ME 254, Lecture 1

Compliant mechanisms —an overview

G. K. Ananthasuresh

suresh@iisc.ac.in

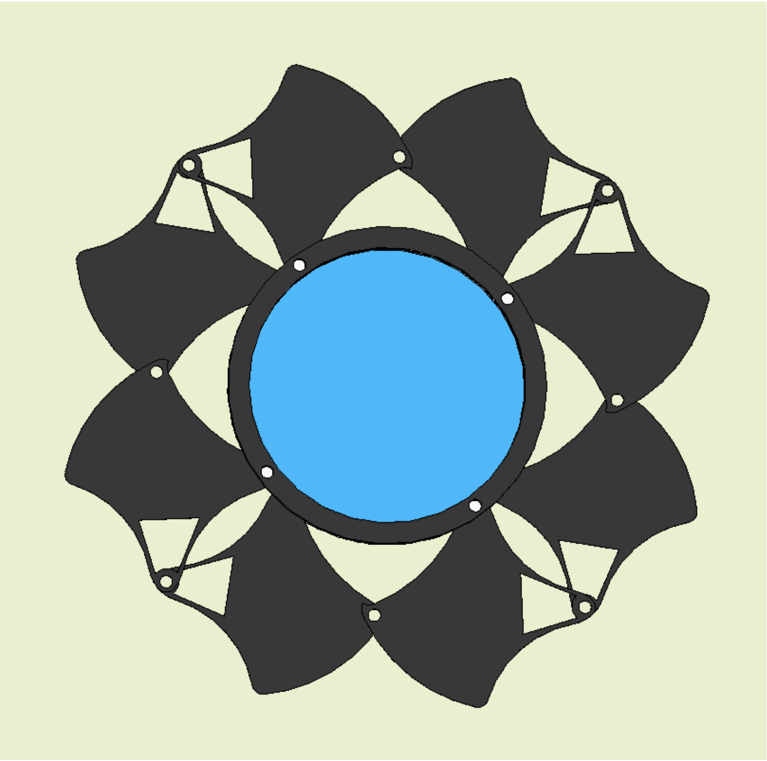

Compliant Mechanisms
macro . meso . micro . nano
DaCM

Overview

Compliant Mechanisms

Motion without Hinges and Sliders

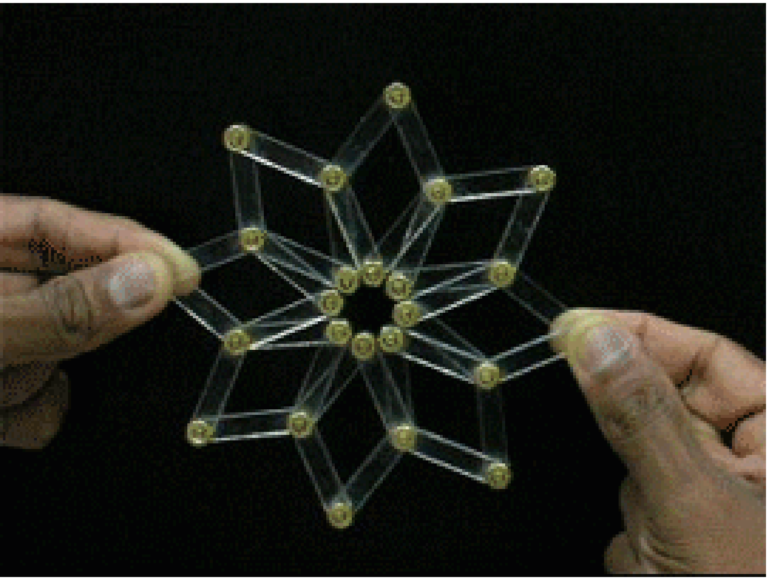
G.K. Ananthasuresh
and
All the current and past members of the
M2D2 Laboratory
Mechanical Engineering
Indian Institute of Science
Bangalore



