State University, Purdue University, and The Missouri University of Science and Technology
- Head of Department at The Missouri University of Science and Technology for 10 years
- Over 140 papers in developing phase of the field of compliant mechanisms ("Father of Compliant Mechanisms")
- Since 2012, ASME named a symposium within IDETC Mechanisms and Robotics after him
- Since 2024, ASME named the Compliant Mechanisms Award (that he installed and sponsored for years) after him
- ASME Fellow (since 2002) and received ASME Mechanisms and Robotics Award (1998)

Pseudo-Rigid Body Modeling (PRBM)



Prof. Ashok Midha
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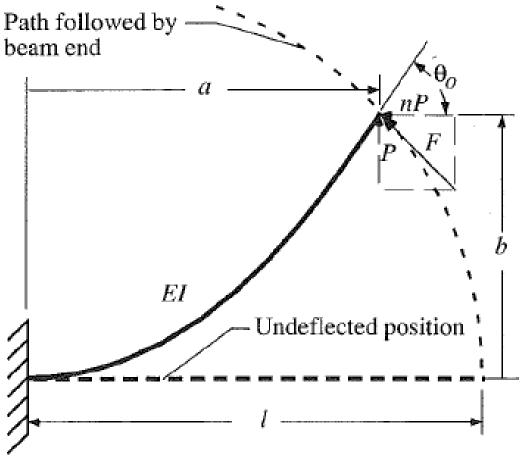
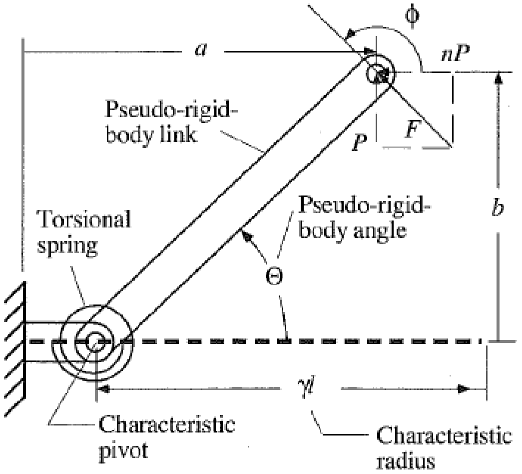
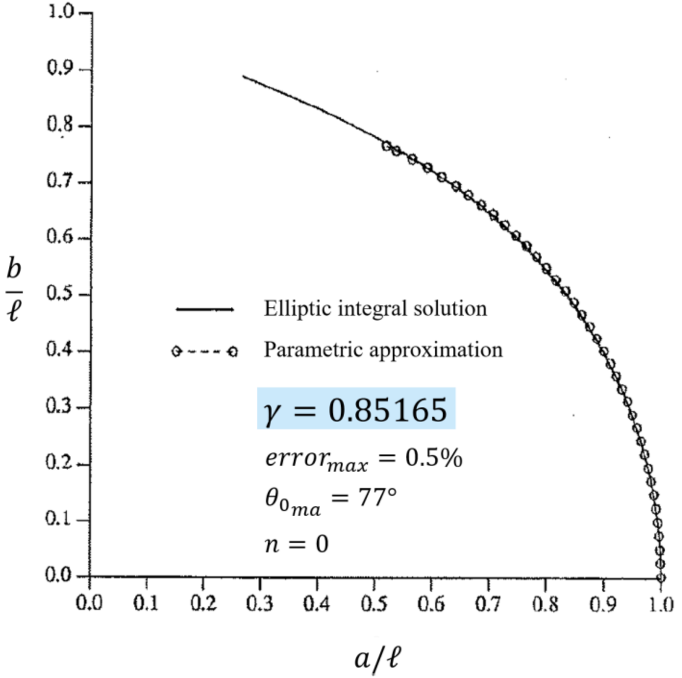


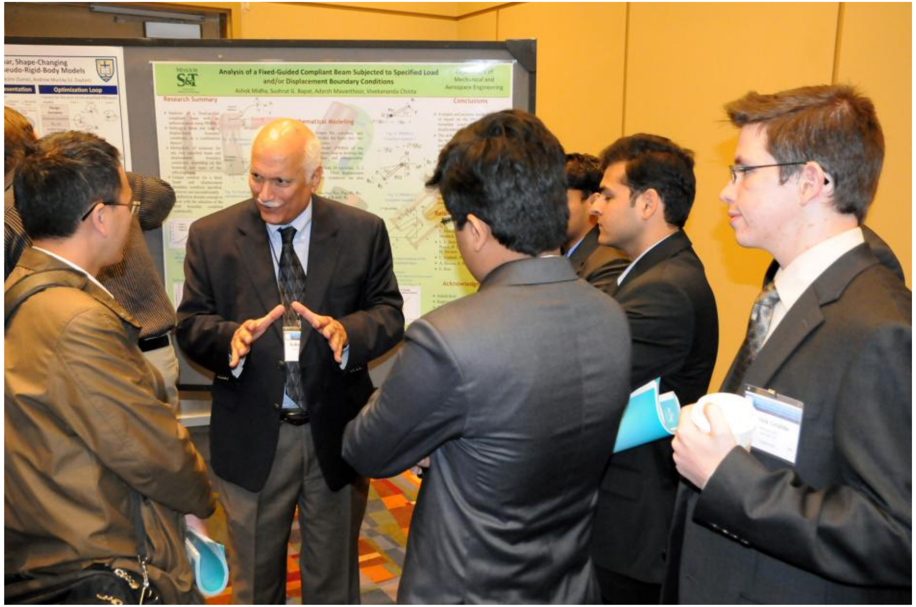




Howell LL, Compliant Mechanisms, Wiley & Sons, 2001


EXIT


ecified Beam End Displacements
se 1: A three degree-of-freedom analysis
oblem (specification of beam end horizontal
sition a, vertical displacement b, and angle
se 2: A two degree-of-freedom analysis
EXIT


Analysis of a Fixed-Guided Compliant Beam Subjected to Specified Load and/or Displacement Boundary Conditions

N.N., Larry Howell, Charles Kim, Just Herder, Ashok Midha, Jonathan Hopkins, Guimin Chen, N.N., Dannis Brouwer, N.N.

Precision Compliant Mechanisms

Just Herder

Characteristics of compliant mechanisms
Well-behaved flexures
Strategies to improve behavior
Static balancing
Trends and prospects

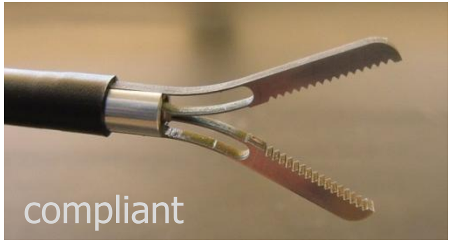
Nature: compliant and strong

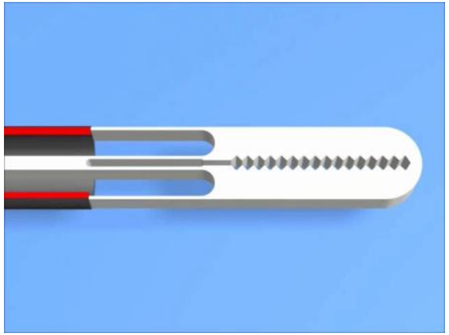
Compliant mechanisms

Motion due to deformation
➢ Flexible AND strong

Essentially monolithic
- No friction or backlash
- No assembly or maintenance
➢ Simpler AND better

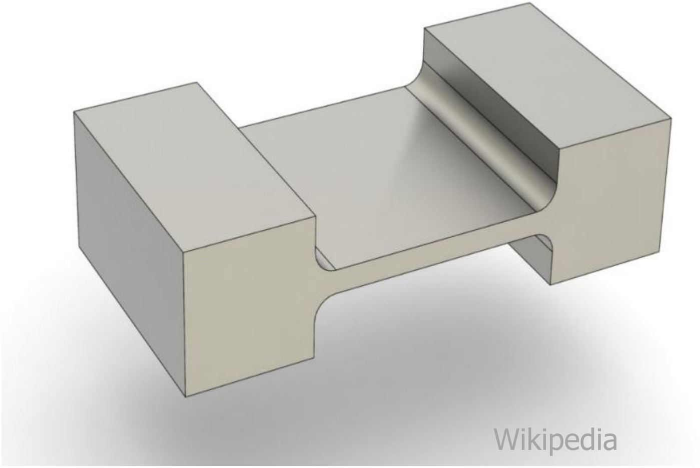
Kinematics and kinetics intertwined
Design more complicated and tailored
Finite support stiffness (ideally infinite)
Finite motion stiffness (ideally zero)

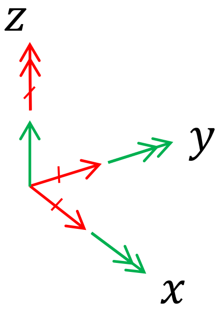




Herder JL, Berg FPA van den (2000) Statically balanced compliant mechanisms (SBCM's), an example and prospects ASME DETC 26th Mechanisms and Robotics Conference, DETC2000/MECH-14144.

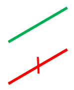
Flexure as a revolute joint





k_f = freedom stiffness, DoF

k_c = constraint stiffness, DoC



Traditional analysis

Bernoulli-Euler beam theory:

$$M = EI\frac{d\theta}{ds} \approx EI\frac{d^2y}{dx^2}$$

$$M = F(l-x) \quad \downarrow \quad \theta = \frac{dy}{dx}$$

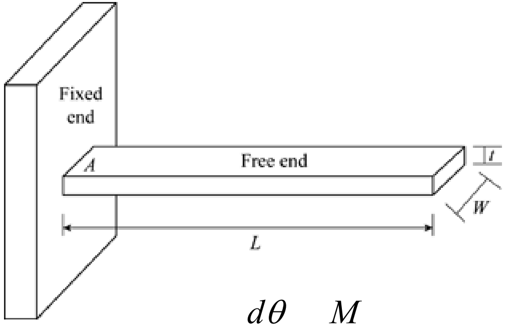
$$F(L-x) = EI\frac{d\theta}{dx}$$

Separating variables and integrating: $\theta = \frac{F}{EI}\left(Lx - \frac{x^2}{2}\right) + C$

Boundary conditions θ=0 at x=0: $\theta = \frac{dy}{dx} = \frac{Fx}{2EI}(2L-x)$

Separating variables and integrating: $y = \frac{Fx^2}{6EI}(3L-x)$

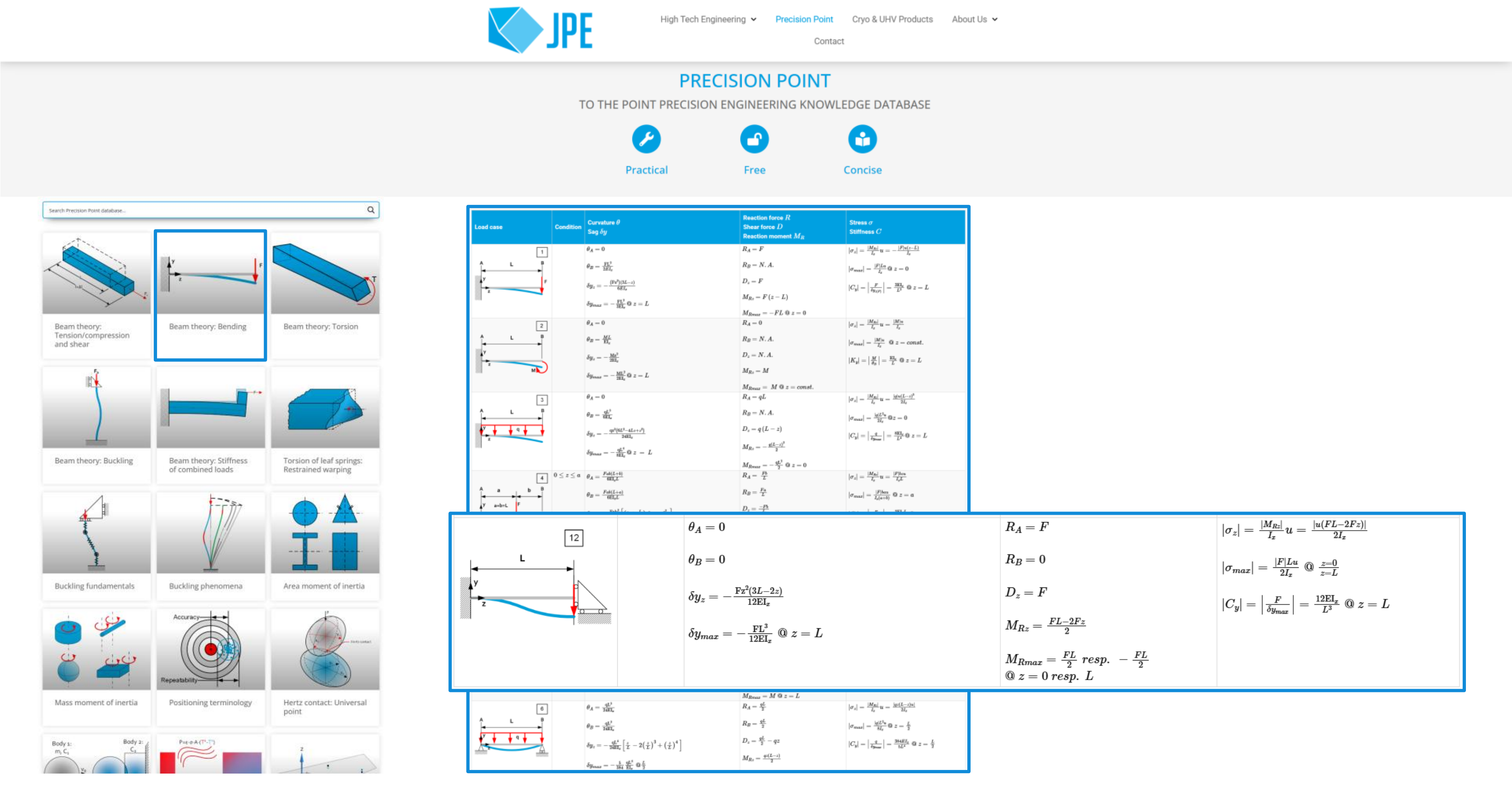
$$y_{x=L} = \frac{FL^3}{3EI}$$



$$\kappa = \frac{d\theta}{ds} = \frac{M}{EI}$$

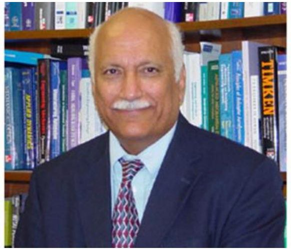
Curvature proportional to moment

Linear beam theory



https://www.jpe-innovations.com/precision-point/

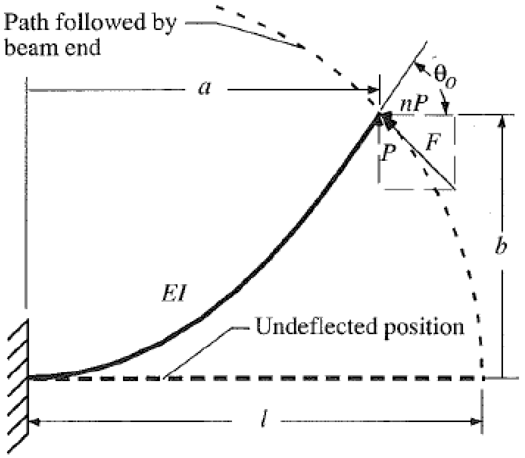
Large deflections

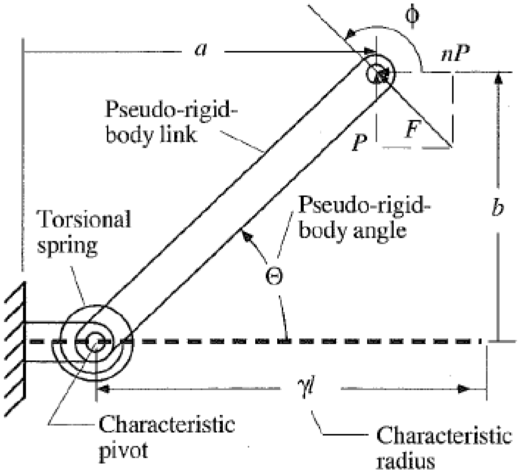


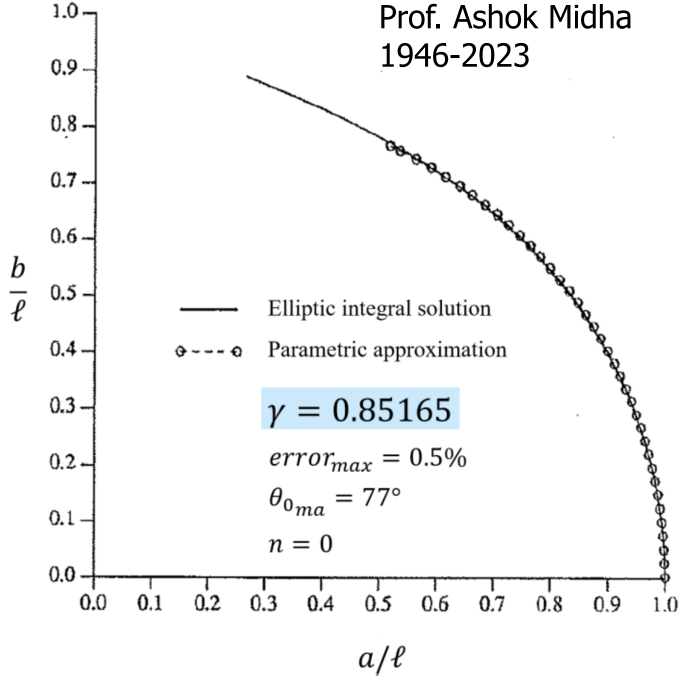
Prof. Ashok Midha
1946-2023

Elliptic integral of $M = EI\frac{d\theta}{ds}$ is cumbersome…

Approximation by arc motion and torsional spring:
Pseudo-Rigid-Body Model (PRBM, Midha and Howell)