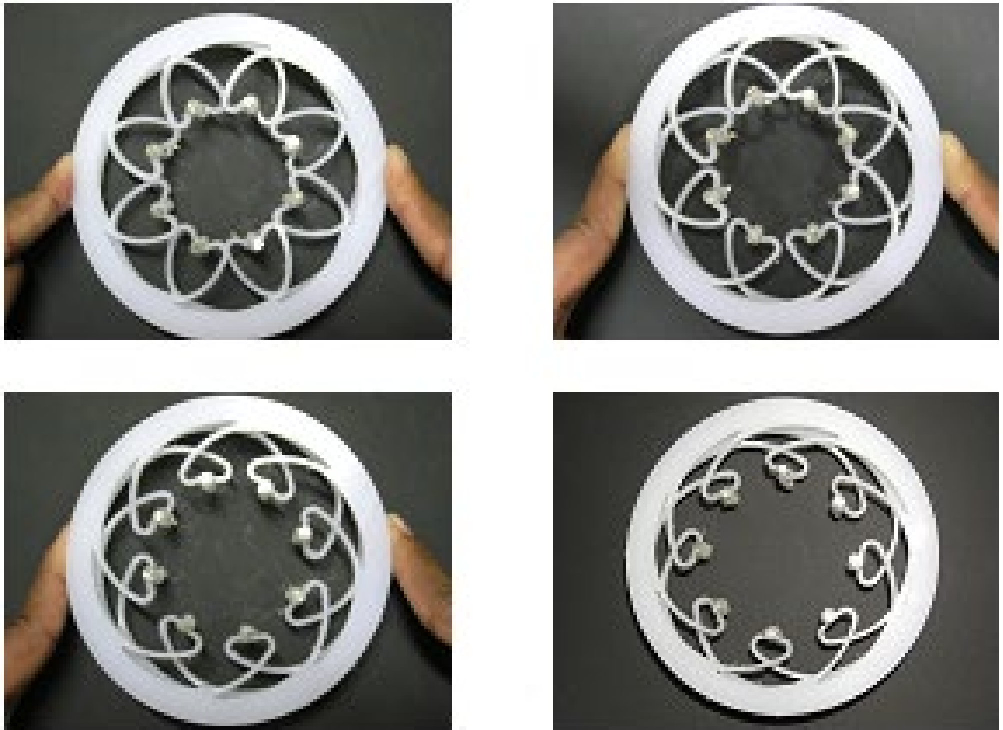
Equivalent compliant mechanism

Int. J. Solids and Structures
44(2007), pp. 6279-6298
With Jiten Patel

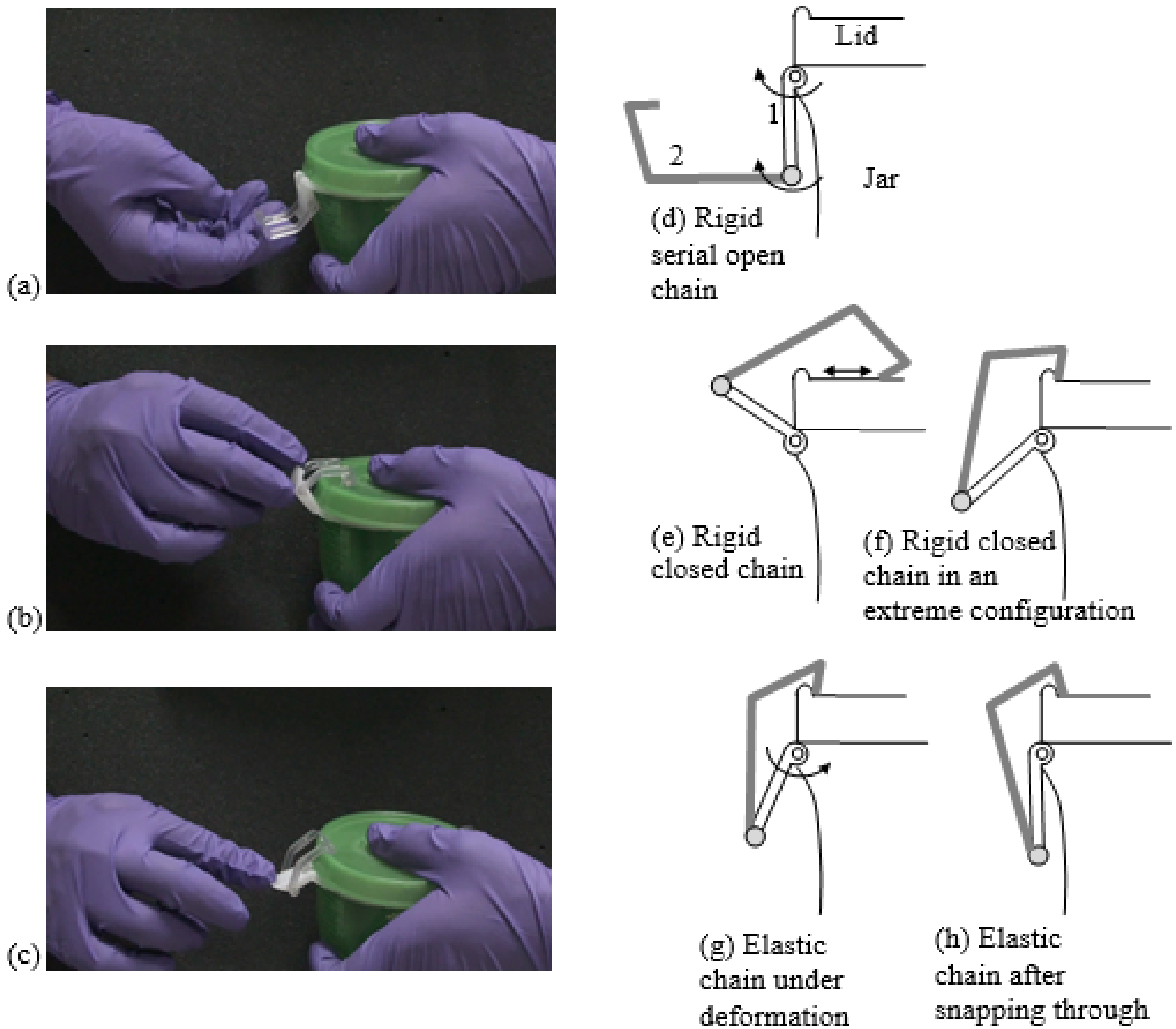
Rigid-body mechanisms



Compliant mechanisms



Smooth transition of mobility

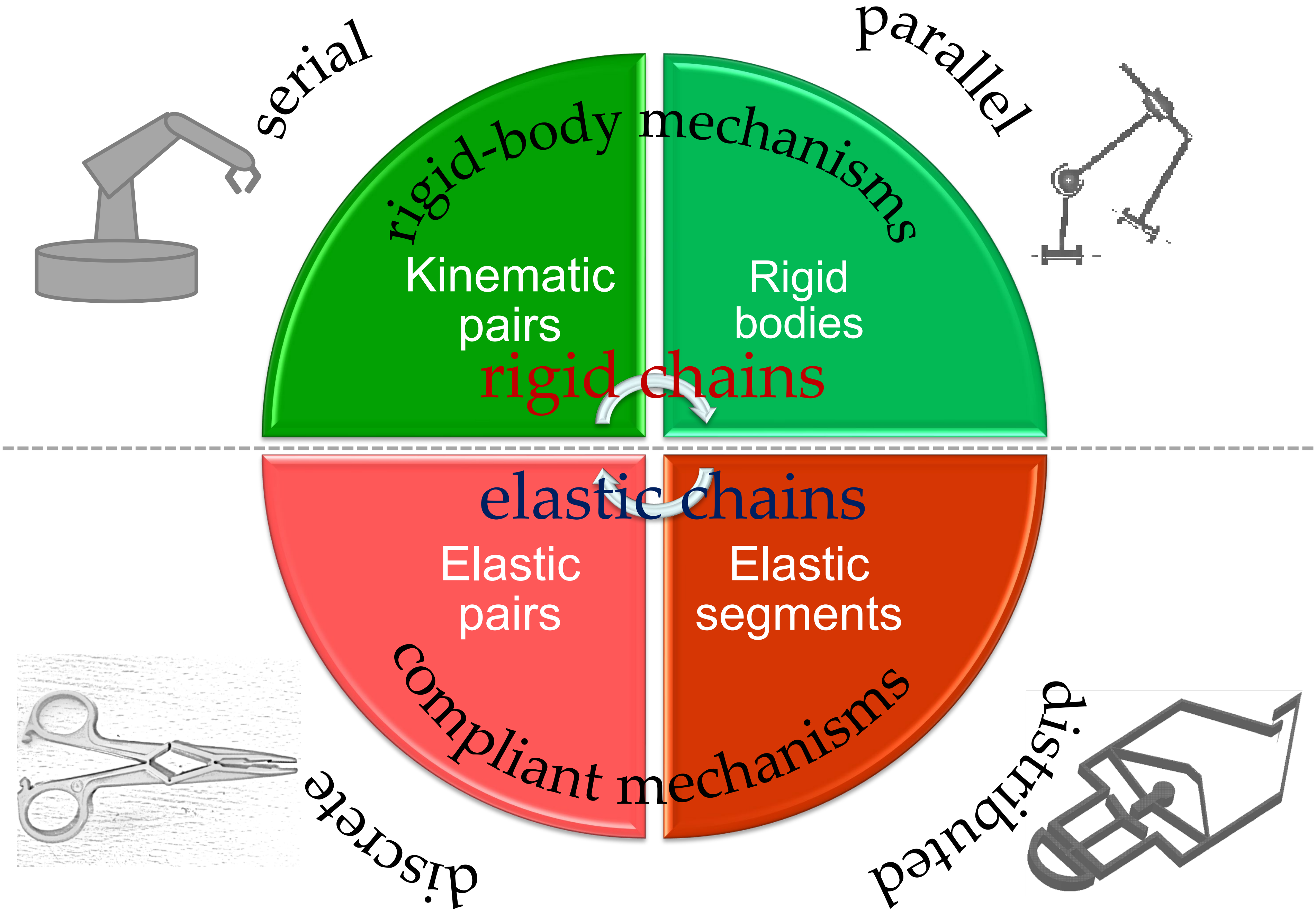


Rigid serial chain

Rigid closed chain

Elastic chain

BRU coffee-jar lid



Ananthasuresh, IISc

Kinematic pairs

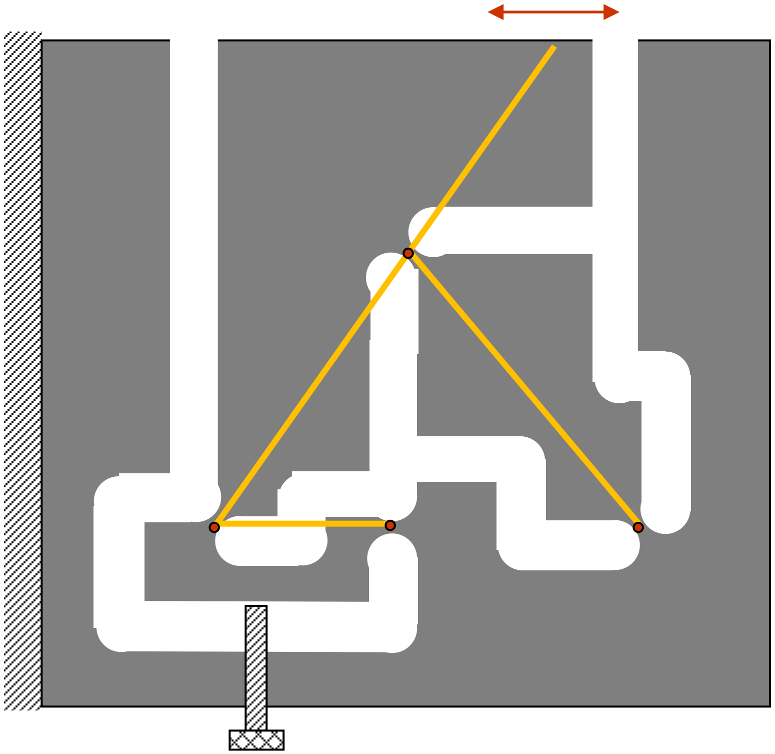
- Lower pairs with surface contact
  - Revolute (hinge-1 DoF)
    - Surface of revolution
  - Prismatic (slider-1 DoF)
    - Prismatic surface
  - Helical (screw-1 DoF)
  - Cylindrical (2 DoF)
  - Toroidal (2 DoF)
  - Spherical (ball-socket-3 DoF)
  - Planar (3 DoF)
- And there are many, many **higher pairs** with line or point contact

Specific shapes for contact surfaces

Prefer hinges to sliders;
flexures to either.

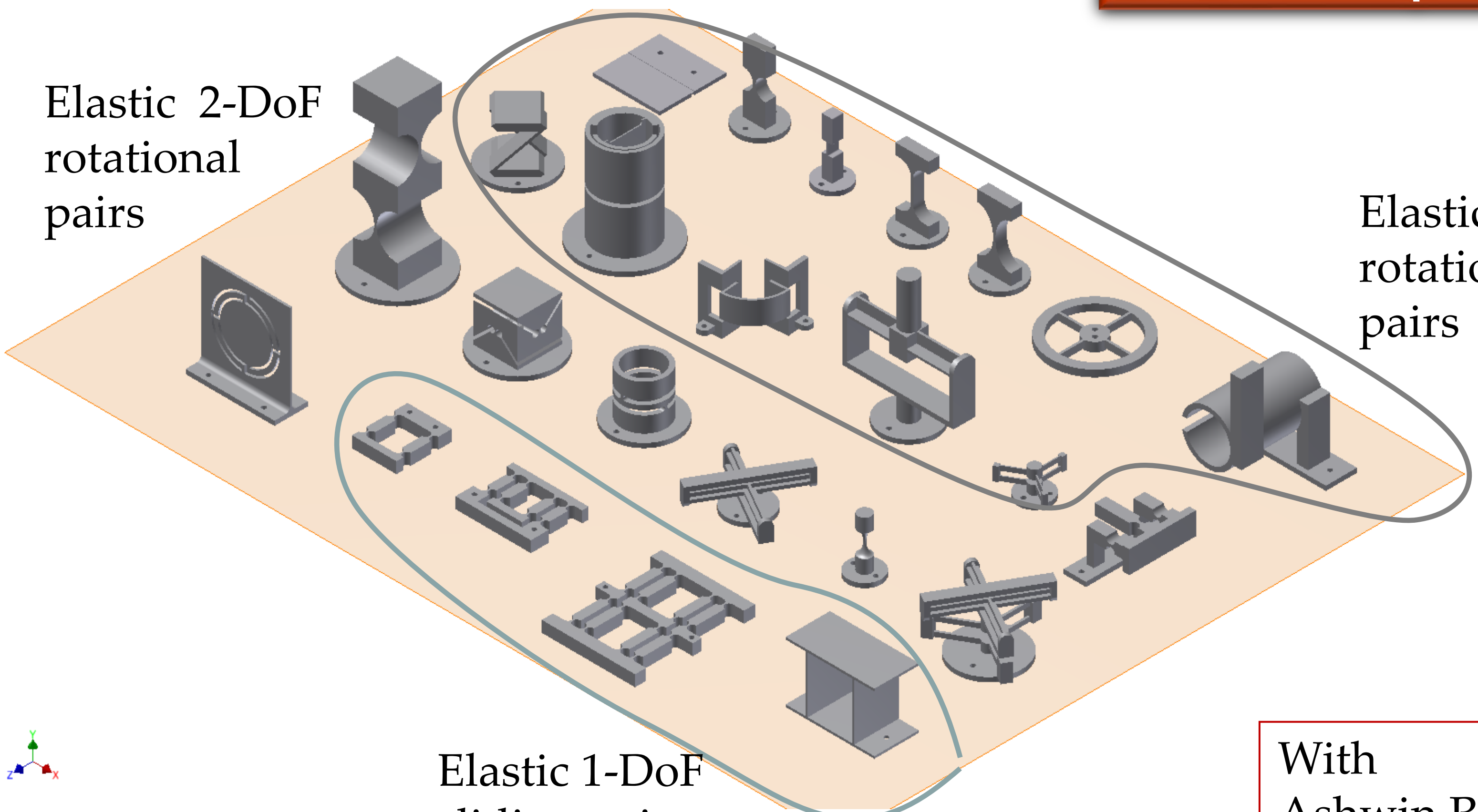
A design principle espoused by M. J. French.