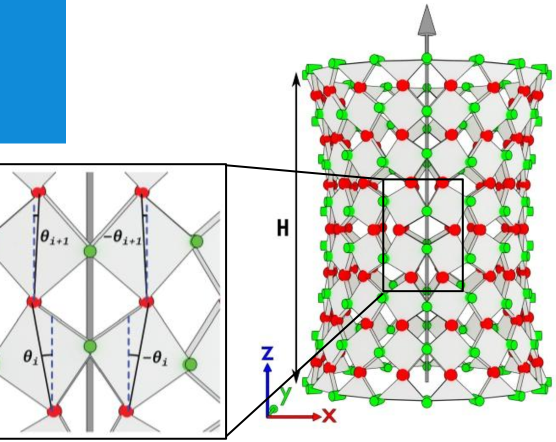


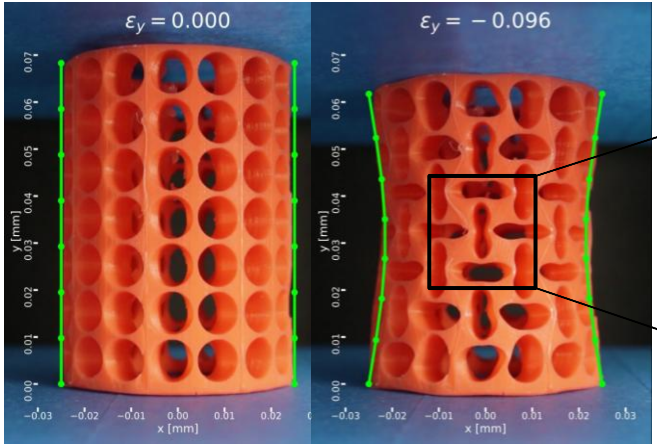


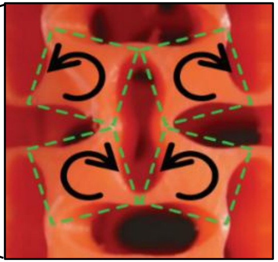


Spatial kinematic modelling

Freek Broeren





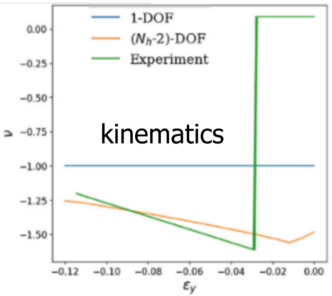


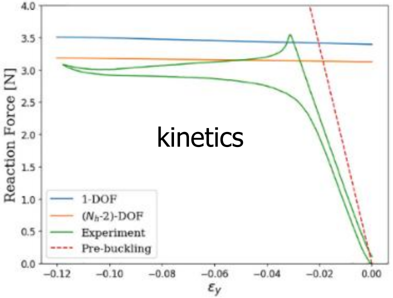
$$r_i = \frac{l\cos(\theta_i)}{2\sin\left(\frac{\pi}{N_c}\right)}$$

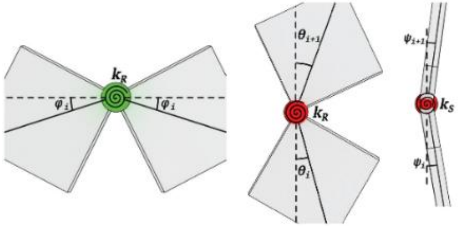
$$h_i = l\cos(\theta_i)\cos(\psi_i)$$

$$H = \frac{h_0 + h_{N_h}}{2} + \sum_{i=2}^{N_h-1} h_i$$

$$\nu = -\frac{H}{r}\frac{\partial r}{\partial H} = -1$$





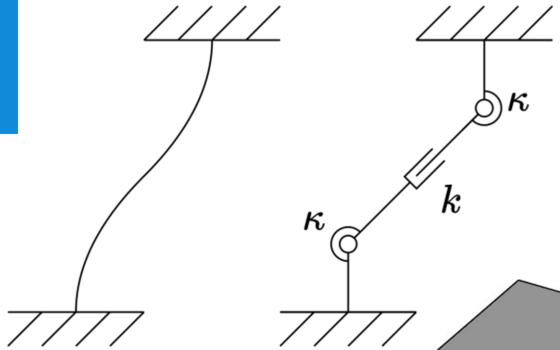


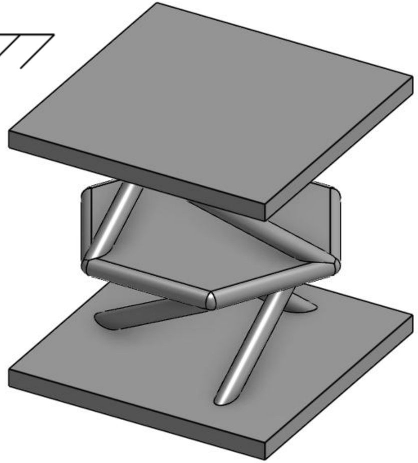
$$E = E_h + E_v + E_s$$
$$= \frac{1}{2} N_c k_R \left(N_h (2\phi(\theta))^2 + (N_h - 1)(2\theta)^2\right)$$

TU Delft

Broeren FGJ, Wijk V van der, Herder JL (2019) Spatial Pseudo-Rigid Body Model for the Analysis of a Tubular Mechanical Metamaterial, *Mathematics and Mechanics of Solids*

Energy method (pyBRM)





Minimization of potential energy

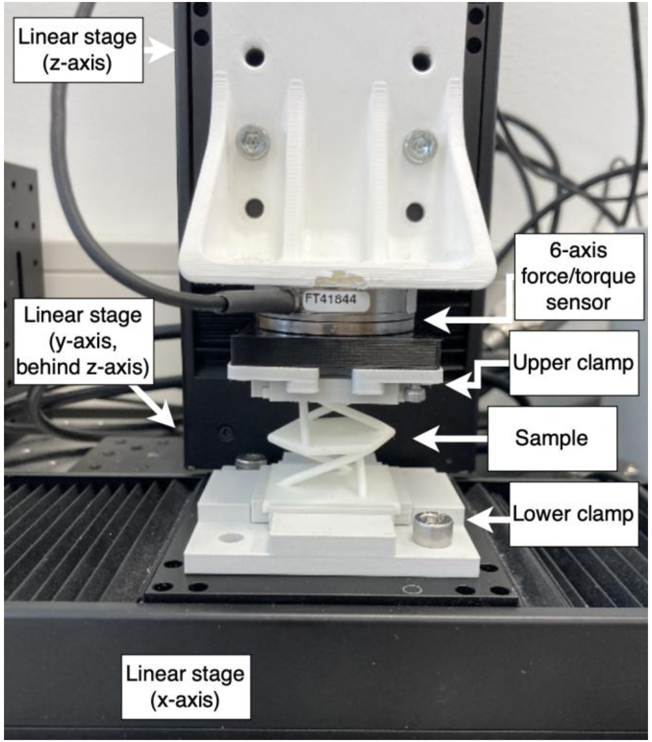
No kinematic analysis needed

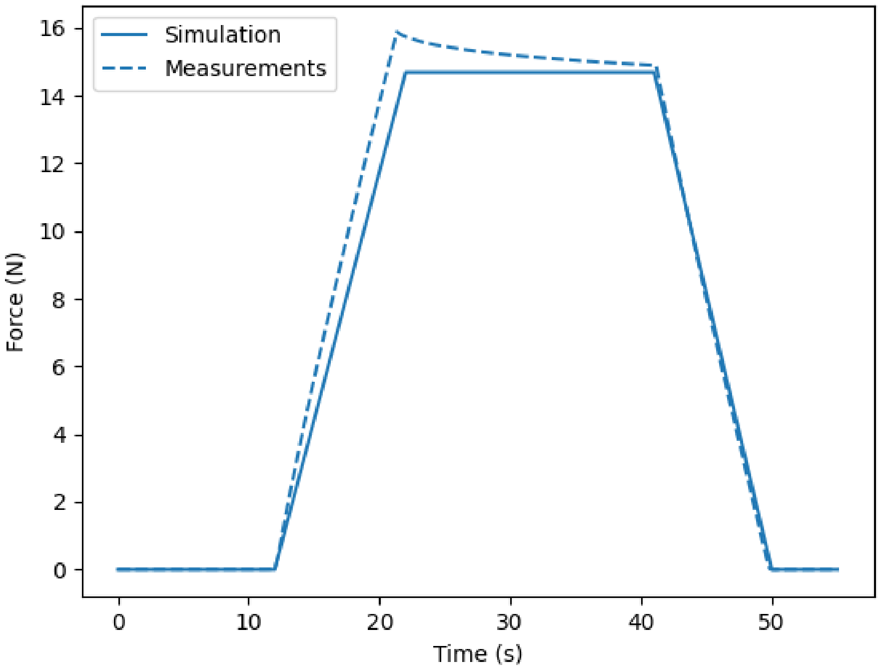
Fast and accurate

Domas Syaifoel

```python
p = PRBM(3)

p.add_body('A', (0, 0, 0))
p.add_body('B', (0, 0, 15*mm))
p.add_body('C', (0, 0, 3*cm))

t = mm
A = pi*t**2
E = 1650e6
I = pi*t**4/2

n = 3
r = 14*mm

for i in range(n):
    p.add_flexure('A', (r*cos(i/n*2*pi), r*sin(i/n*2*pi), 0),
                  'B', (r*cos((i + 1)/n*2*pi), r*sin((i + 1)/n*2*pi), 0))
    p.add_flexure('C', (r*cos((i - .5)/n*2*pi), r*sin((i - .5)/n*2*pi), 0),
                  'B', (r*cos((i + .5)/n*2*pi), r*sin((i + .5)/n*2*pi), 0))

p.show()
```

Energy method (pyBRM)

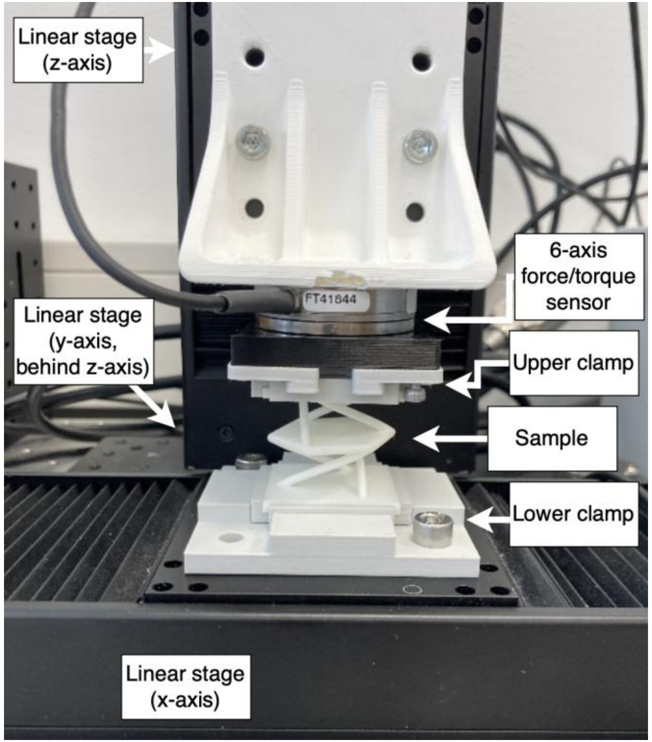


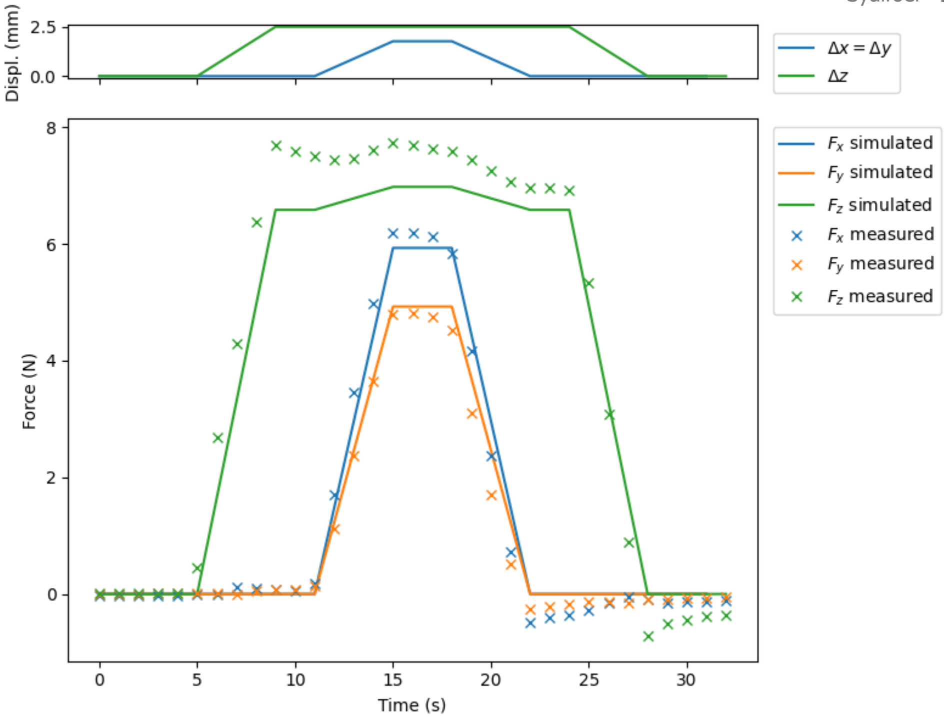


Domas Syaifoel

Energy method (pyBRM)


Domas Syaifoel





Precision Compliant Mechanisms

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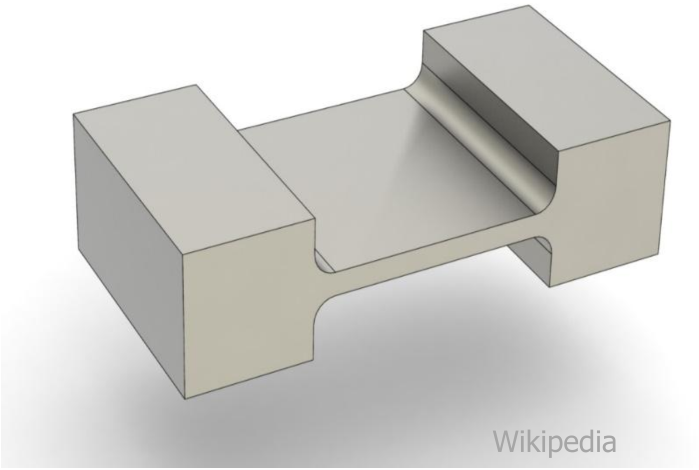
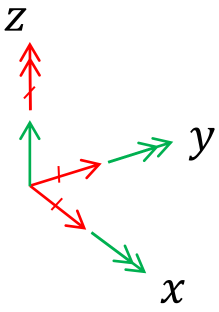
Flexure as a revolute joint





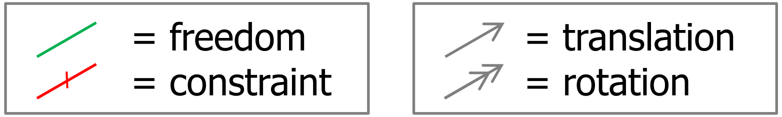
'Good' flexure:

$$\frac{k_f}{k_c} \gg 150$$

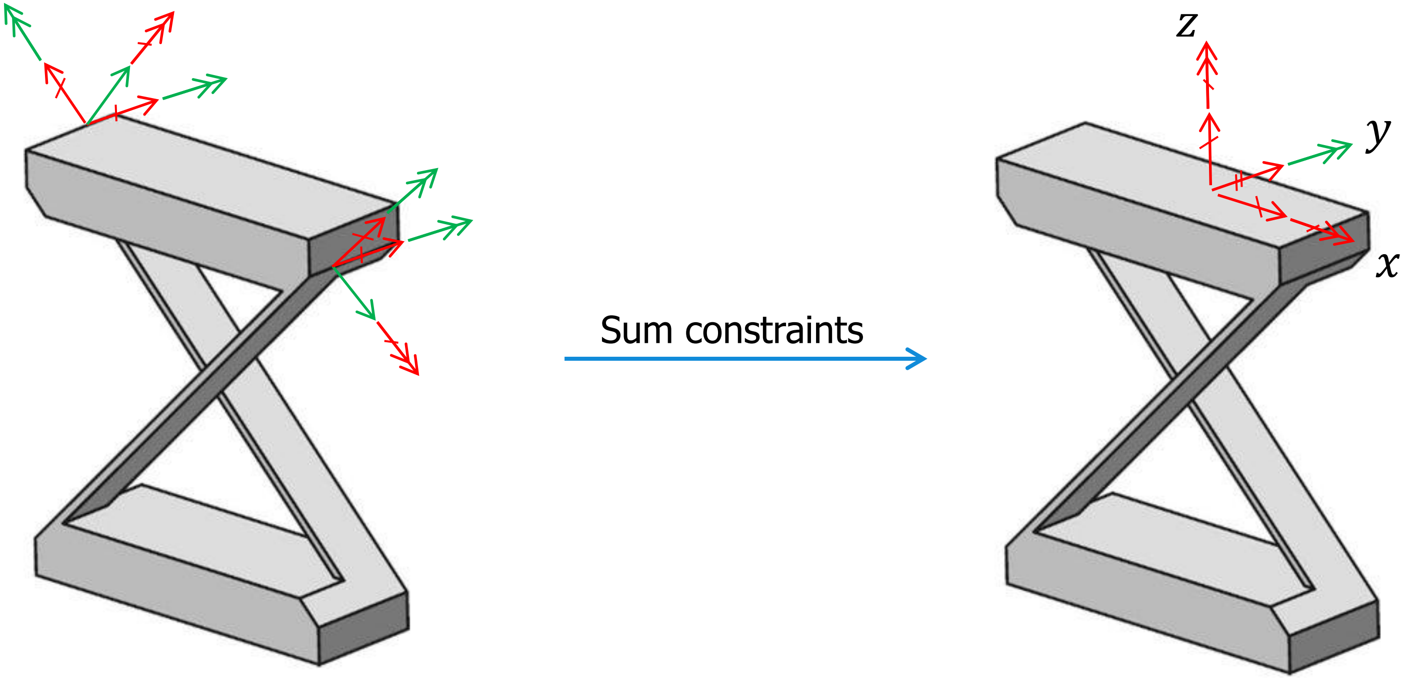
$$\frac{k_{c,\,max}}{k_{c,min}} \ll 50$$

k_f = freedom stiffness, DoF

k_c = constraint stiffness, DoC

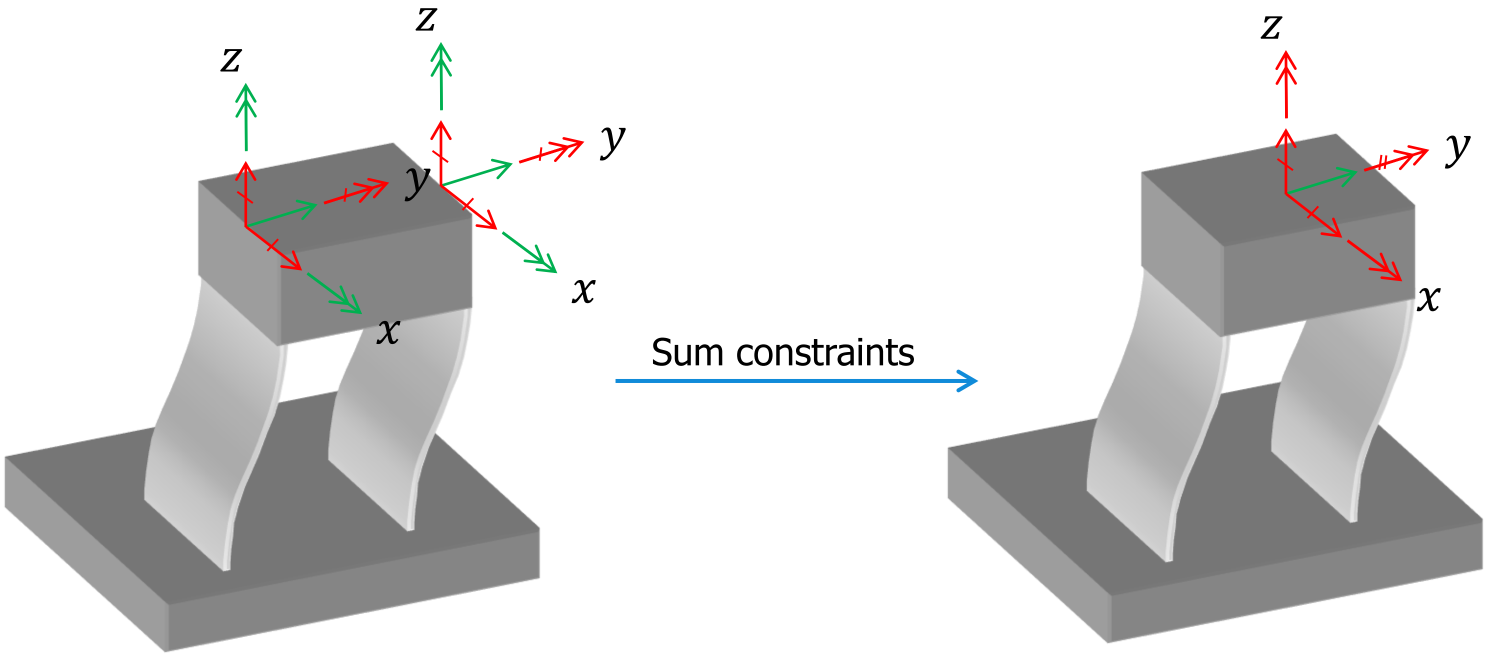


Cross-flexure as a better revolute joint



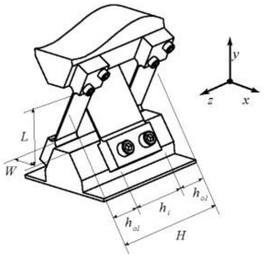
Adapted from: K. Marković and S. Zelenika, Proc. SPIE 9517, 2015