Discrete compliance

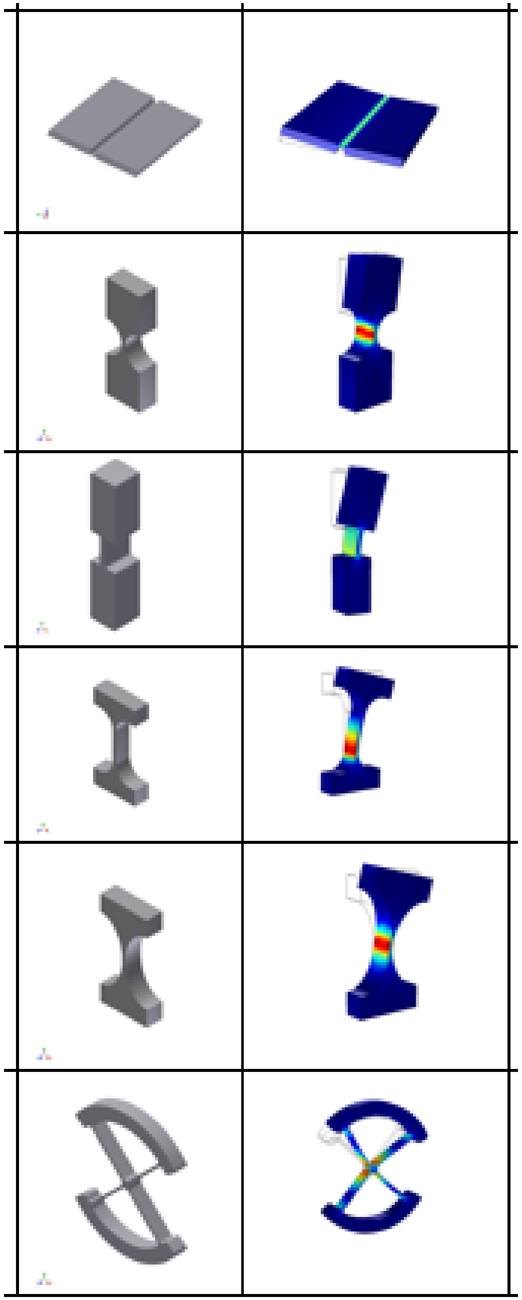


Elastic pairs

No specific shape



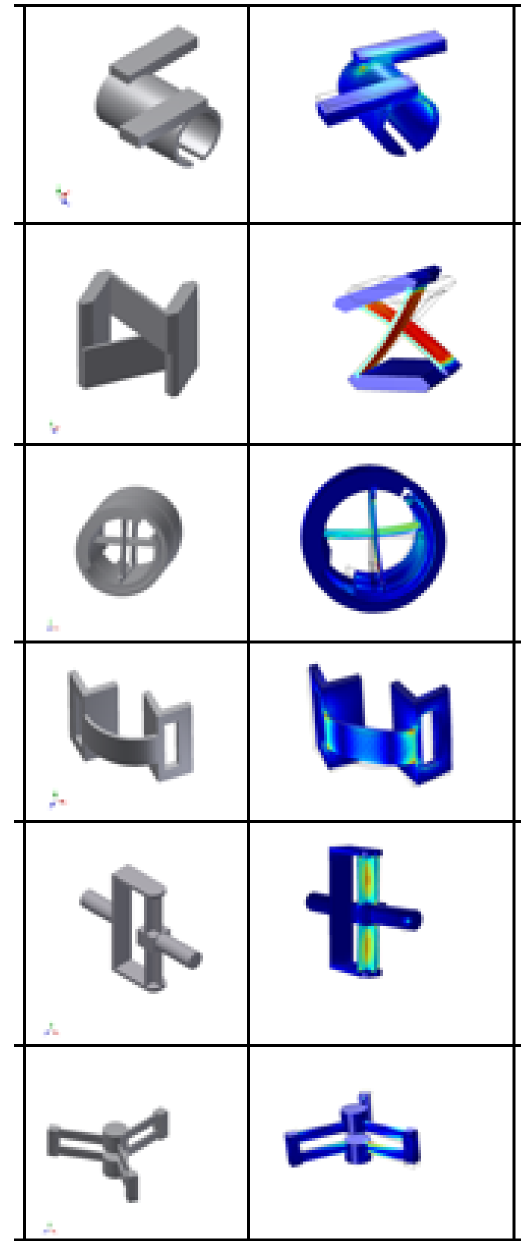
With
Ashwin Rao
Santosh Bhargav



1-DoF rotational elastic pairs

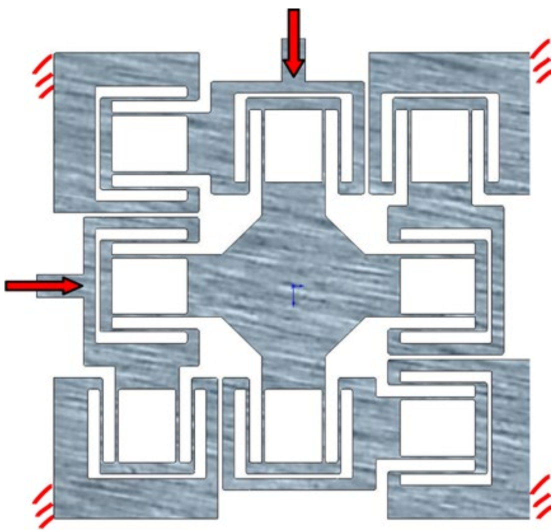
More than a dozen shapes for 1-DoF elastic rotational pairs!

Bendix elastic rotational pair

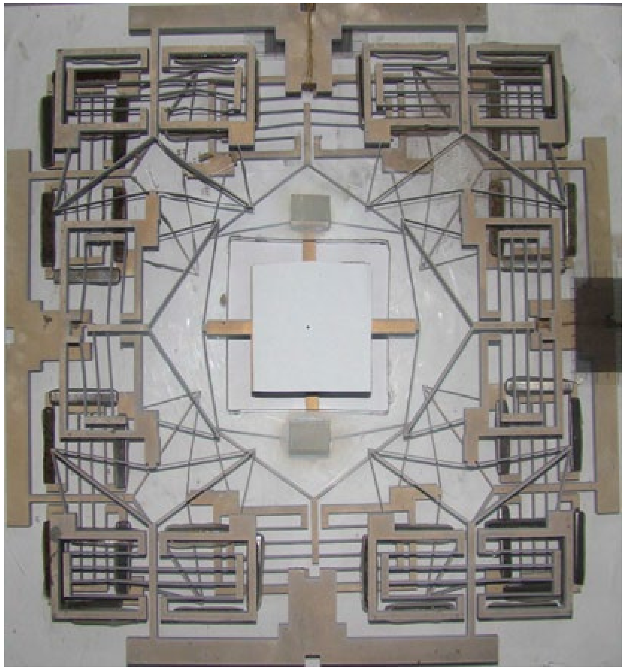


Shapes of elastic pairs can be quite complicated.