Double flexure prismatic joint

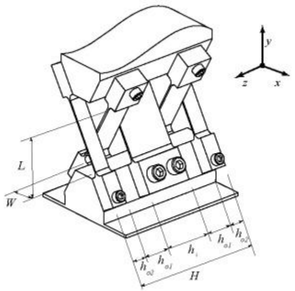


Adapted from: H. Soemers, Design Principles, 2011

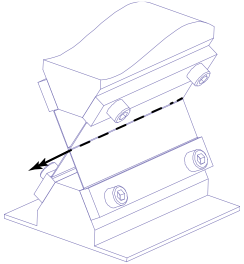
Problem: stiffness decay at deflection



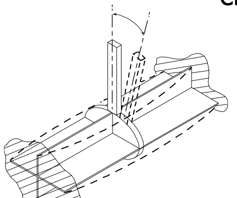
Three flexure cross hinge



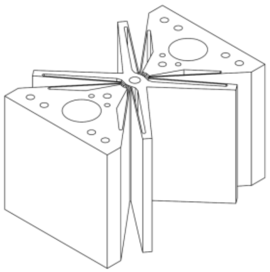
Five flexure cross hinge



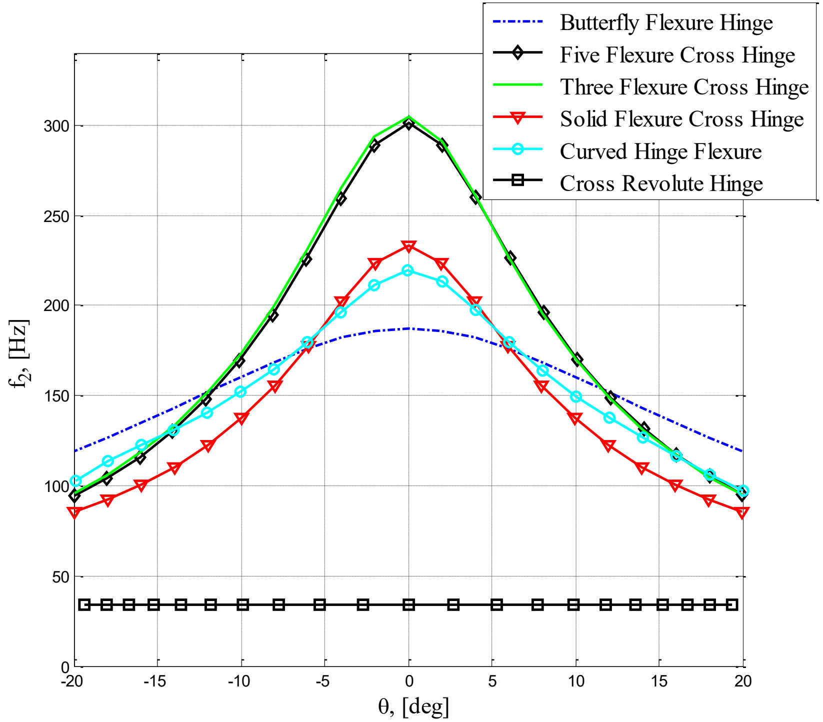
Solid flexure cross hinge



Cross Revolute hinge



Butterfly flexure hinge

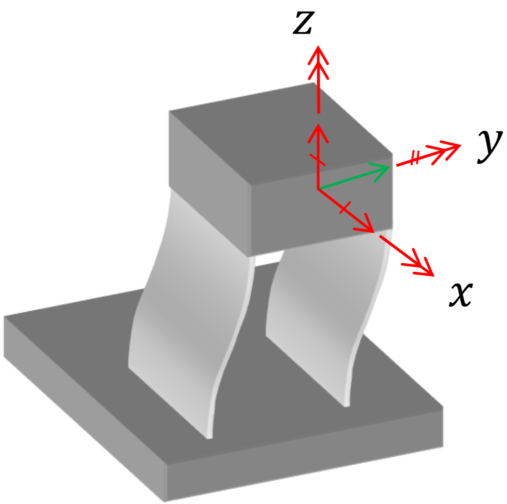


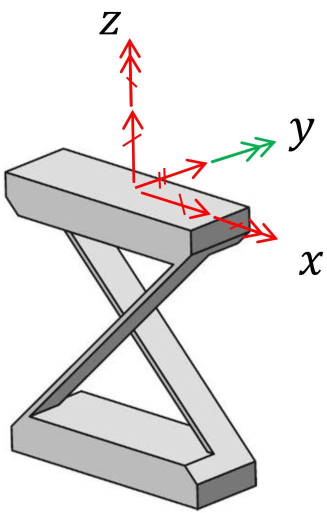
D.H. Wiersma, et al., Design and Performance Optimization of Large Stroke Spatial Flexures, ASME Journal of Computational and Nonlinear Dynamics

What makes a good compliant joint

Degrees of freedom (green): low freedom stiffness k_f
Constraint directions (red): high constraint stiffness k_c

} High stiffness ratio $\frac{k_c}{k_f}$





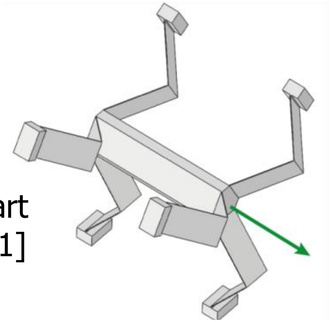
Torsion reinforcement

Increase range of motion:
- Series-parallel
- Initial stress or curve

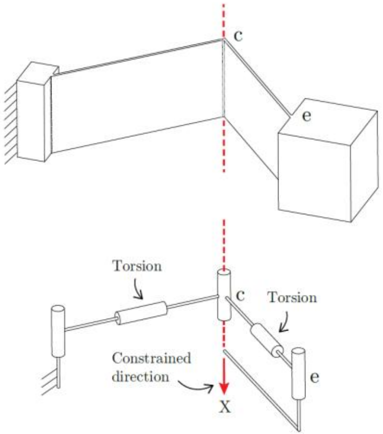
Increase stiffness ratio:
- Reduce k_f: static balance
- **Increase k_c: reinforcement**

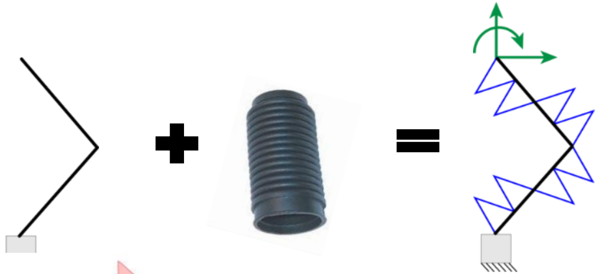
Reinforcement

State-of-the-art linear guide [1]

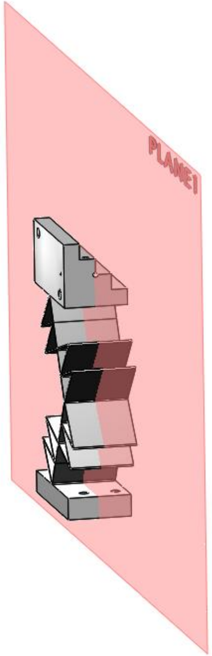


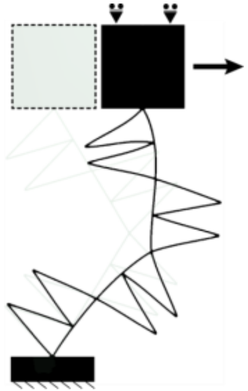
Based on 6 folded flexures:





Jelle Rommers



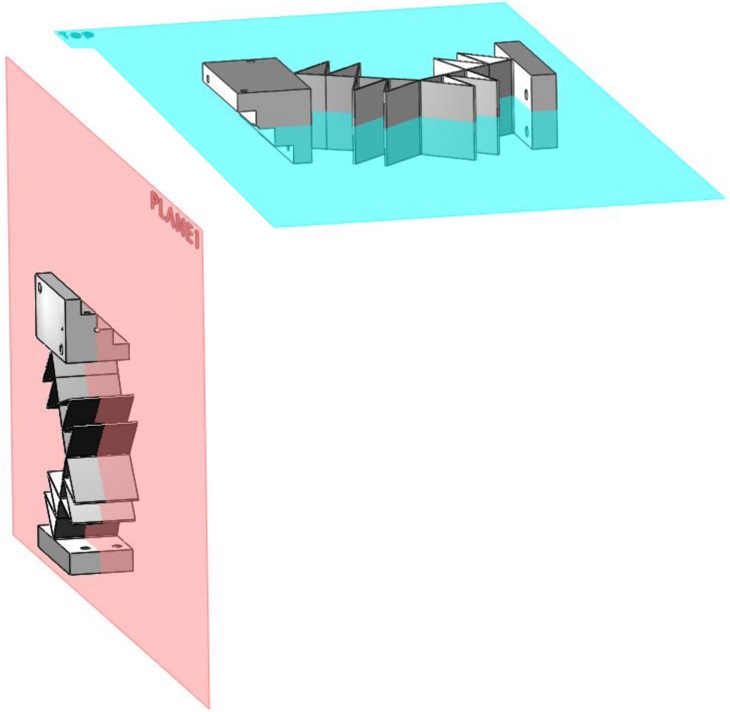


Distributed compliance

[1] Herman Soemers. Design Principles for precision mechanisms. T-Pointprint, 2011

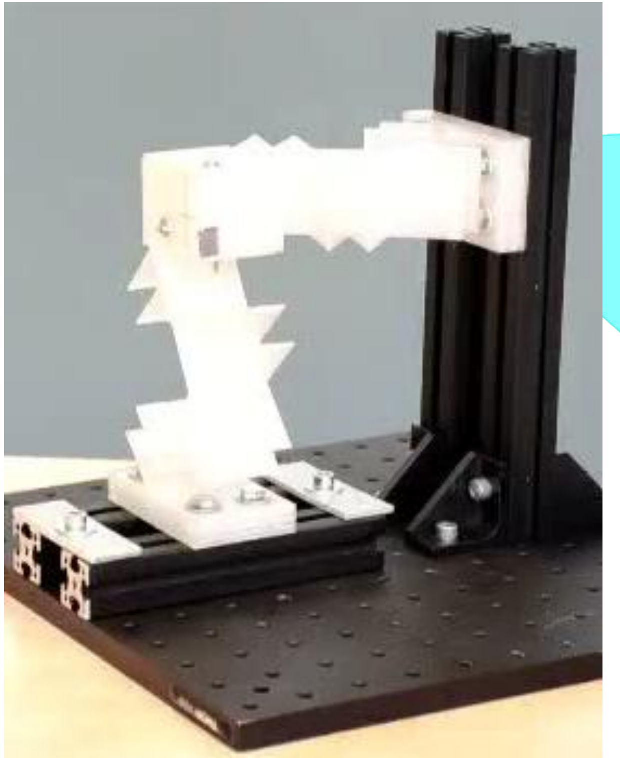
Rommers J, Naves M, Brouwer DM, Herder JL (2021) A flexure-based linear guide with torsion reinforcement structures, J Mechanisms Robotics (DOI: 10.1115/1.4052971)

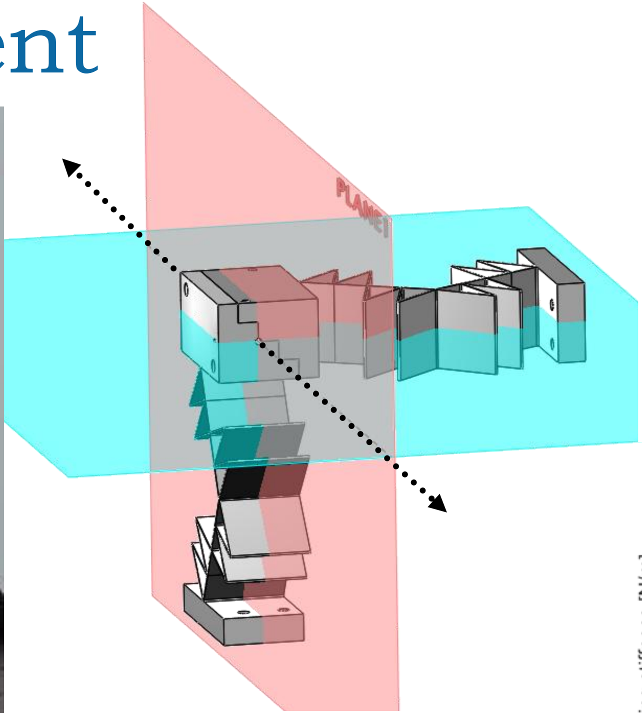
Reinforcement



Rommers J, Naves M, Brouwer DM, Herder JL (2021) A flexure-based linear guide with torsion reinforcement structures, J Mechanisms Robotics (DOI: 10.1115/1.4052971)

Reinforcement





Advantages
- Less obstructive build volume
- Fewer elements
- Higher support stiffness

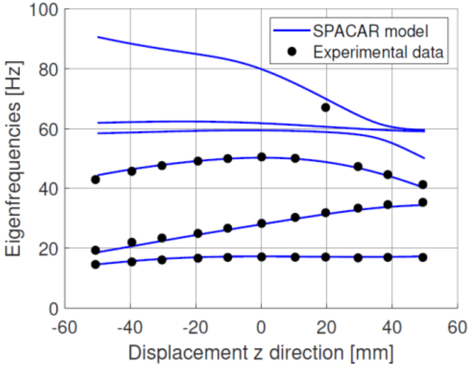
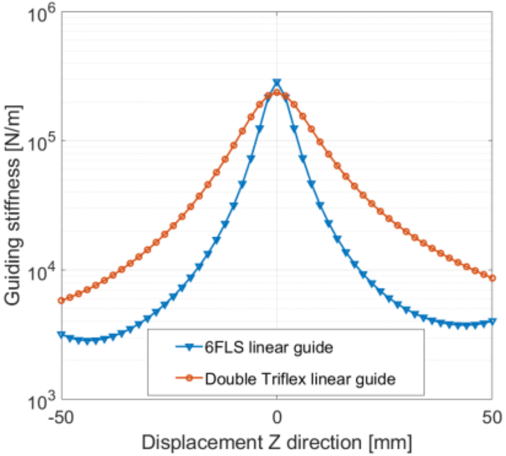
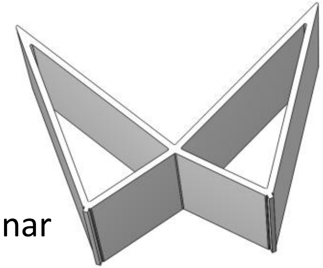


Fig. 15: Measured and modelled parasitic eigenfrequencies of the Nylon prototype of the 2-TR-FLS design. The eigenfrequency in motion direction (not displayed) is 2.1 Hz.

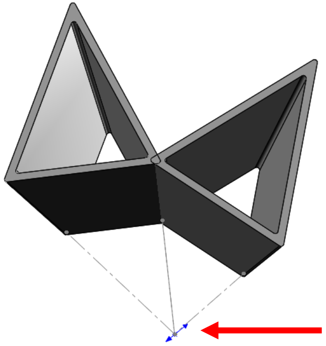


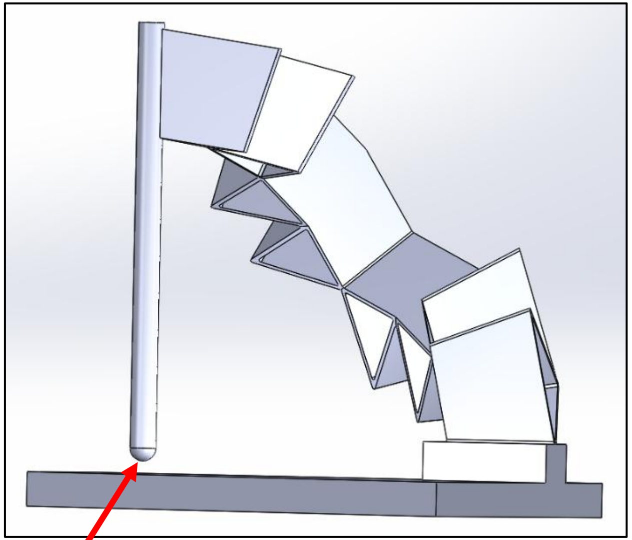
Reinforcement

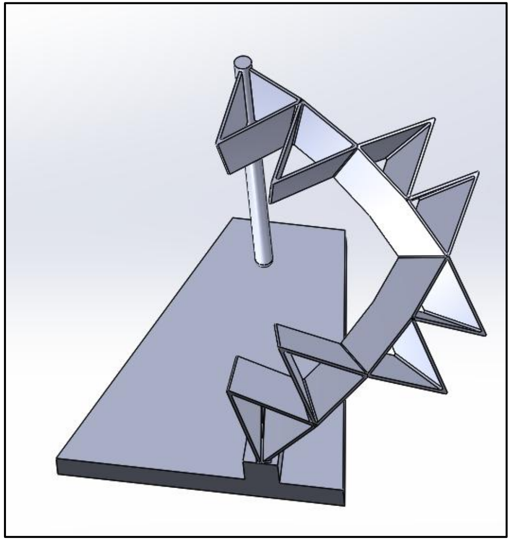


Planar

Spherical



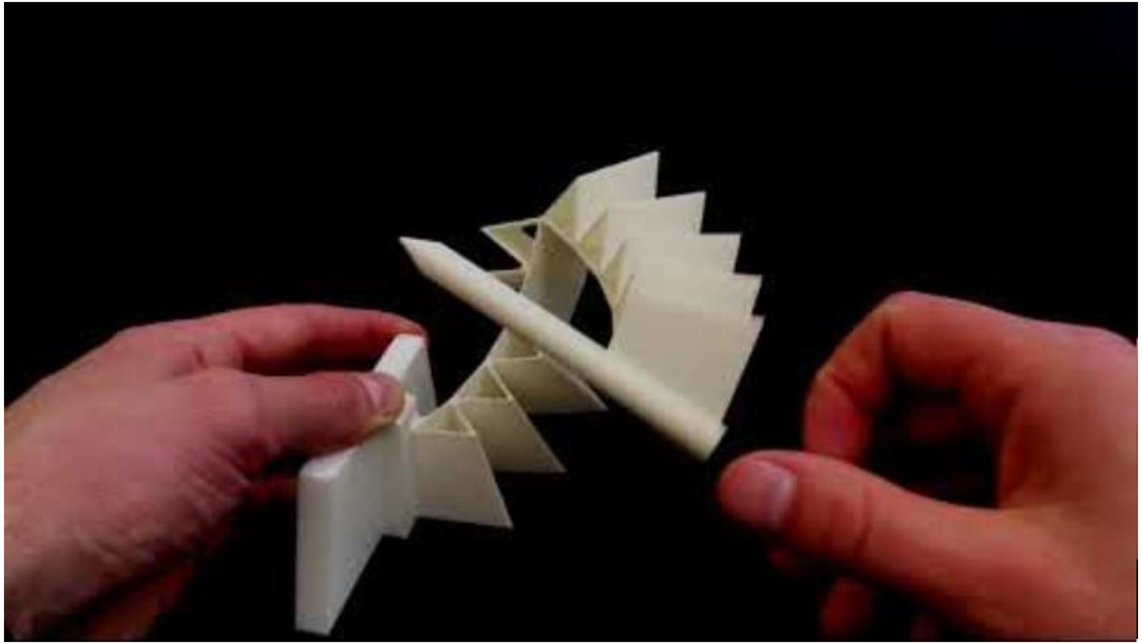




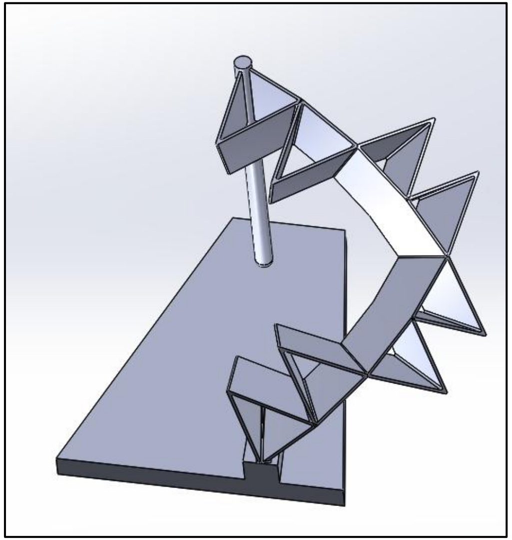
Remote center of rotation

Rommers J, Wijk V van der, Herder JL (2021) A new type of spherical flexure joint based on tetrahedron elements, *Precision Engineering* (71)130-140

Reinforcement

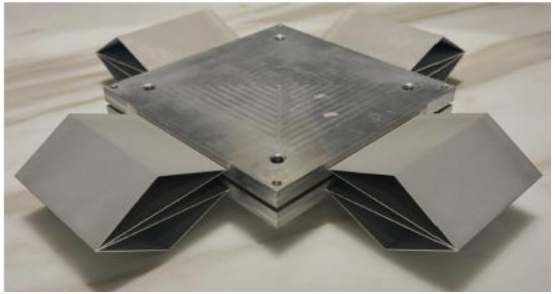


https://www.youtube.com/watch?v=DAngcygU7tc 390k views

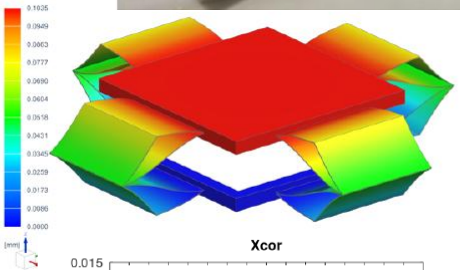


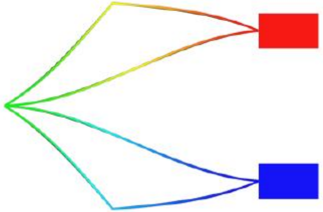
Rommers J, Wijk V van der, Herder JL (2021) A new type of spherical flexure joint based on tetrahedron elements, *Precision Engineering* (71)130-140

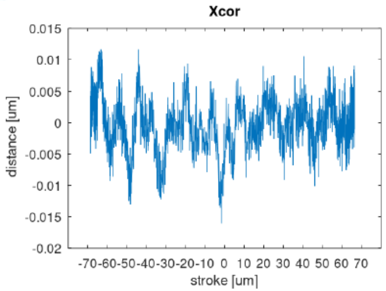
Reinforced compliant Sarrus mech.

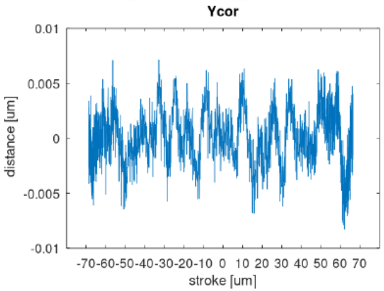


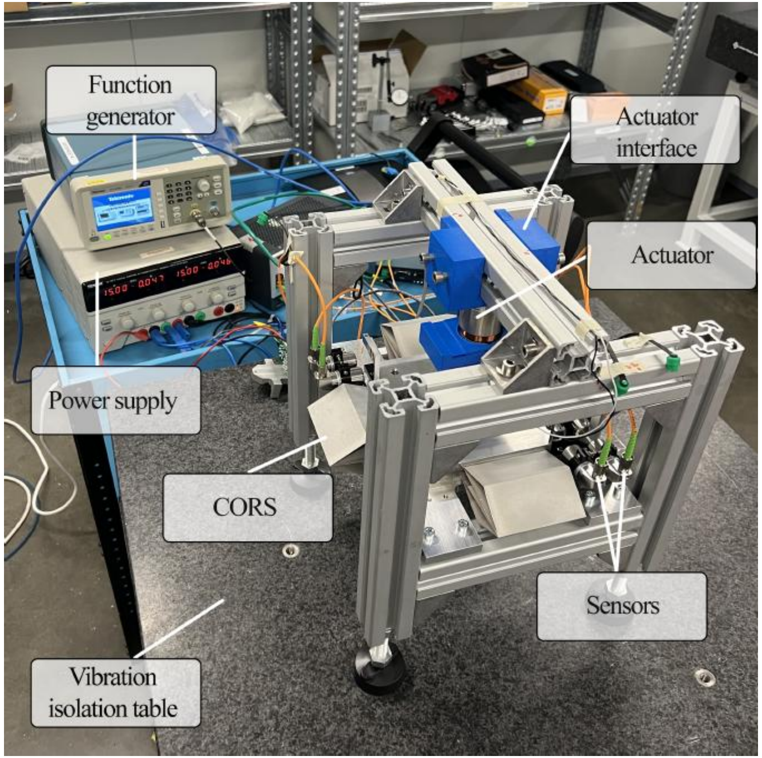
0.7 nm/µm
5 nm over 140 µm
total stroke of 5 mm











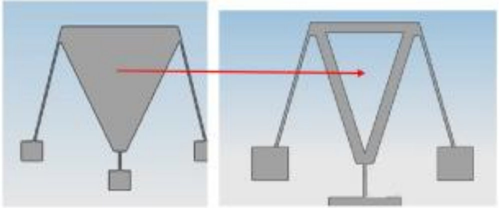
Velden J van, Herder JL (2025) A compact ultra linear compliant torsion reinforced Sarrus mechanism, *ASME Journal of Mechanisms and Robotics*

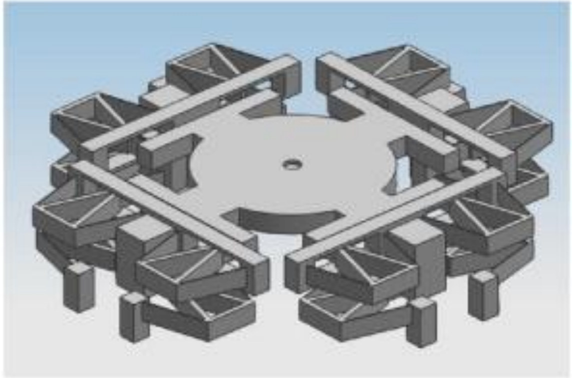
Initial stress or curve

Increase range of motion:
- Series-parallel
- **Initial stress or curve**

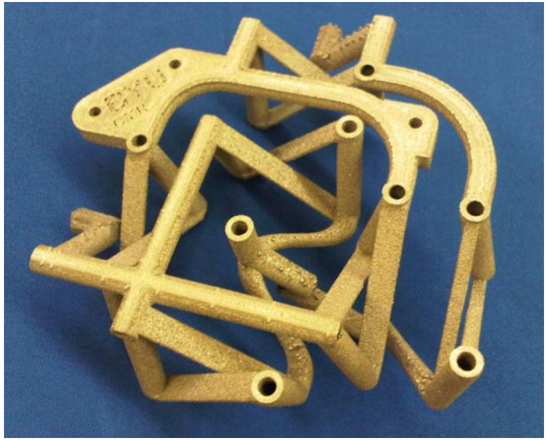
Increase stiffness ratio:
- Reduce k_f: static balance
- Increase k_c: reinforcement

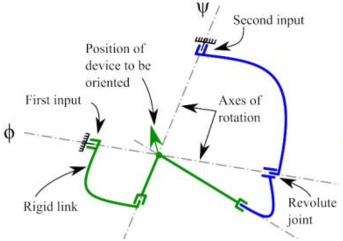
Modern compliant mechanisms

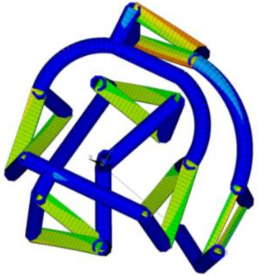


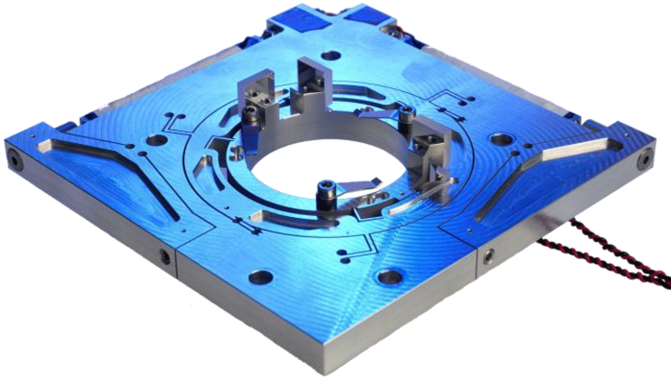


S Wan, Q Xu, Design and analysis of a new compliant XY micropositioning stage based on Roberts mechanism, *Mech. Mach. Theory*, 2016









EG Merriam, JE Jones, SP Magleby, LL Howell, Monlithic 2DoF fully compliant space pointing mechanism, *Mechanical Sciences*, 2013

Pjotr Sebek, Jesse van Koppen et al., yet unpublished

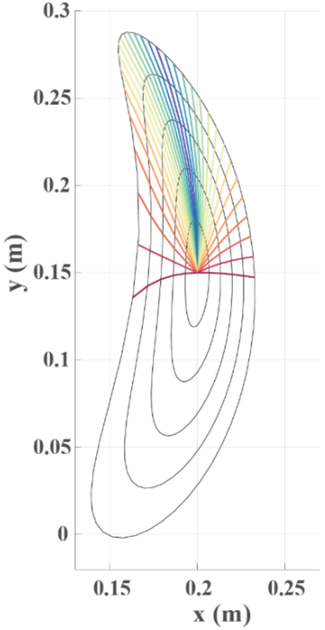

Optimized for:
Straight-line motion
Constant support stiffness
Second modal frequency

Flip Colin

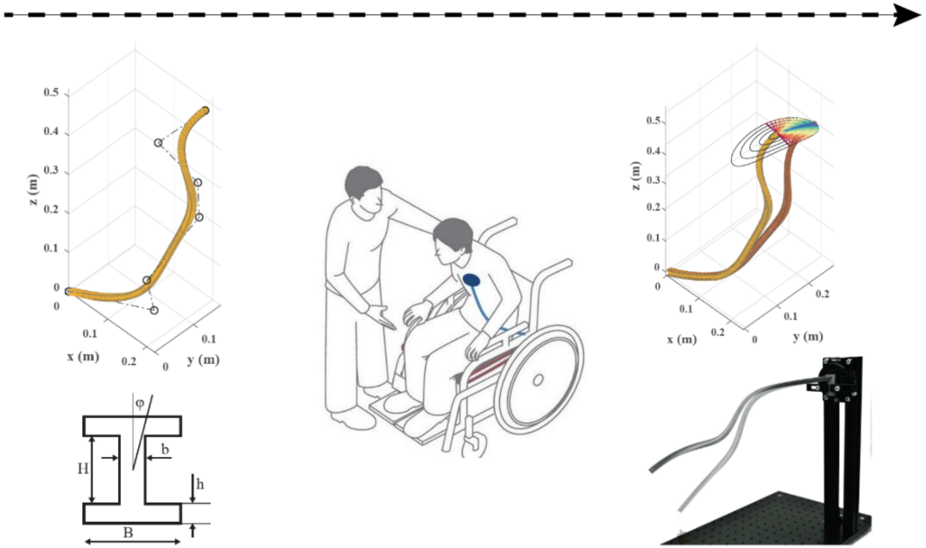
Curved with symmetric stiffness

Ali
Amoozandeh

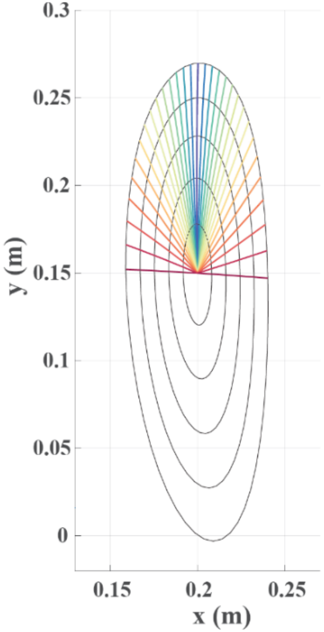
Typical asymmetric behavior



Optimizing section and shape

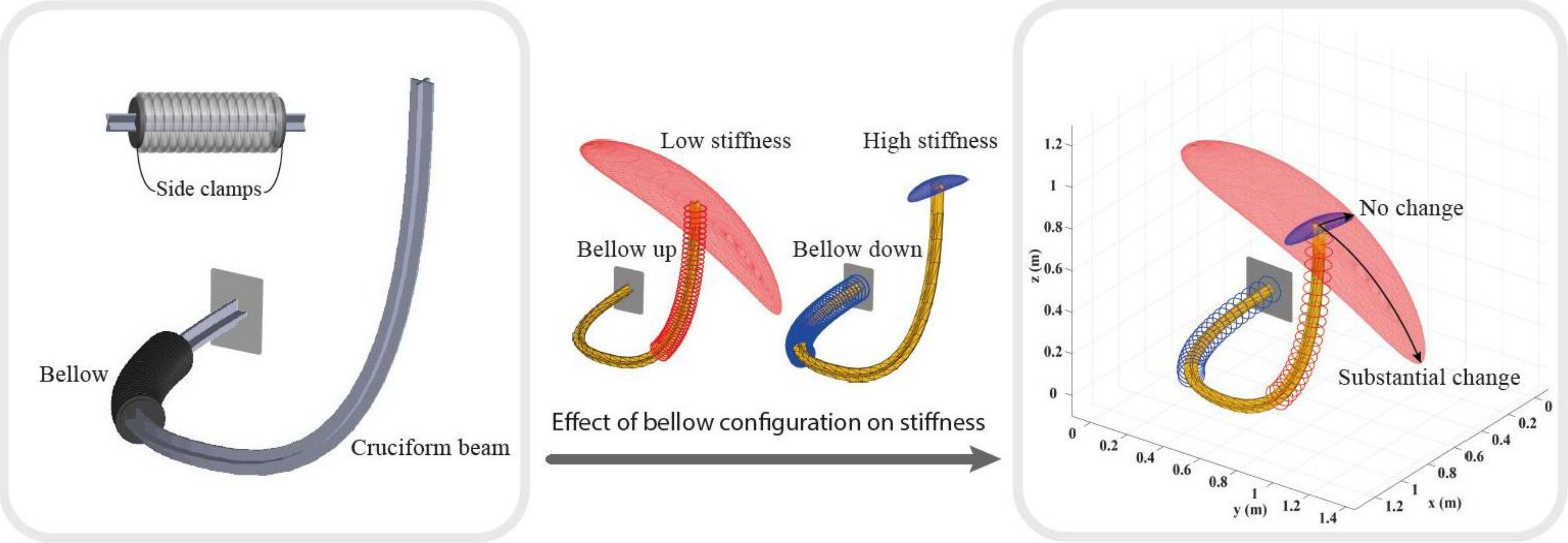


Corrected symmetric behavior



Amoozandeh Nobaveh A, Radaelli G, Herder JL (2021) Asymmetric Spatial Beams with Symmetric Kinetostatic Behaviour, ROMANSY 2020

Anisotroptically adaptive



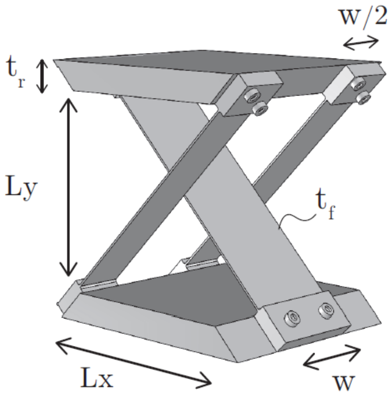
Bellow acts as a sliding torsional stiffener