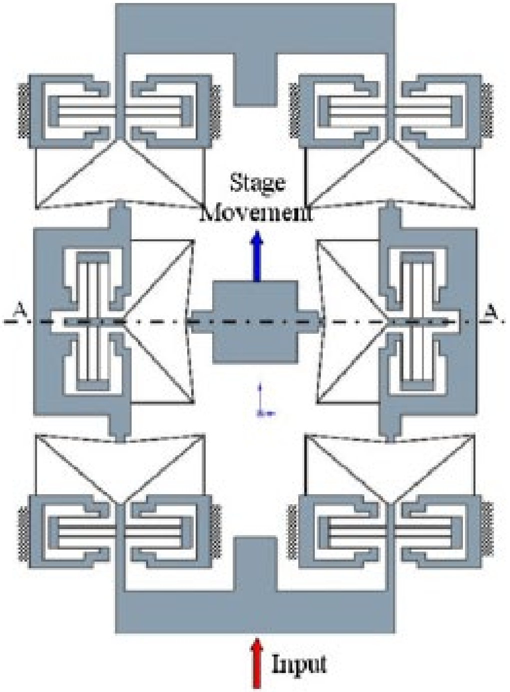
You can even call them compliant mechanisms in their own right!



Awtar, 2003



With Dinesh Mana



Distinguishing the pairs quantitatively

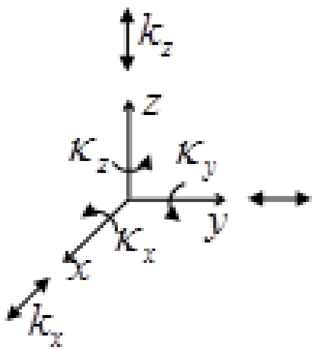
Kinematic

- Ideally…
  - Zero stiffness along or about the intended axis.
  - Infinite stiffness along or about all other five axes.
  - Almost no cross-axis errors.
- Friction and backlash cause deviation from the ideal condition.

Elastic

- Ideally and realistically…
  - Finite but low stiffness along or about the intended axis.
  - Finitely large stiffness along or about all other five axes.
  - Finite cross-axis errors
- Friction and backlash are absent.
- Viscoelastic behavior may cause deviations.
- Axis may drift.

Multi-axis stiffness of an elastic pair



$$
\mathbf{Ku} = \mathbf{f} \Rightarrow \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} & k_{x\theta} & k_{x\phi} & k_{x\psi} \\ & k_{yy} & k_{yz} & k_{y\theta} & k_{y\phi} & k_{y\psi} \\ & & k_{zz} & k_{z\theta} & k_{z\phi} & k_{z\psi} \\ & & & k_{\theta\theta} & k_{\theta\phi} & k_{\theta\psi} \\ & \text{Symmetric} & & & k_{\phi\phi} & k_{\phi\psi} \\ & & & & & k_{\psi\psi} \end{bmatrix} \begin{Bmatrix} u_x \\ u_y \\ u_z \\ \theta \\ \phi \\ \psi \end{Bmatrix} = \begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix}
$$

Elastic deformation analysis, analytical or numerical, via the compliance matrix can be used to compute **K**.

Computing the multi-axis compliance matrix

$$\mathbf{K}^{-1} = \mathbf{C} \Rightarrow \begin{bmatrix} c_{xx} & c_{xy} & c_{xz} & c_{x\theta} & c_{x\phi} & c_{x\psi} \\ & c_{yy} & c_{yz} & c_{y\theta} & c_{y\phi} & c_{y\psi} \\ & & c_{zz} & c_{z\theta} & c_{z\phi} & c_{z\psi} \\ & & & c_{\theta\theta} & c_{\theta\phi} & c_{\theta\psi} \\ & \text{Symmetric} & & & c_{\phi\phi} & c_{\phi\psi} \\ & & & & & c_{\psi\psi} \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{Bmatrix} u_x \\ u_y \\ u_z \\ \theta \\ \phi \\ \psi \end{Bmatrix}$$

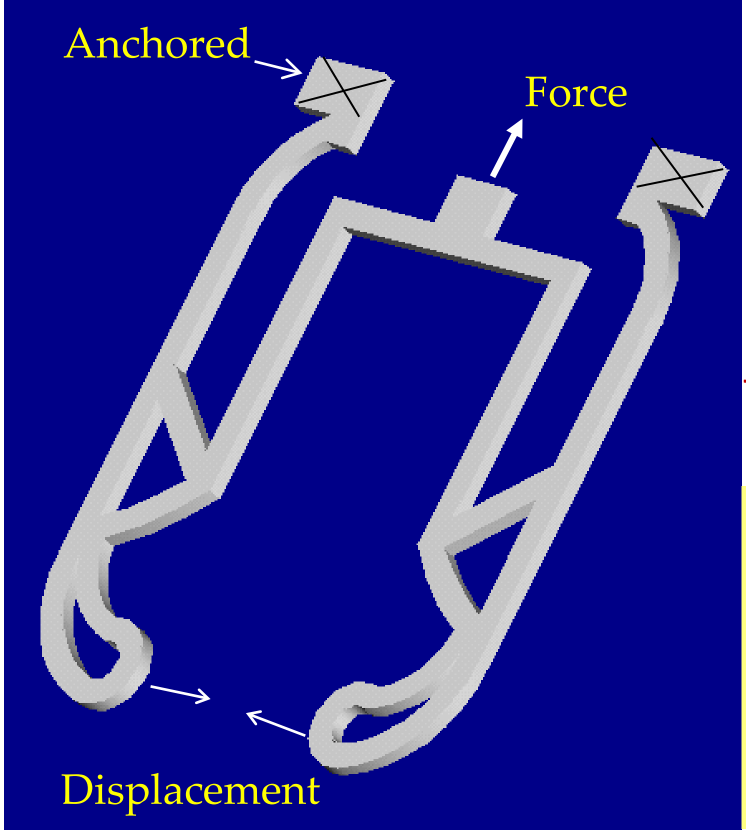
Up to six analysis runs…

Three finite element analysis runs in 2D.

Six finite element analysis runs in 3D.

No joints (pairs) at all

A compliant mechanism with elastic segments



Elastic segments instead of elastic pairs.

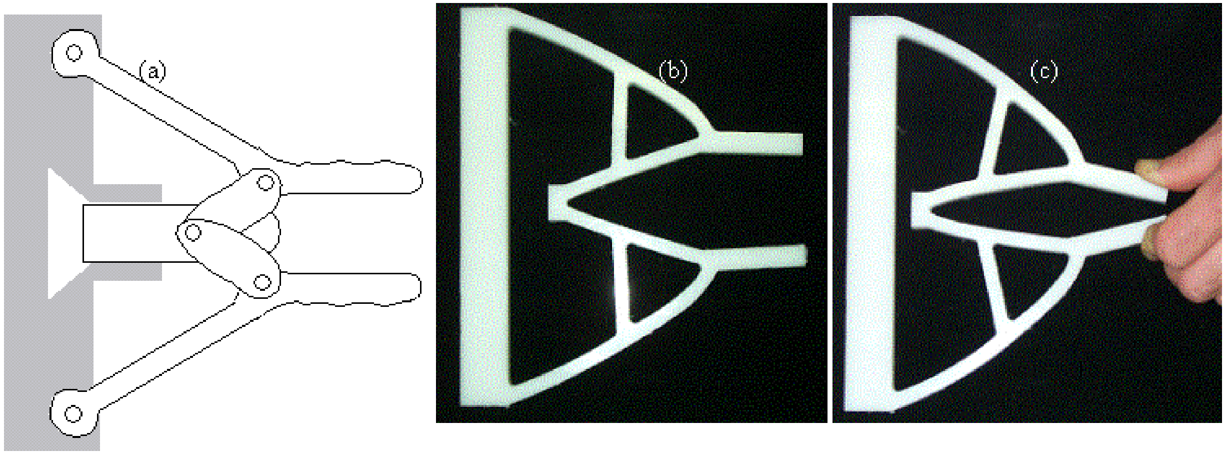
Distributed compliance

No elastic pairs.
Uniformly distributed deformation.
Large displacement with small strain.
Stronger than elastic pairs.
Enhanced scope for design.

A compliant gripper

Compliant Mechanism: the definition

- A mechanism that uses elastic deformation to transmit or transform force, motion, and energy.

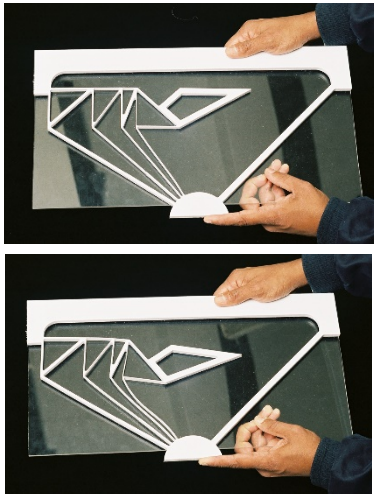


Replace many parts with one part.

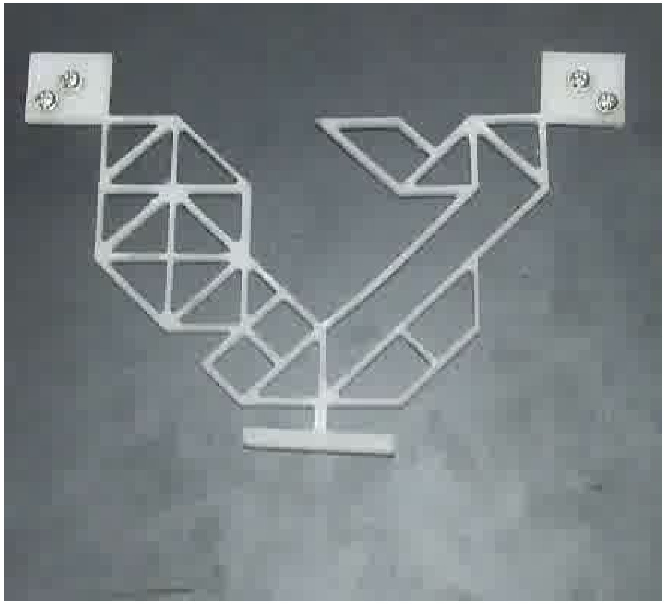
Transmission

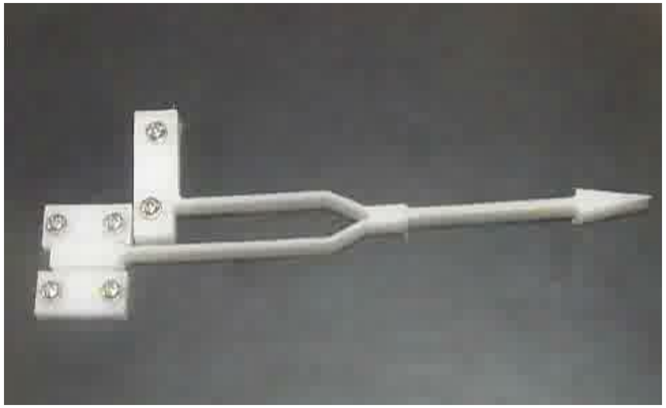
Transmission

- Amplify force or motion
- Change direction
- Change the dynamics
- Change state