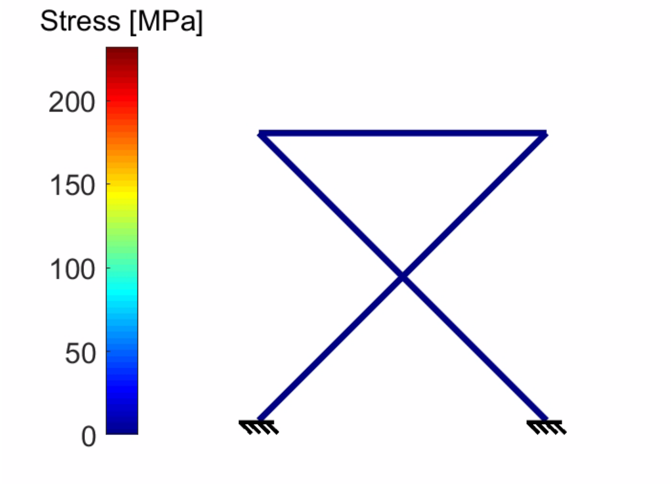
Anisotropically adaptive stiffness

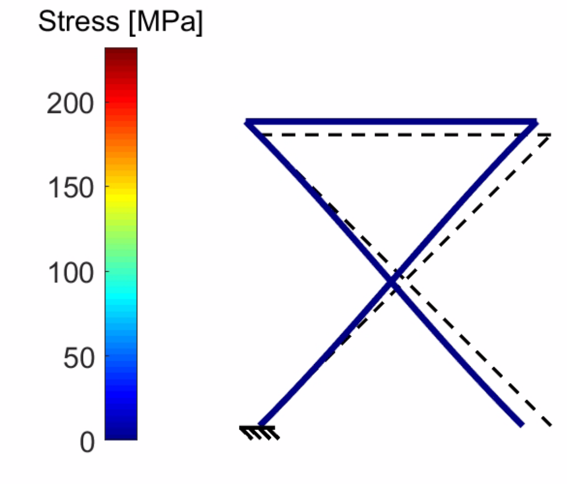
Amoozandeh A, Radaelli G, Herder JL (2022) Characterization of spatially curved beams with anisotropically adaptive stiffness using sliding torsional stiffeners, Intl J Mechanical Sciences, MS_107687

Stress and Geometry (STAGE)

Jelle
Rommers







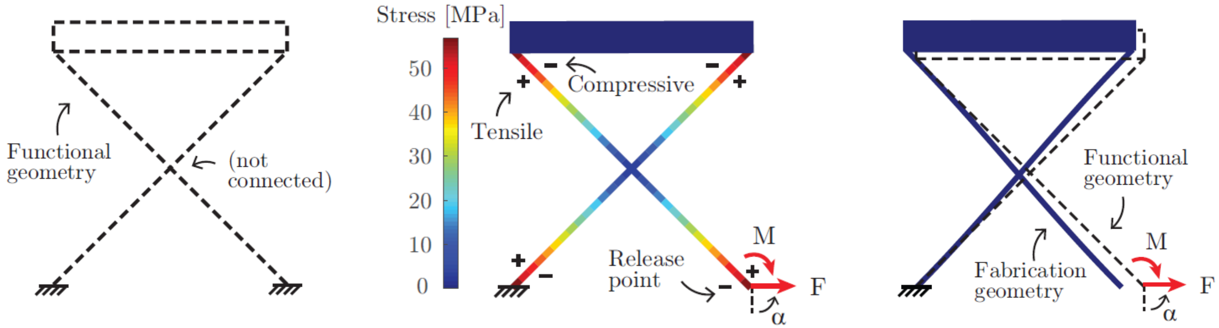
Conventional design:
Initial state is stress-free,
High stress in extreme poses.
Max stress asymmetric.

Pre-stressed design:
Fabrication shape is stress-free,
initial state is pre-stressed.
Reduced stress in extreme poses.

Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

Stress and Geometry (STAGE)

Jelle
Rommers



Step 1 Design of the functional geometry

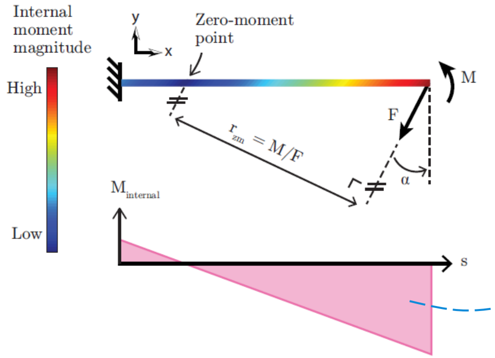
Step 2 Design of the internal stress distribution by loading a release point

Step 3 Calculation by inverse FEM of the stress-free geometry for manufacturing

Step 4 Assembly to obtain the functional geometry with the desired initial stress

Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

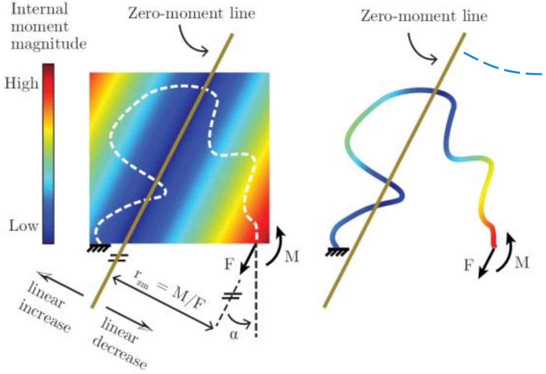
Initial stress or curve



Stress dominated by bending: $\sigma = M_i \frac{t_f}{2I}$

Stress proportional with internal moment, use this to visualize internal stress:

$$M_i(s) = cos(\alpha)F(L - s) - M$$



From this, the zero-moment line (ZML) can be derived:

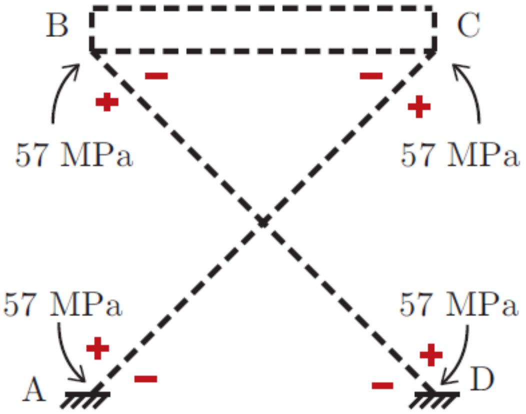
$$M_i(r) = Fr - M$$

Design of stress distribution:

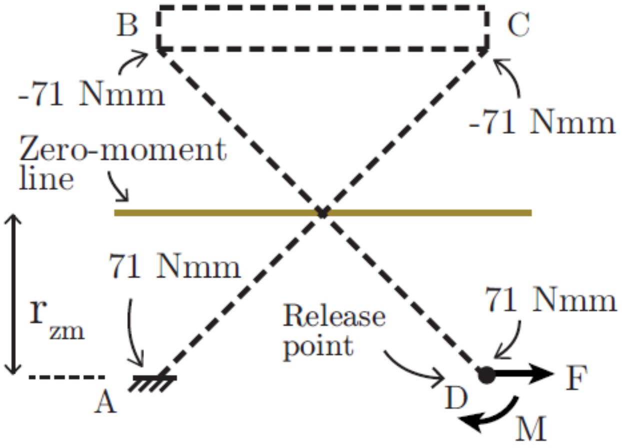
- ZML parallel to external force F
- Distance ZML to action line F is: $r_z = M/F$
- Gradient M-field (perp to ZML) equal to $|F|$

Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

Stress and Geometry (STAGE)



Desired designed stress field



Corresponding load field

Initial stress or curve

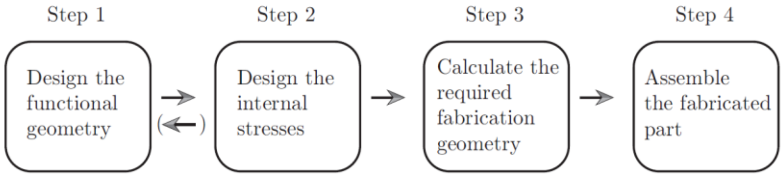
Procedure:

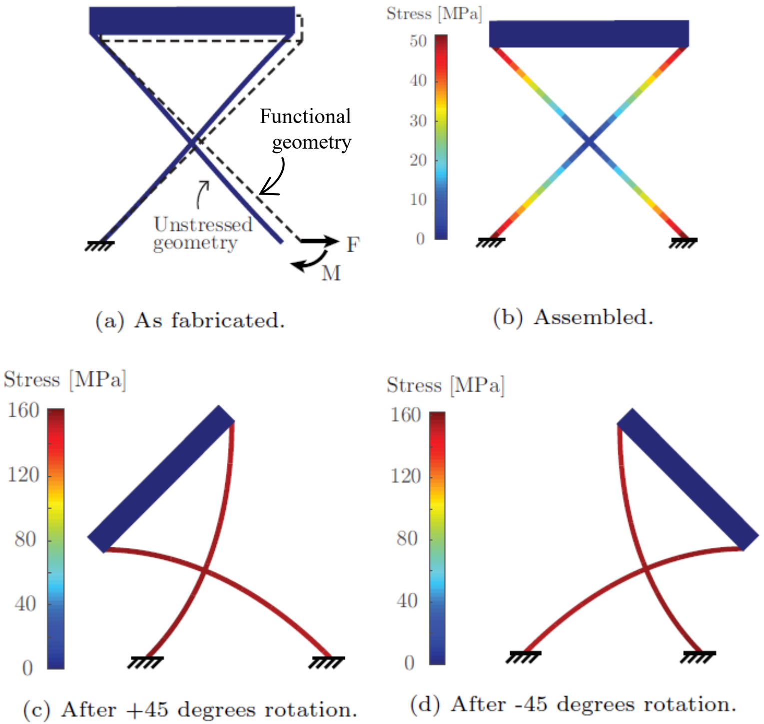
Step 1: Design the functional geometry as in a conventional way

Step 2: Design the initial stress configuration

Step 3: Calculate the required fabrication geometry (optim or iFEM)

Step 4: Assemble the fabricated part in the initially designed geometry

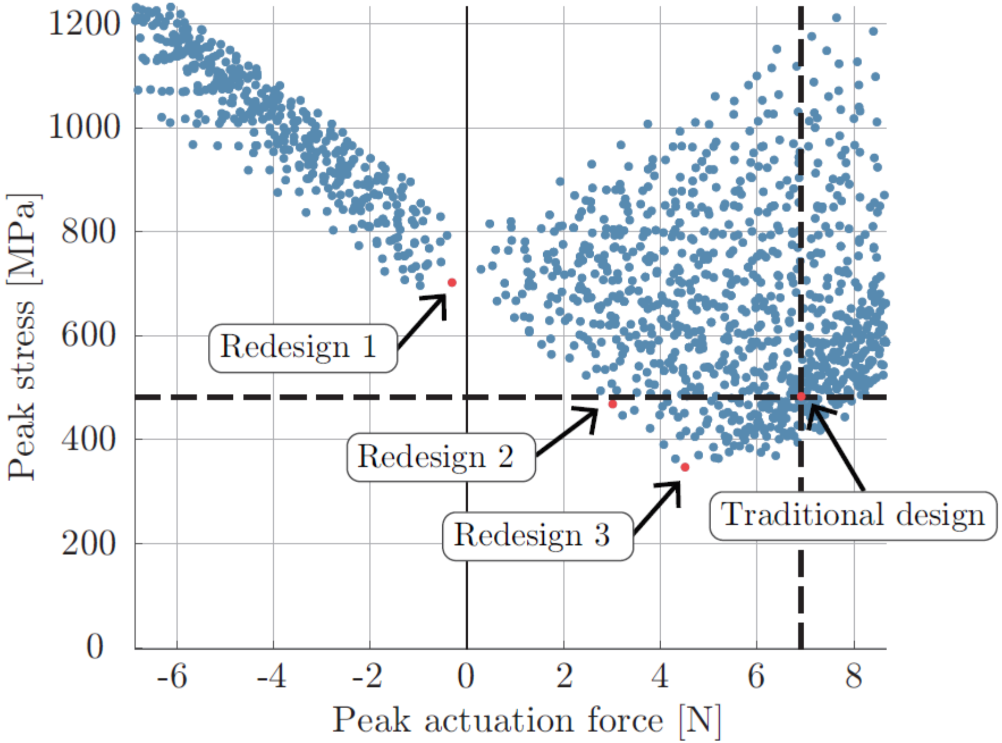




(a) As fabricated.
(b) Assembled.
(c) After +45 degrees rotation.
(d) After -45 degrees rotation.

Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

Initial stress or curve

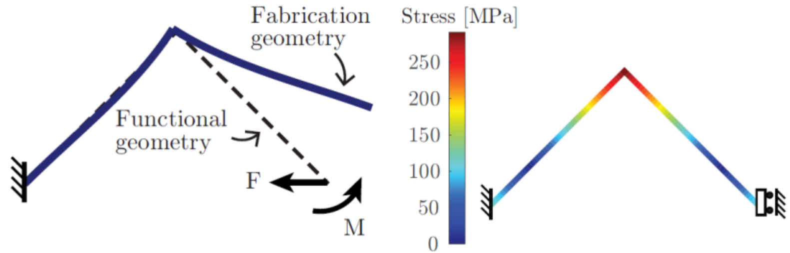


Any closed-loop flexure can be optimized by initial stress:

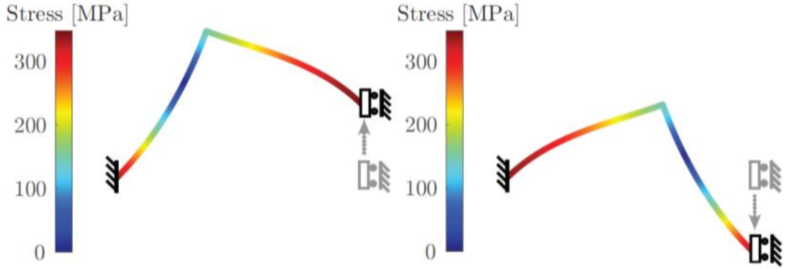
- Reduced motion stiffness
- Reduced maximum stress
- Both

Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

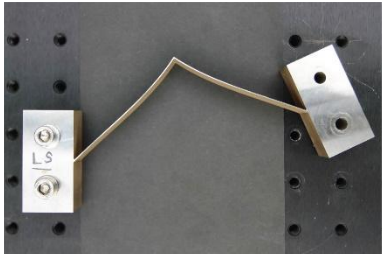
Initial stress or curve

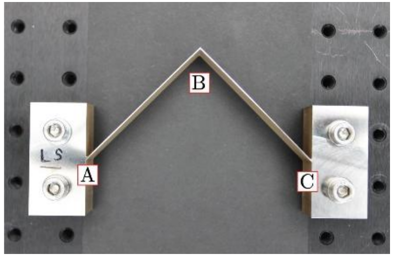


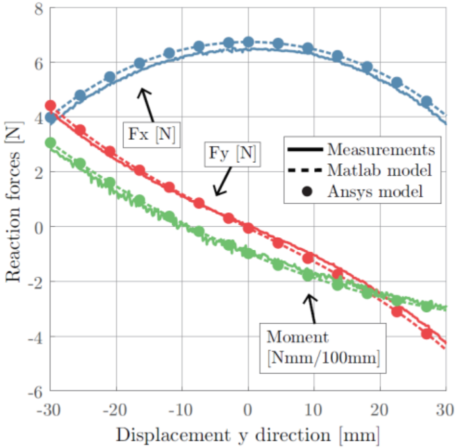
(a) As fabricated. (b) Assembled.

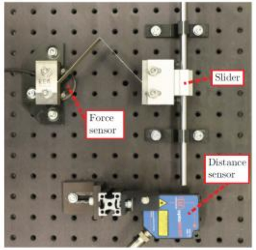


(c) After +30 mm displacement. (d) After -30 mm displacement.







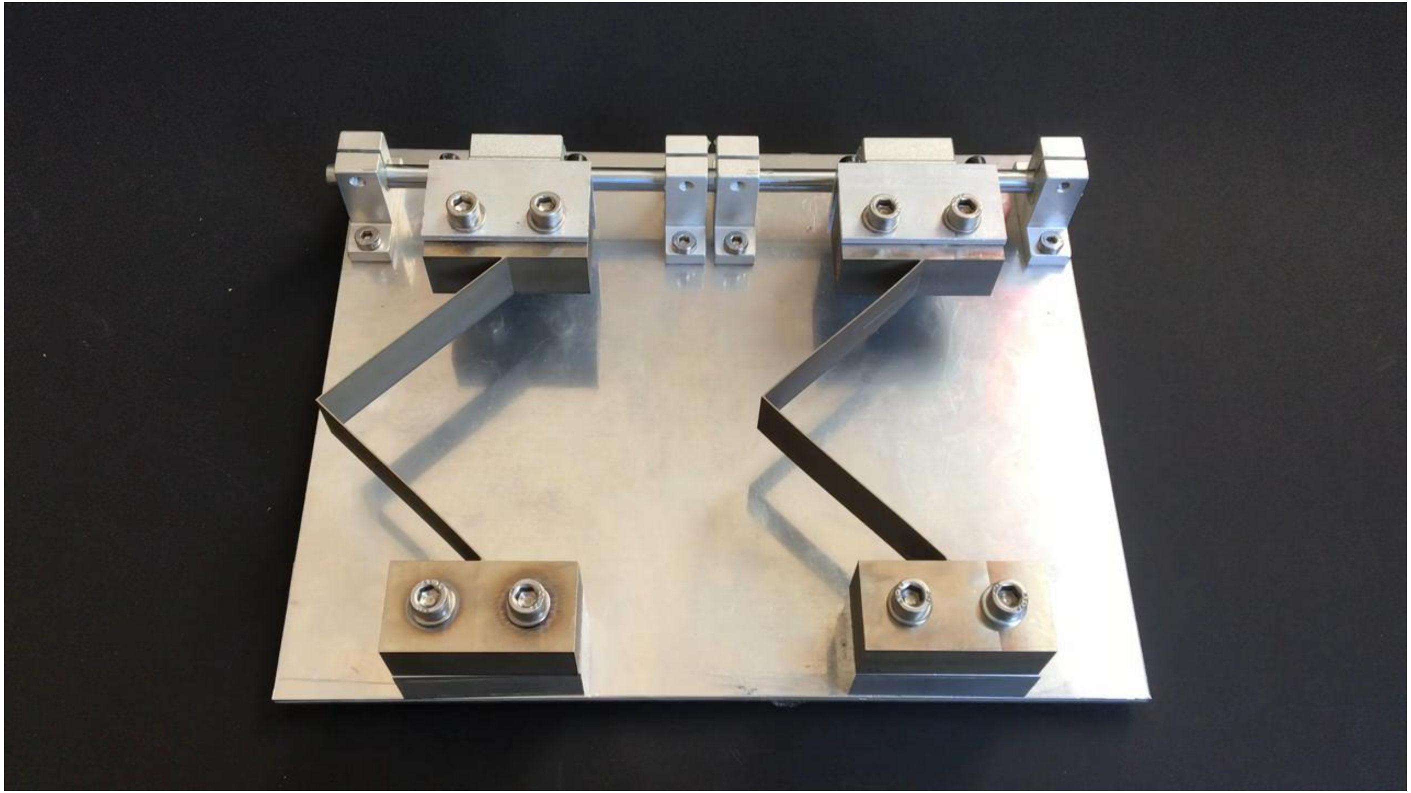


28% reduction in peak stress

TU Delft

Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

Initial stress or curve



Rommers J, Wijk V van der, Aragon A, Herder JL (2024) The STAGE method for simultaneous design of the stress and geometry of flexure mechanisms, Precision Engineering, (DOI: 10.1016/j.precisioneng.2024.05.021)

Static balancing

Increase range of motion:

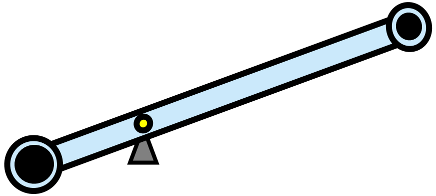
- Series-parallel
- Initial stress or curve

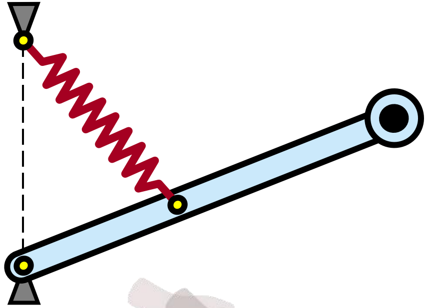
Increase stiffness ratio:

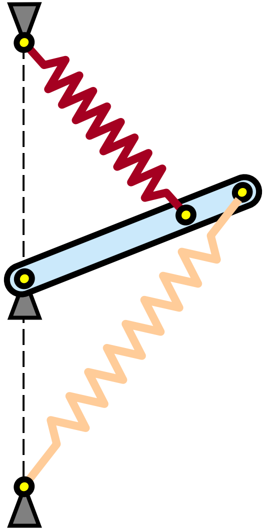
- **Reduce k_f: static balance**
- Increase k_s: reinforcement

Static Balancing

All conservative forces can be cancelled out!