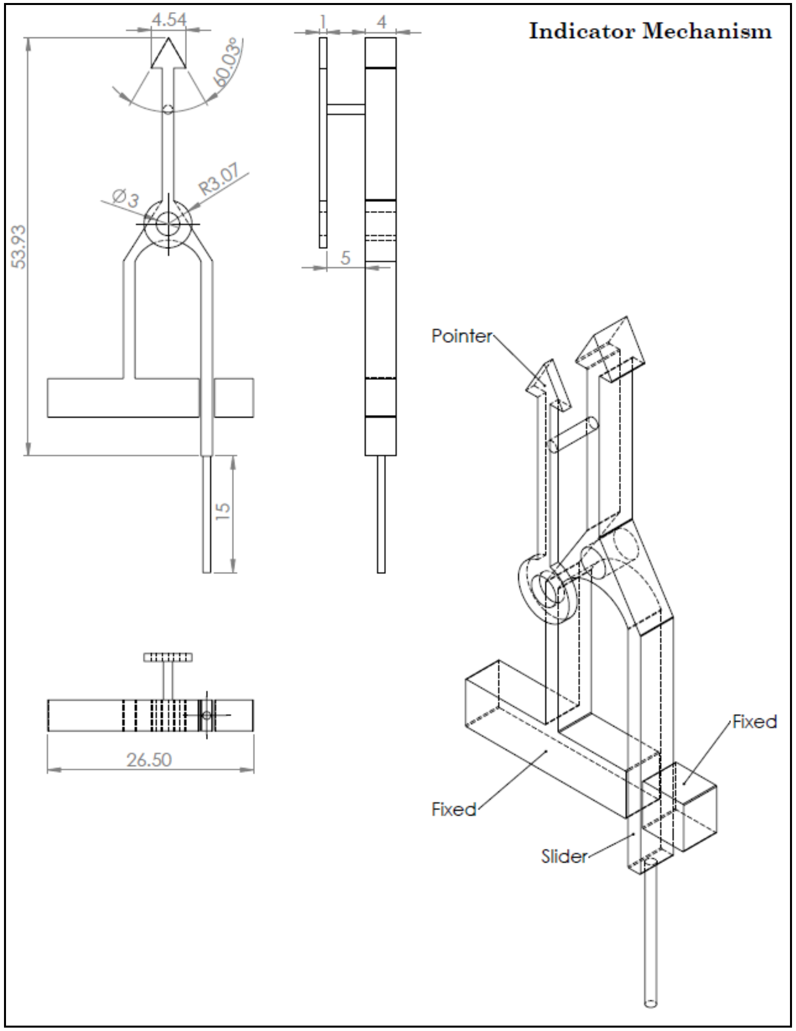


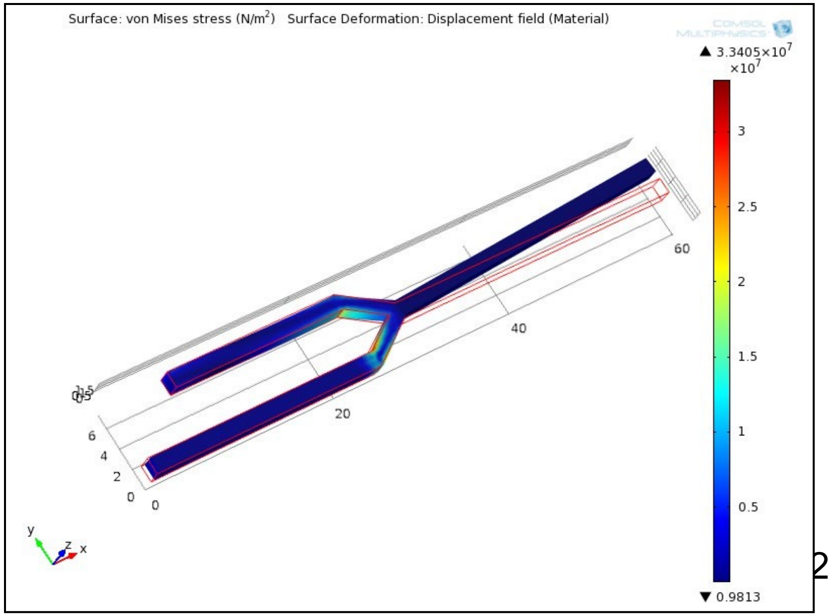
With Anupam Saxena and Luzhong Yin





Soil-moisture sensor (no electrical power):
swelling of a super-adsorbent polymer + mechanically amplified motion