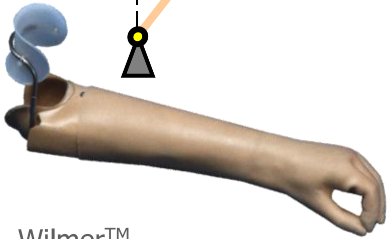






Meager Bridge (Amsterdam)

Anglepoise™

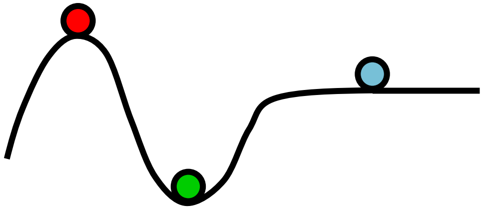


Wilmer™

Static Balancing

All conservative forces can be cancelled out!

- Continuous equilibrium
- Constant potential energy
- Neutral stability

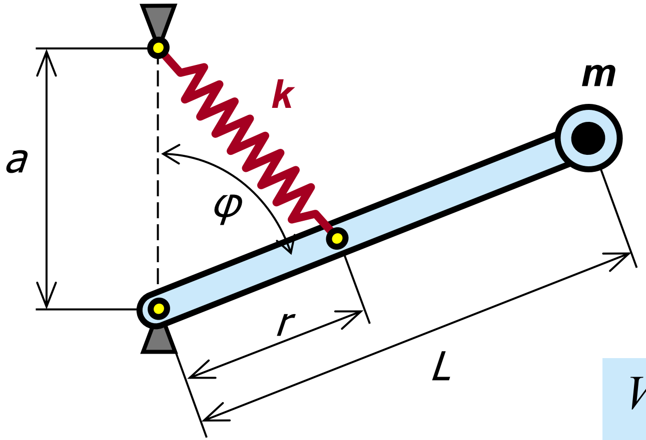


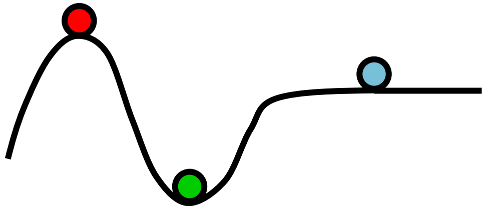
Meager Bridge (Amsterdam)

Anglepoise™

Wilmer™

Constant potential energy





Assuming zero-free-length springs:

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

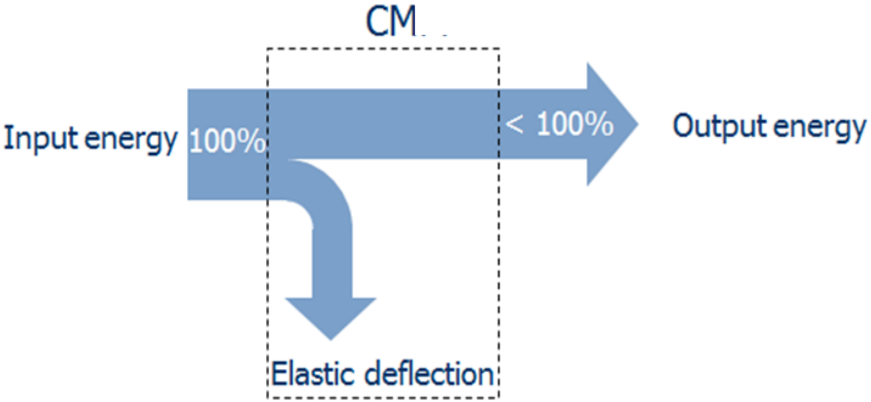
$$V_m = mgL\cos\varphi$$

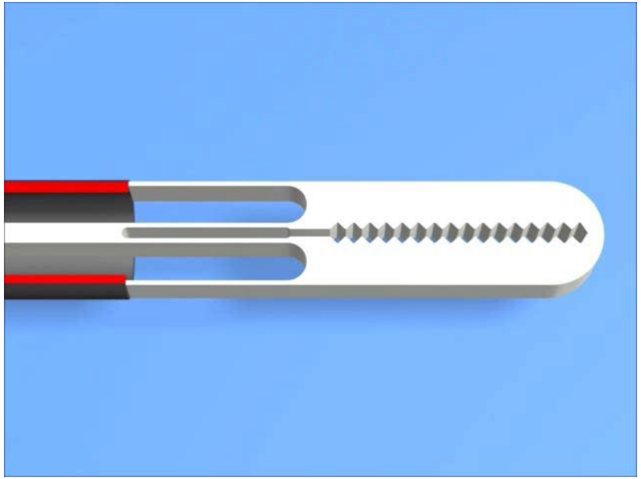
$$V_s = \tfrac{1}{2}k\ell^2 = \tfrac{1}{2}k\left(a^2 + r^2\right) - kar\cos\varphi$$

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

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

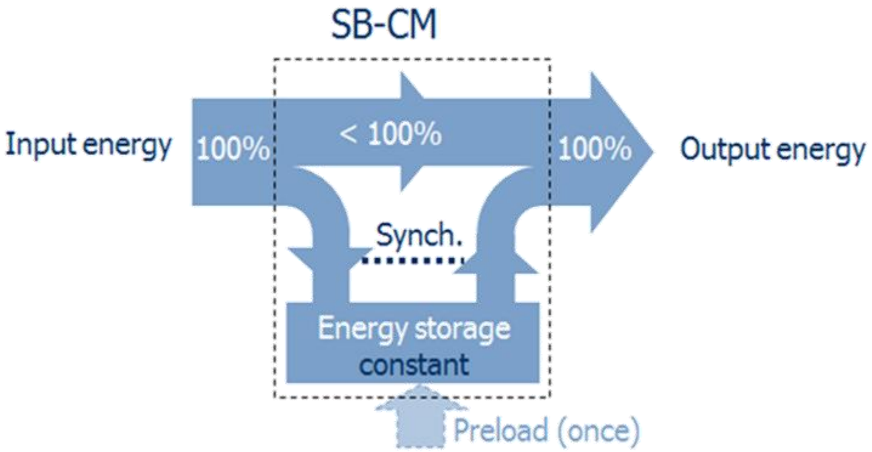
Static balance

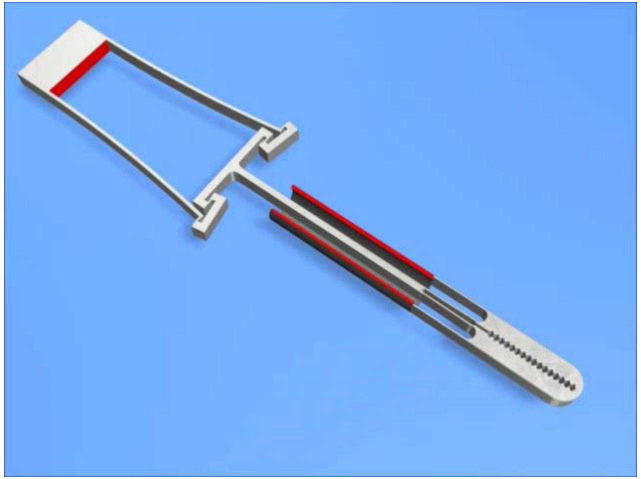




Motion → elastic deformation → energy → motion stiffness

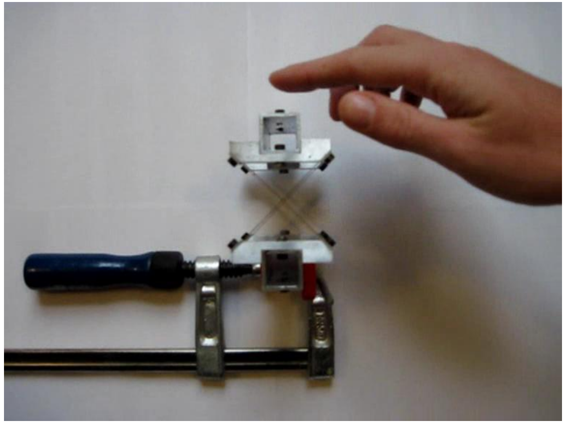
Static balance

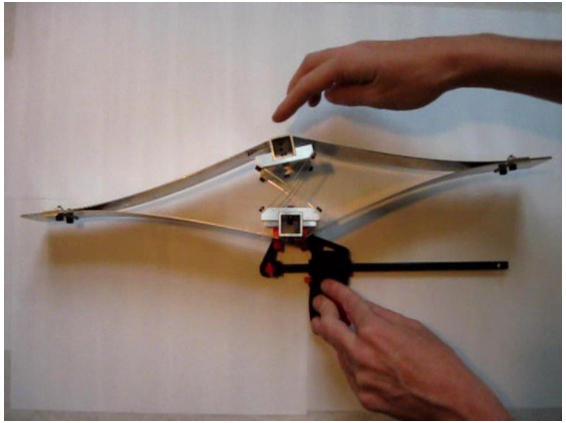


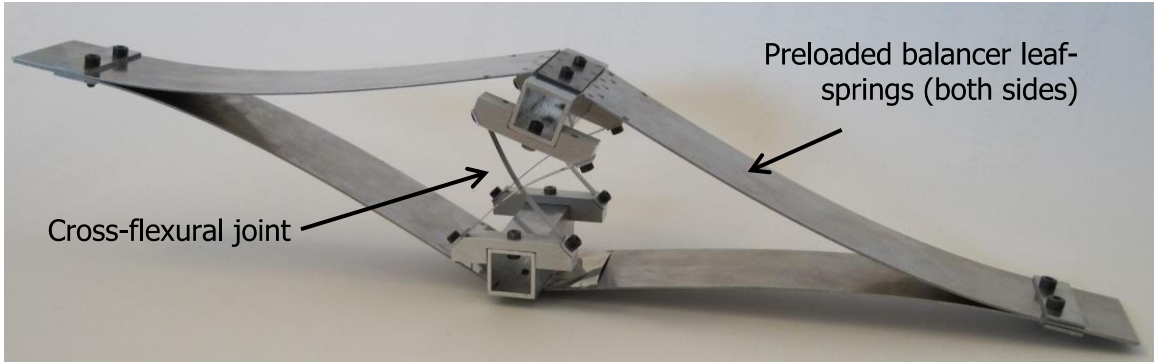


Constant total potential energy → net zero motion stiffness

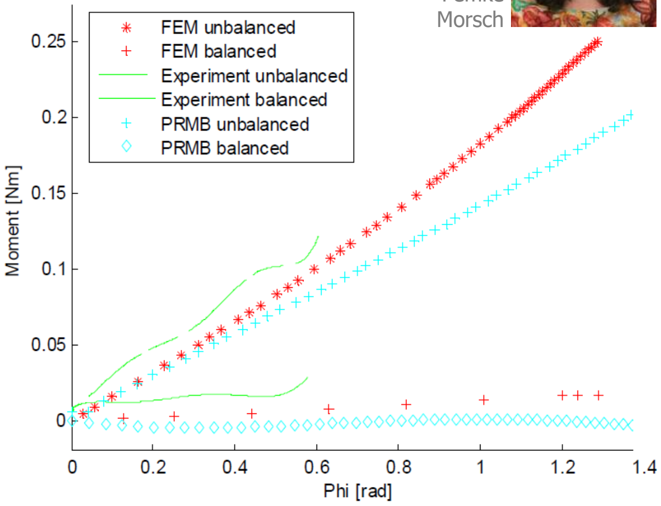
Static balance







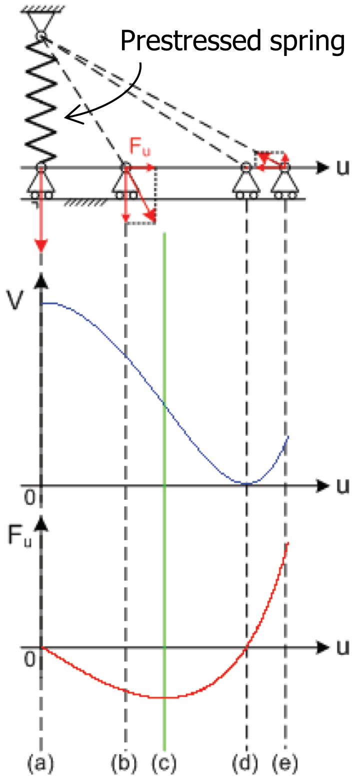
Femke Morsch

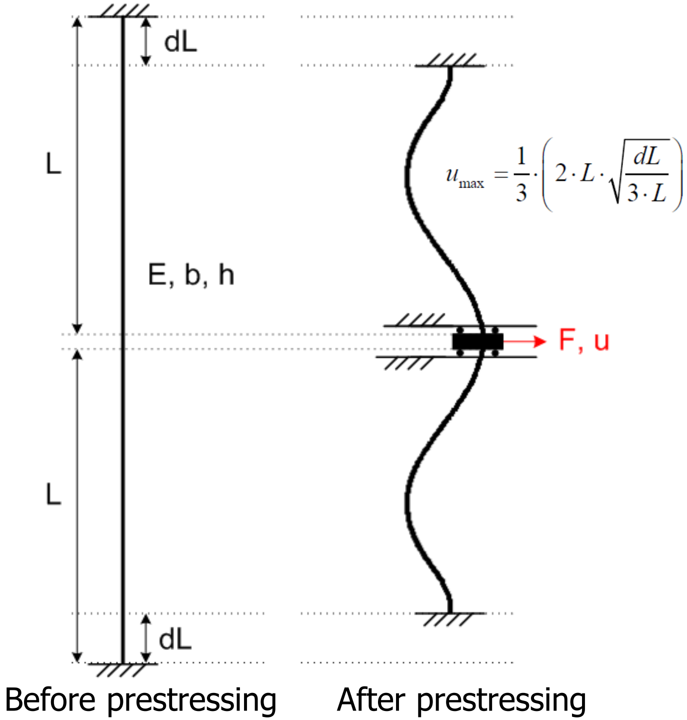


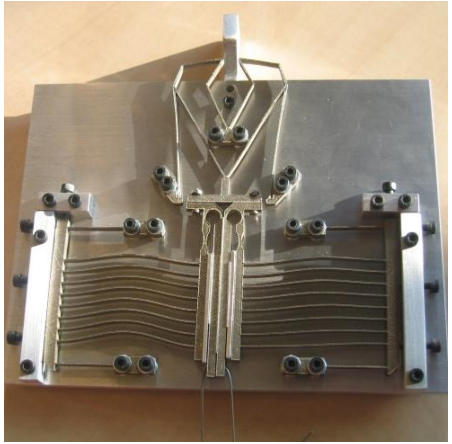
	Average moment reduction, φ = 0-end trajectory [%]	Max moment reduction, φ = 0-end trajectory [%]	End trajectory [rad]
PRBM	95	98	1.42
FEM	93	93	1.28
Experiment	70	63	0.58

Morsch F, Herder JL (2010) Design of a generic zero stiffness compliant joint, 2010 ASME International Design Engineering Technical Conferences, August 15-18, 2010, Montreal, Canada, Paper number DETC2010-28351

Static balance

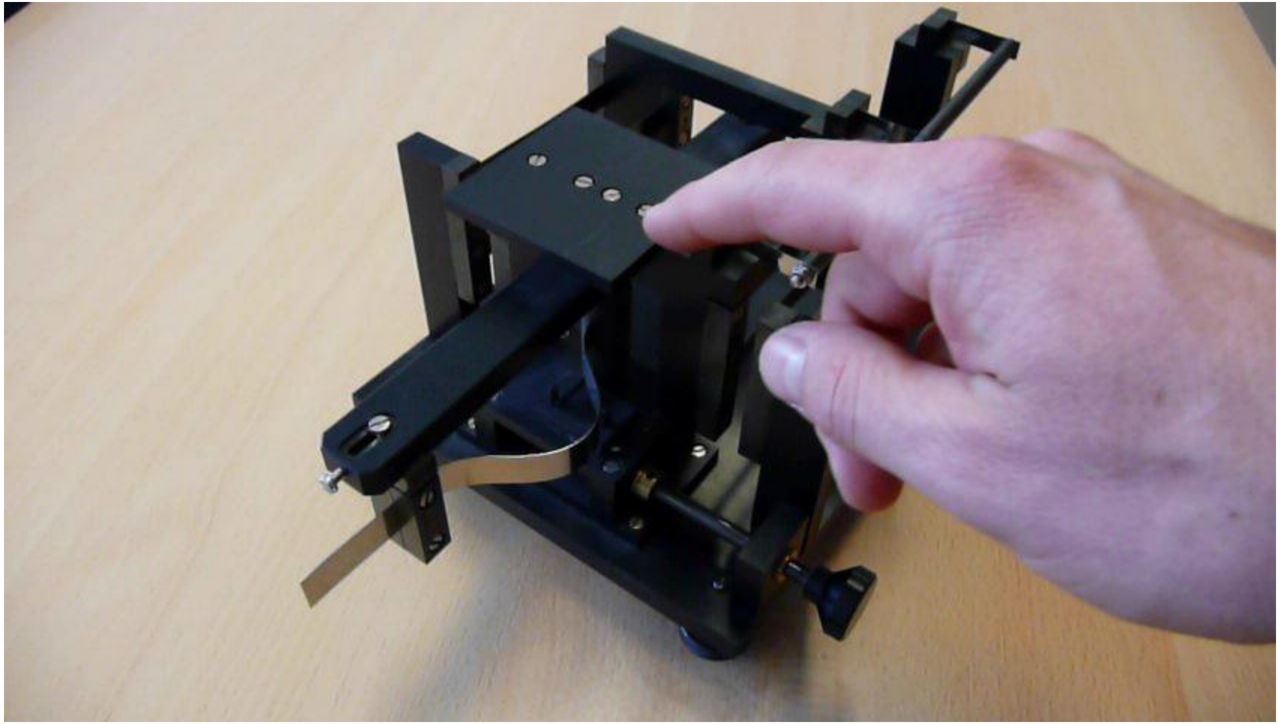






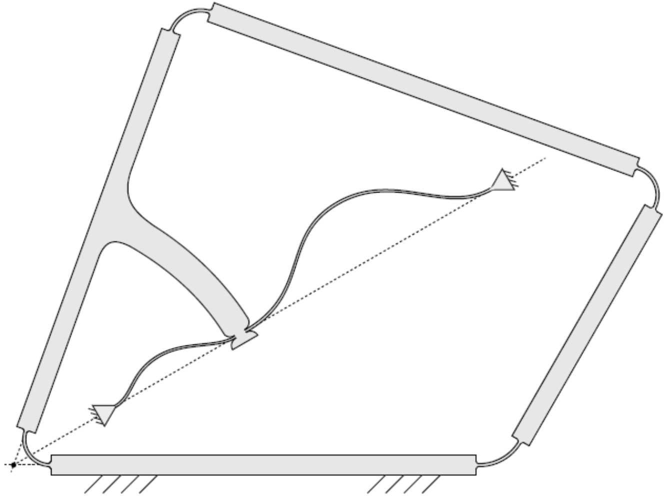
Hoetmer K, Woo G, Kim C, Herder JL (2010) Negative stiffness building blocks for statically balanced compliant mechanisms: design and testing, ASME Journal of Mechanisms and Robotics, 2(4)041007 (DOI: 10.1115/1.4002247, IF 1.04).

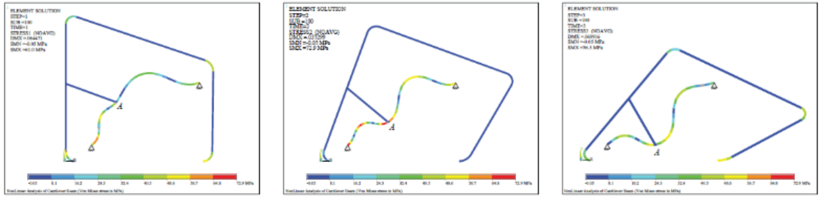
Static Balancing of Compliant Mech.



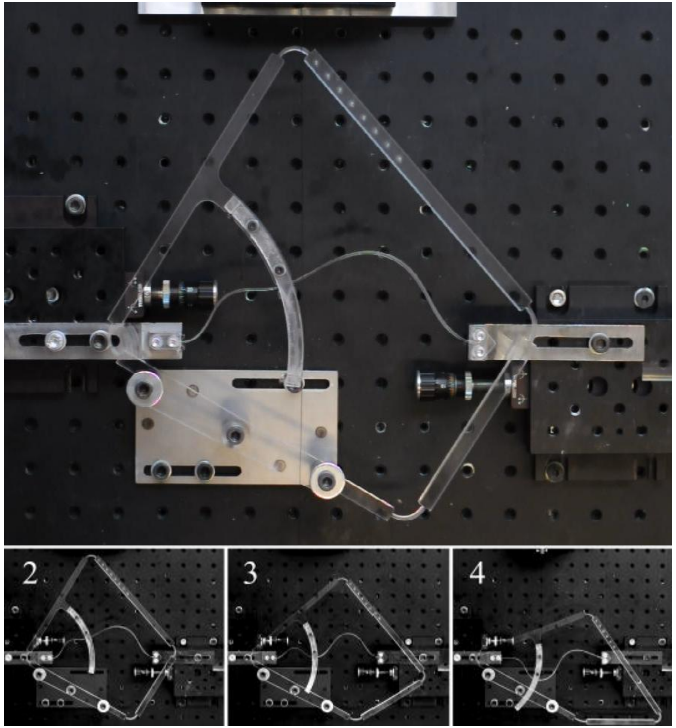
Eijk J van (1985) *On the design of plate-spring mechanisms*, PhD-Thesis, Delft University of Technology, Delft.

Static Balancing of Compliant Mech.



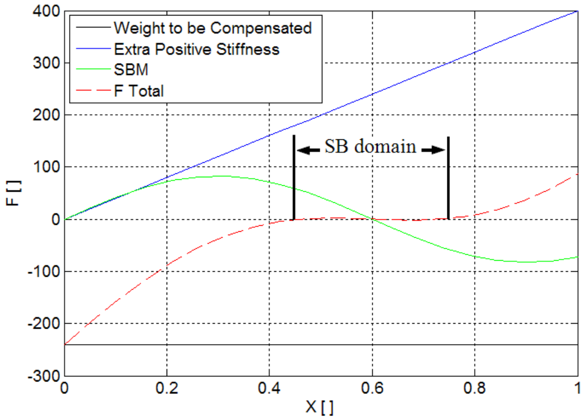


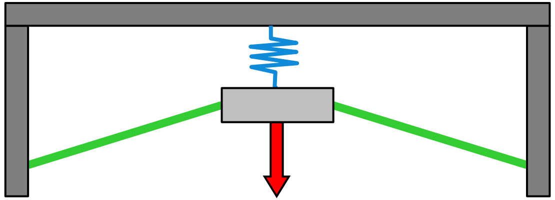
Luc Berntsen
Daan Gosenshuis



Berntsen L, Gosenshuis D, Herder JL (2014) Design of a Compliant Monolithic Internally Statically Balanced Four-Bar Mechanism, *ASME Intl Design Engineering Technical Conferences,* Buffalo NY, Aug 17-20, paper number DETC2014-35054

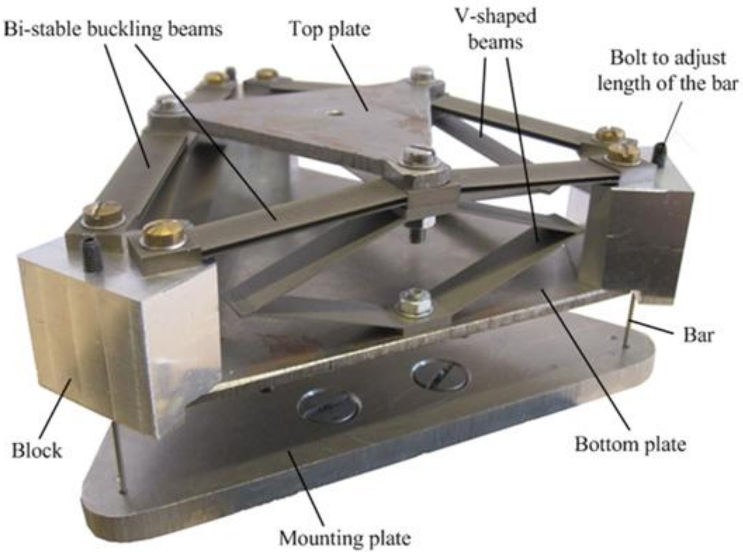
Constant force unit

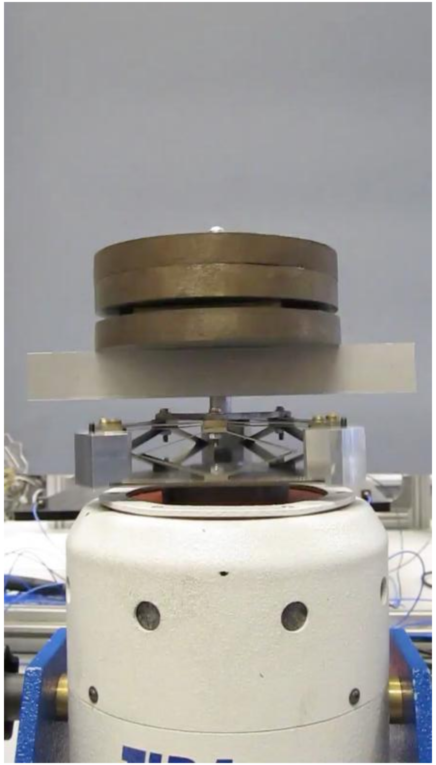




Dunning AG, Tolou N, Herder JL (2013) A Compact Low-Stiffness Six Degrees of Freedom Compliant Precision Stage, *Precision Engineering* 37(2)380-388

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

Advantages of static balancing

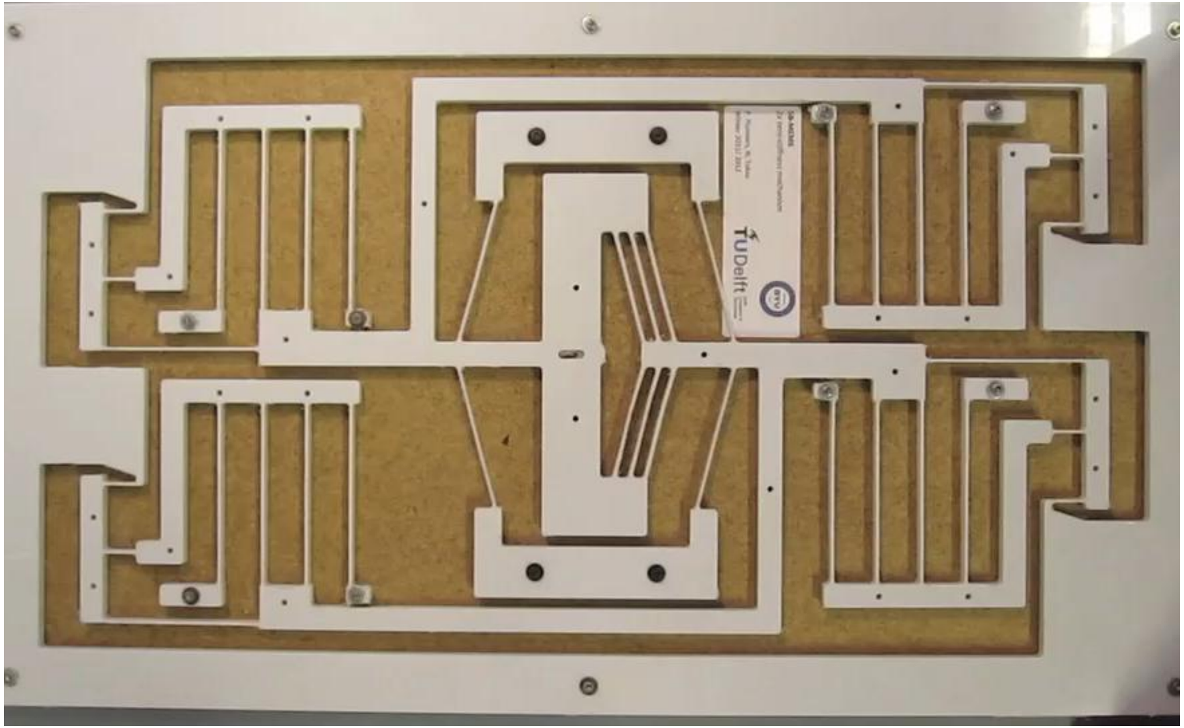
- Reduced operating effort
  - Less energy consumption
  - Less heat generation
  - Increased safety
- Pure force transmission (signal)
- System efficiency, e.g. elastic transmission in actuators
- Eliminate backlash by preloading
- Vibration isolation
- Extreme anisotropy, approximate conventional joints
- …

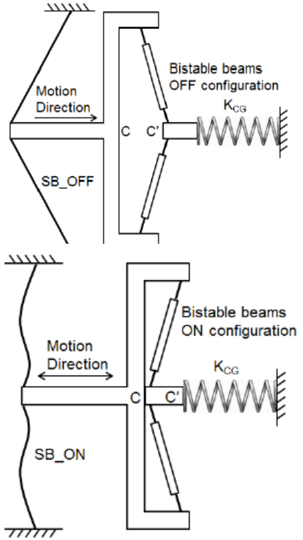

Davood Farhadi

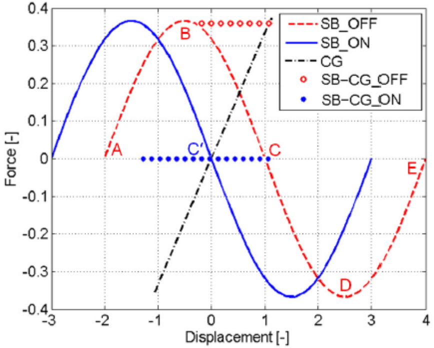

Cedrat


Davood Farhadi

Switchable static balance







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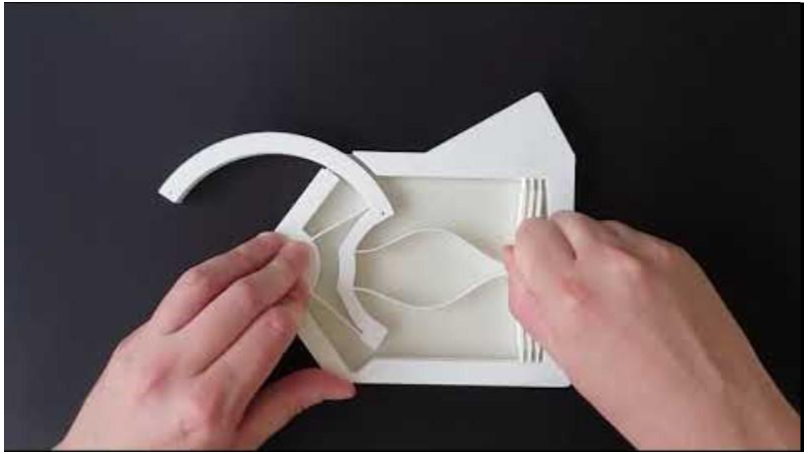
Switchable static balance

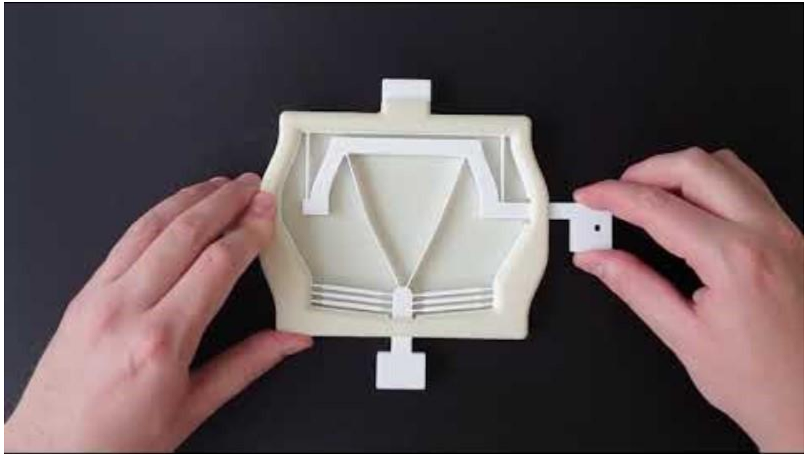
Reinier Kuppens

Switchable revolute unit cell



https://www.youtube.com/watch?v=T5wnomW_CJE 1.9M views

Switchable prismatic unit cell



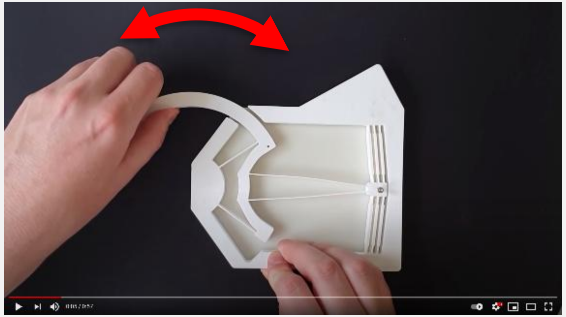
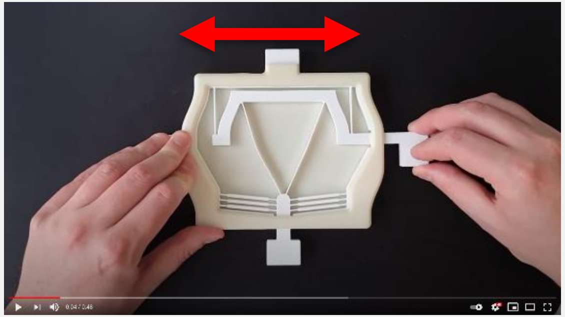
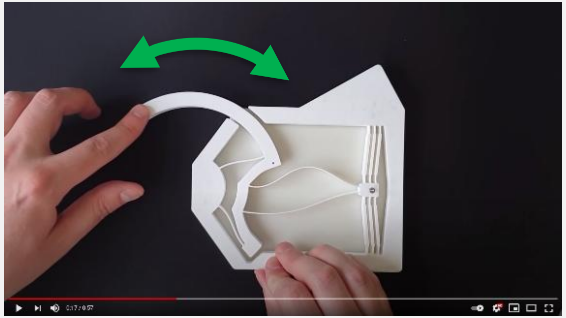
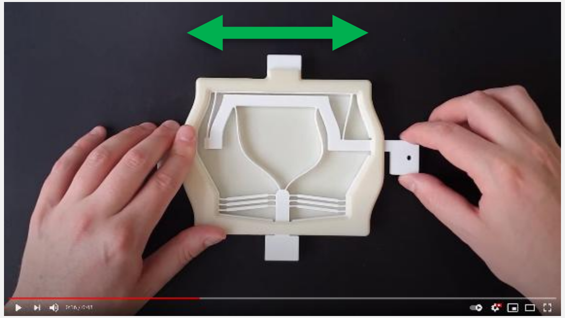
https://www.youtube.com/watch?v=X2tRcEME14w

Soft mode is more than three orders of magnitude more compliant than stiff mode

TU Delft

Kuppens et al. 2020, Extreme Mechanics Letters, DOI:10.1016/j.eml.2020.101120

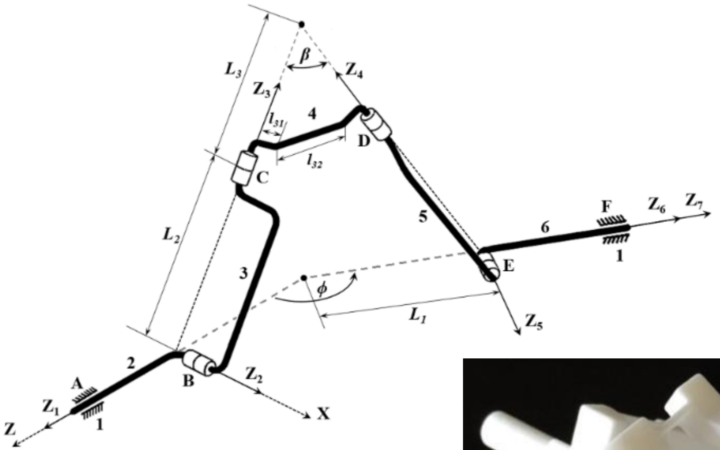
Switchable static balance

	Revolute unit cell	Prismatic unit cell
Stiff mode (locked, “off”)		
Soft mode (free, “on”) Three orders of magnitude more compliant		

Kuppens et al. 2020, Extreme Mechanics Letters, DOI:10.1016/j.eml.2020.101120

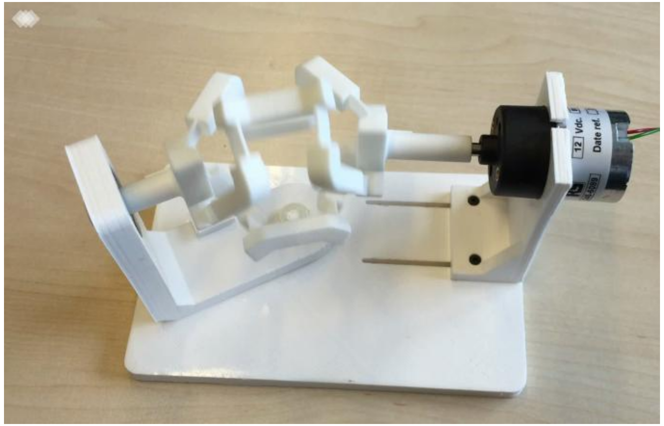
Spatial arrangements

Davood Farhadi



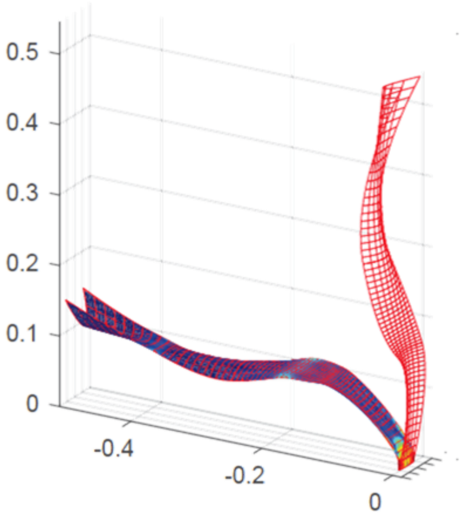
Bennett 6R hybrid linkage

Fully compliant constant velocity coupling



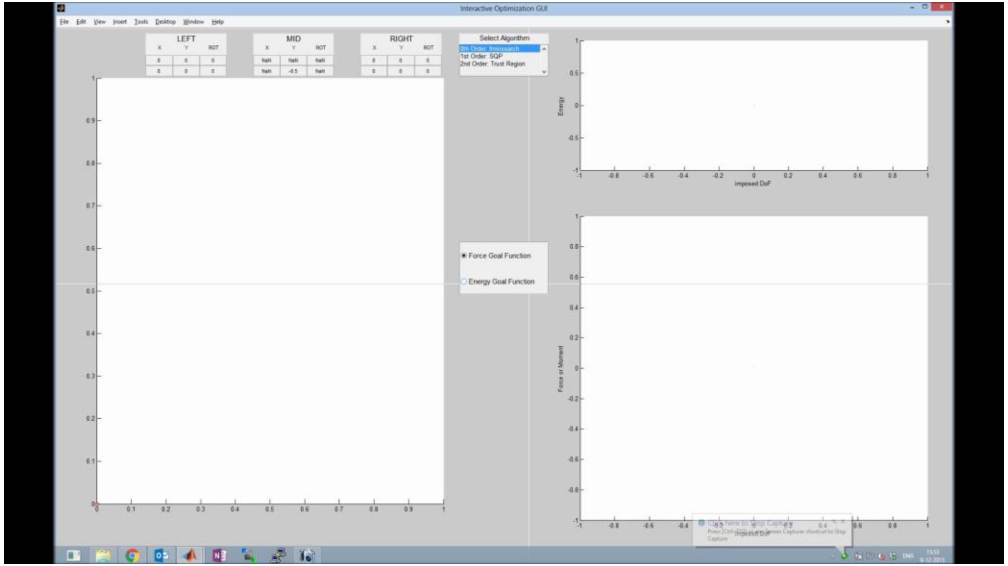
Farhadi D, Tolou N, Herder JL (2018) A fully compliant homokinetic coupling, *J. Mech. Des.* 140(1): 012301

Shell mechanisms



Spatial compliant mechanisms
Tailored stiffness
Analysis and synthesis

Giuseppe Radaelli



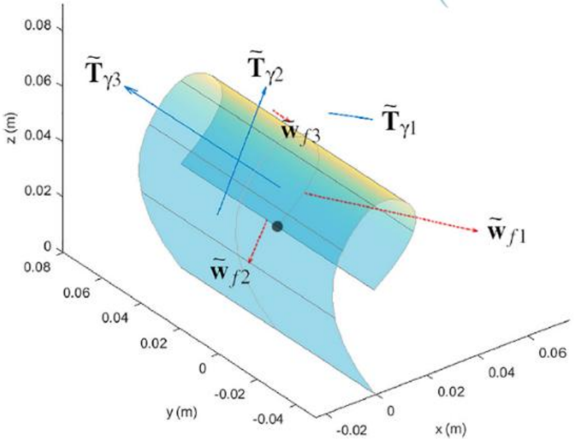
Radaelli G, Herder JL, Mechanism and Machine Theory (102)55-67
Radaelli G, Herder JL, ASME IDETC2014-35373, Best Paper Award

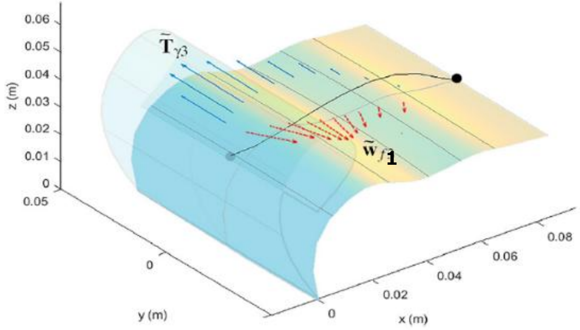
Eigendecomposition

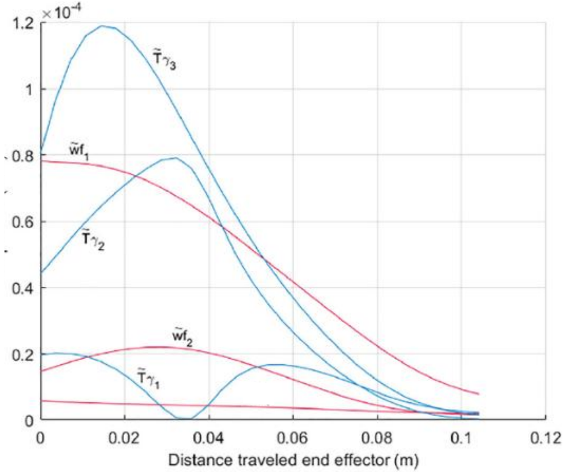
Joost Leemans

Werner van de Sande

$$\tilde{a}_{f_i} = \frac{\delta_{eq_i}}{F_{eq_i}} = \left(h_i^2 + |r_i|^2\right)\frac{\theta_i}{M_i}$$







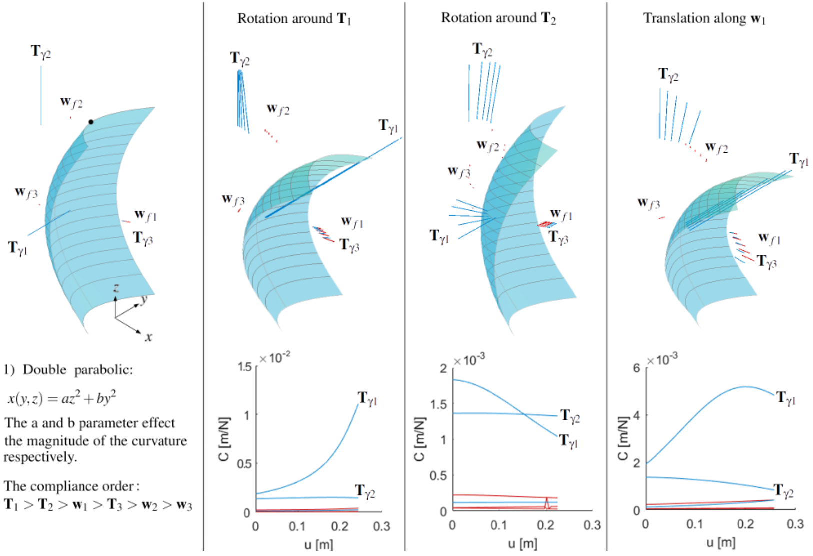
Leemans JR, Kim CJ, Sande WWPJ van de, Herder JL (2019) Unified Stiffness Characterization of Non-Linear Compliant Shell Mechanisms, *J Mechanisms Robotics* 11(1)011011 (DOI: 10.1115/1.4041785)

Shell building blocks

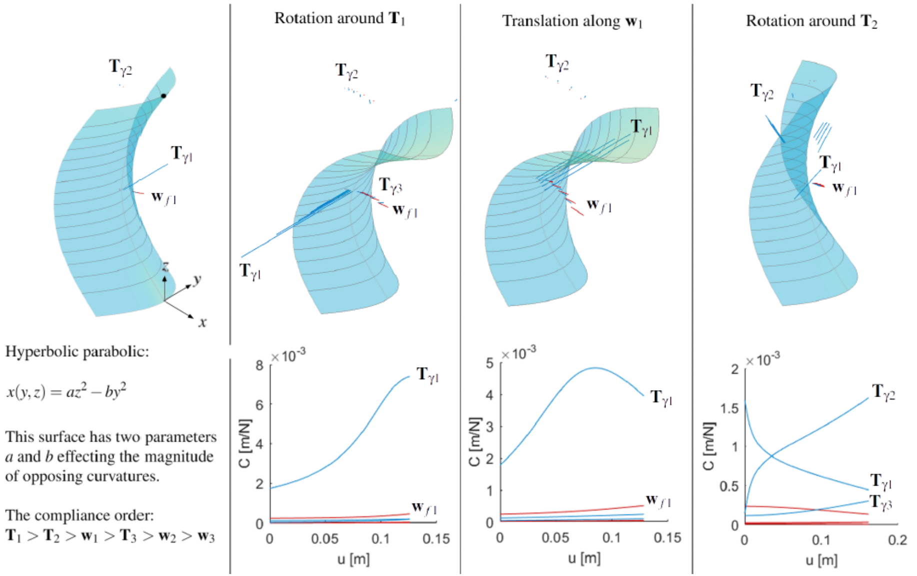
Joost Leemans

Werner van de Sande

Double parabolic



Hyperbolic parabolic



Leemans JR, Kim CJ, Sande WWPJ van de, Herder JL (2019) Unified Stiffness Characterization of Non-Linear Compliant Shell Mechanisms, *J Mechanisms Robotics* 11(1)011011 (DOI: 10.1115/1.4041785)

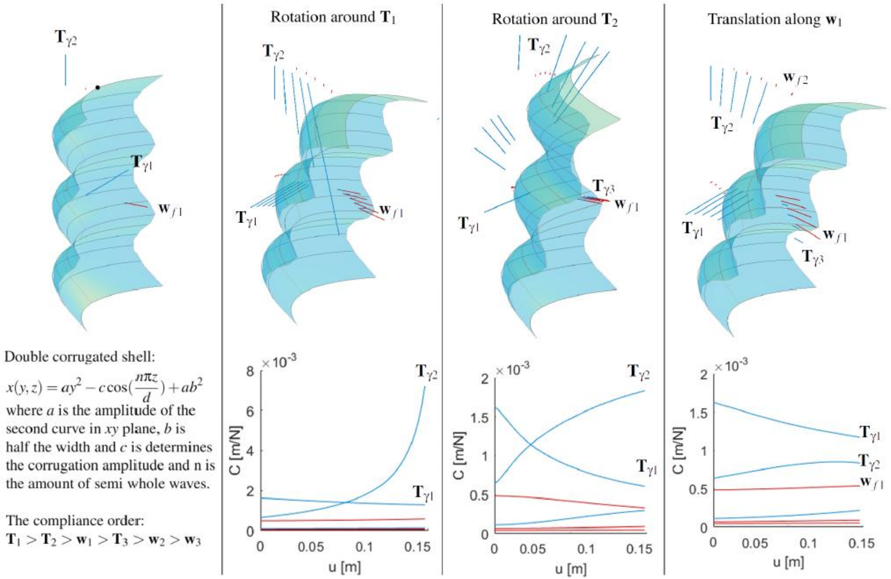
Shell building blocks

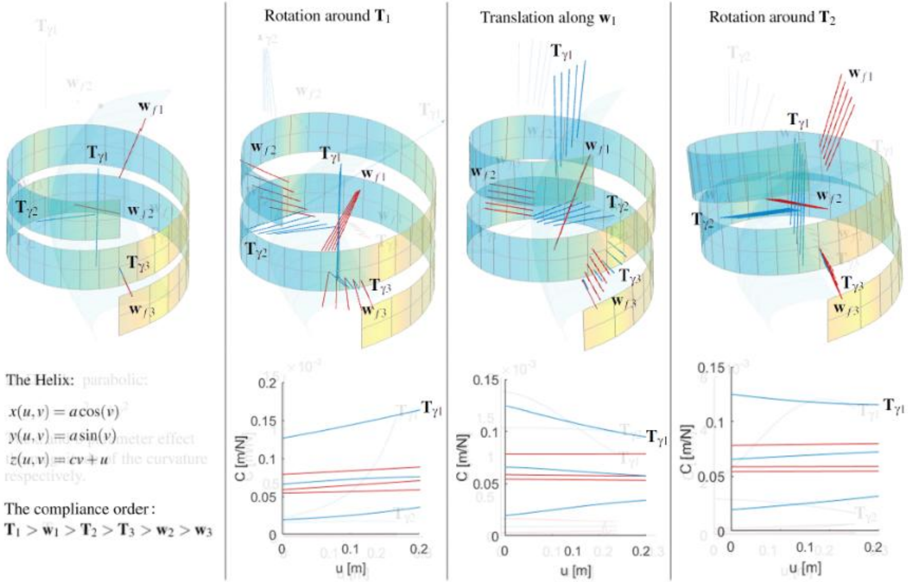
Joost Leemans

Werner van de Sande

Double corrugated

Helix





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Folkersma KGP, Boer SE, Brouwer DM, Herder JL, Soemers H (2012) A 2-DOF large stroke flexure based positioning mechanism, *ASME 2011 International Design Engineering Technical Conferences*, Aug 12-15, Chicago, DETC2012-70377, Compliant Mechanisms Award.

New book and website

THEME – INITIATIVE BY DUTCH UNIVERSITIES AND DSPE IN COLLABORATION WITH INDUSTRY

UPDATING DDP

An initiative to produce updated design principles for precision mechatronics has been developed by Dutch universities of technology in association with DSPE, in close collaboration with the Dutch high-tech industry. Building on the legacy of Wim van der Hoek, the Dutch doyen of design principles, the aim of the initiative is to collect over 100 cases that demonstrate the proper application of contemporary design principles. The cases will be presented on a dedicated website and collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

Initiators

The initiative to update the design principles for precision mechatronics came from the professors of precision engineering and mechatronics at the three Dutch universities of technologies – Delft, Eindhoven and Twente – in association with DSPE.

From left to right:
Dannis Brouwer is professor of Precision Engineering at the University of Twente, Enschede (NL).
Just Herder is professor of Interactive Mechanisms and Mechatronics at Delft University of Technology, Delft (NL).
Pieter Kappelhof is vice president of DSPE, director of Technology at Hittech Group, located in Den Haag (NL), and hybrid teacher of Opto-mechatronics at Eindhoven University of Technology (TU/e), Eindhoven (NL).
Hans Vermeulen is part-time professor of Mechatronic System Design at TU/e and senior principal architect EUV Optics System at ASML, located in Veldhoven (NL).

PIETER.KAPPELHOF@DSPE.NL / J.P.M.B.VERMEULEN@TUE.NL

Dannis Brouwer U Twente
Just Herder TU Delft
Pieter Kappelhof DSPE, Hittech
Hans Vermeulen TU/e, ASML

DPPM Cases

Design Principles for Precision Mechatronics. A collection of applications categorized in themes known from construction principles.

How to design mechanical hardware as part of a modern precision mechatronic system.

The precision mechatronics community has a long history of continuous updates on DDP (*"Des Duivels Prentenboek"*) content by Wim van der Hoek and his 'heritage keepers'. It is considered relevant to prolong this process with new examples from the field of precision mechatronics, incl. opto-mechanics, electro-mechanics and material science.

In the coming year(s), we write a book and a website containing examples of precision mechatronics elements. DSPE members can contribute by writing clear examples to be freely used. Company and designer can be mentioned. Examples should no be complete systems.

Overview of the design principles for accuracy and repeatability, as of ~1970, and their evolution, as of ~2000 (in green) and ~2010 (in red).

Design principle	Implementation
Kinematic design	▶ Exact constraints ▶ Mechanical decoupling via flexures and elastic hinges
Design for stiffness	▶ Structural loops with high static stiffness and favourable dynamic stiffness
Lightweight design	▶ Design for low mass and high eigenfrequencies
Design for damping	▶ Energy dissipation that slows down motion without introducing position uncertainty
Design for symmetry	▶ Symmetry in geometry and external loads ▶ Over-actuation
Design for low friction and hysteresis	▶ Minimisation of friction and virtual play in high-precision structures, connections and guideways
Design for low sensitivity	▶ Thermal centre and thermal (compensation) loops with high stability ▶ Low-expansion materials ▶ Isolation of disturbances, e.g. via isolated metrology loop ▶ Offset minimisation, e.g. Abbe principle and Bryan principle, and drive-offset minimisation relative to the centre of mass ▶ High-bandwidth feedback control
Design for stability	▶ Minimisation of heat dissipation and microslip in interfaces ▶ Minimisation of material creep and drift
Design for load compensation	▶ Weight compensation, reaction force compensation and (parasitic) stiffness compensation ▶ Position-dependency compensation
Design for minimal complexity	▶ Balancing and hence minimisation of complexity and related cost via a multidisciplinary system approach

Design principles

Conclusion

Improve behavior

- Initial stress or curve
- Reduce k_f: static balance
- Increase k_c: reinforcement

Future trends

- Combination of above techniques
- Methods for 3D compliant mechanisms
- Mechanical metamaterials
- Topology opt. (large defl., stat. balance)
- High loads & large deflection
- Alternative manufacturing, e.g. origami