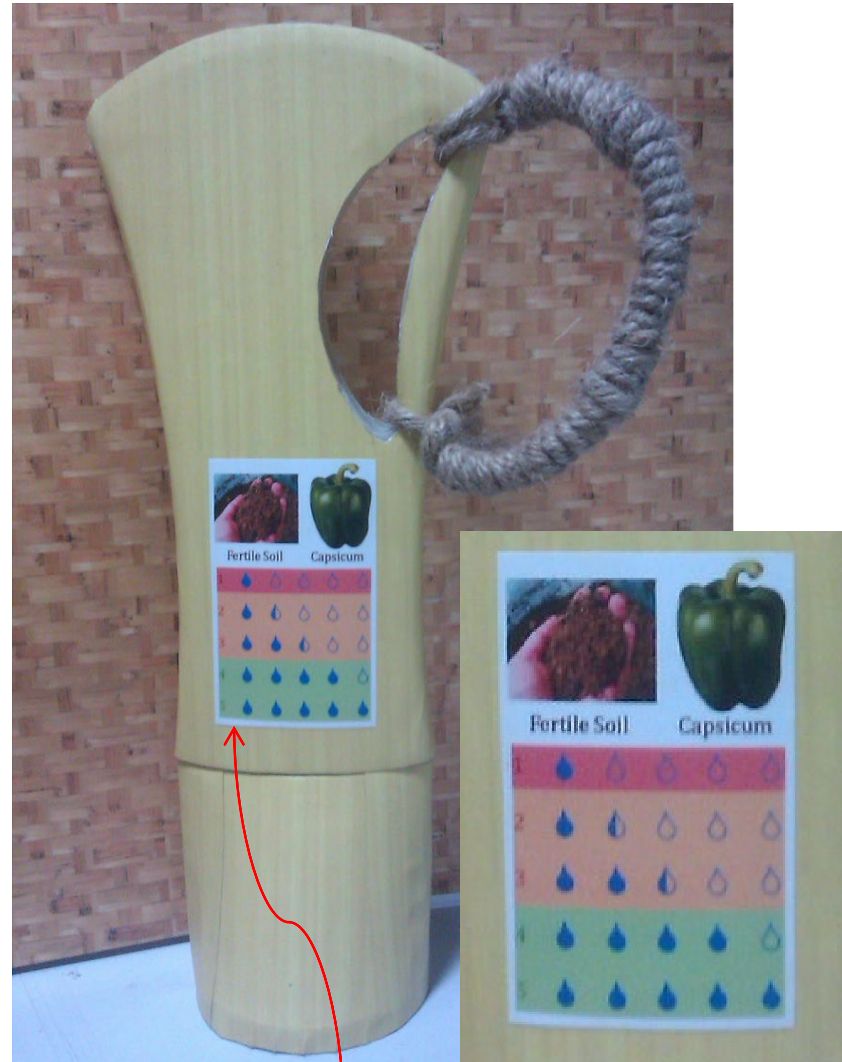
Ananthasuresh, IISc

Dial

Indicator

Holder

Soil Sample Holder

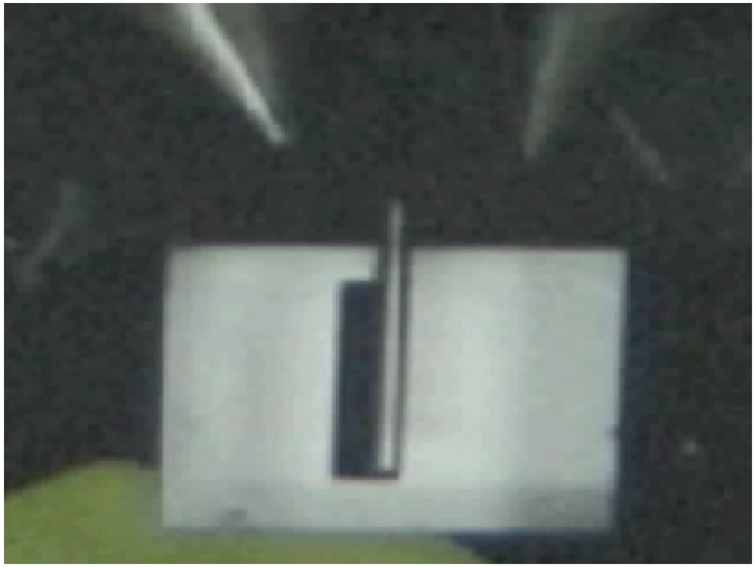


Suggestive remarks as per the crop and soil

Neer Samiksh

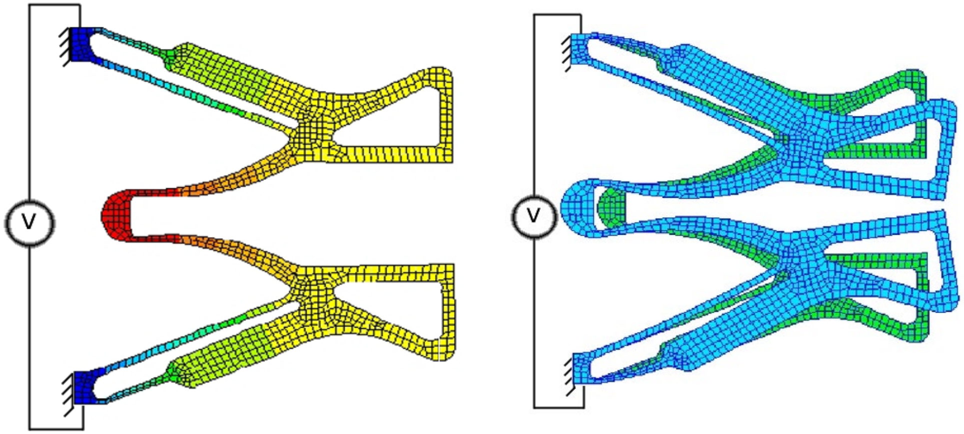
Soil-moisture sensor

Transmission is fine; *transformation?*



Transduction

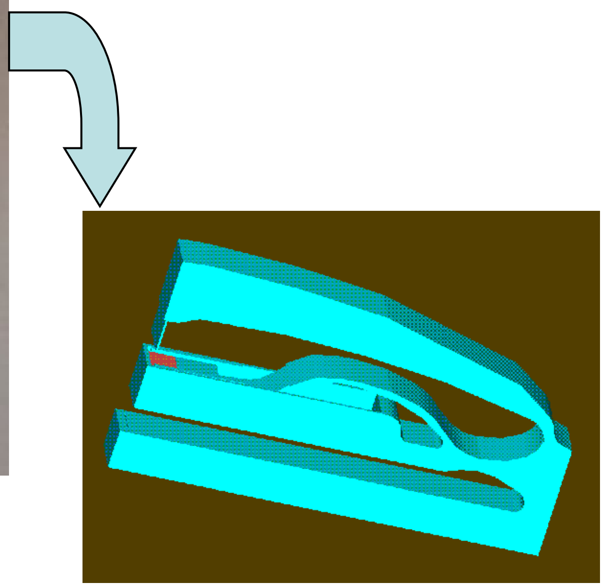
- Convert non-mechanical energy into mechanical energy and vice versa.
- Smart or active materials



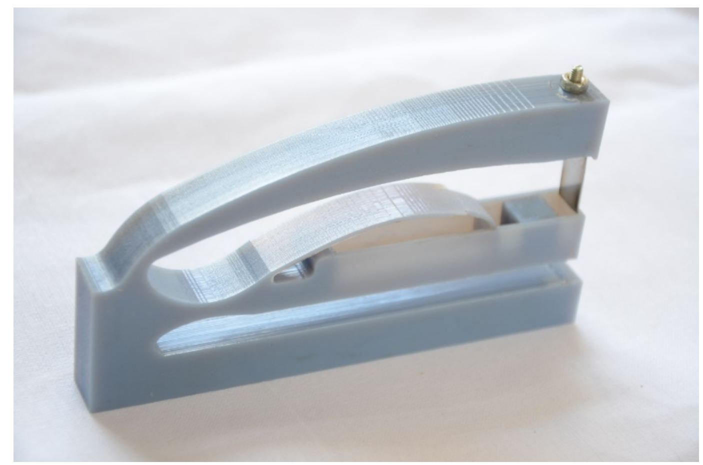
With Moulton

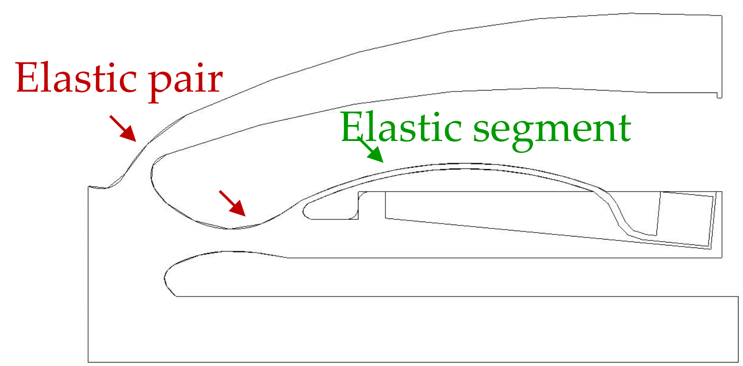
Monolithic (uni-body; single-piece) construction

- Ease of manufacture – reduced or no assembly



Ananthasuresh and Saggere, 1994





Monoform compliant designs from FlexSys

Shape-shifting Things to Come

Sridhar Kota

May 2014, ScientificAmerican.com

One inside the other… multi-scale graspers

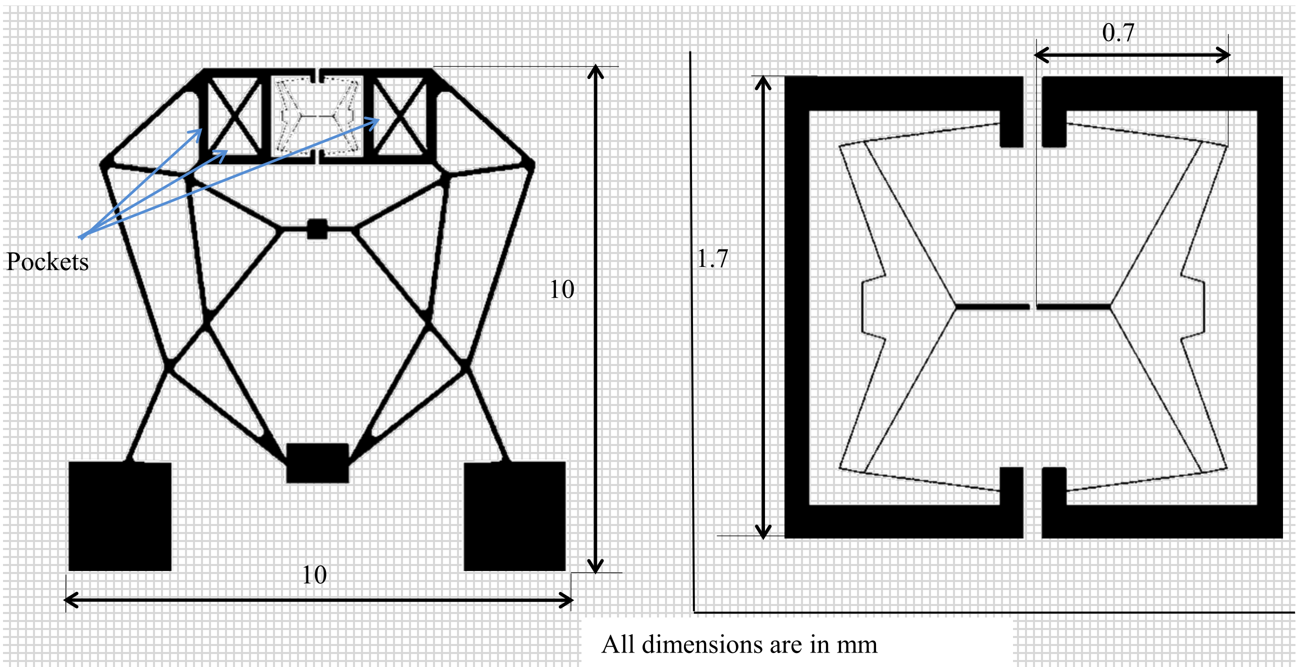
Stiffness matched to that of the biological cells

Zebrafish egg squeezing

Zebrafish egg rolling

Too soft for drosophila embryo

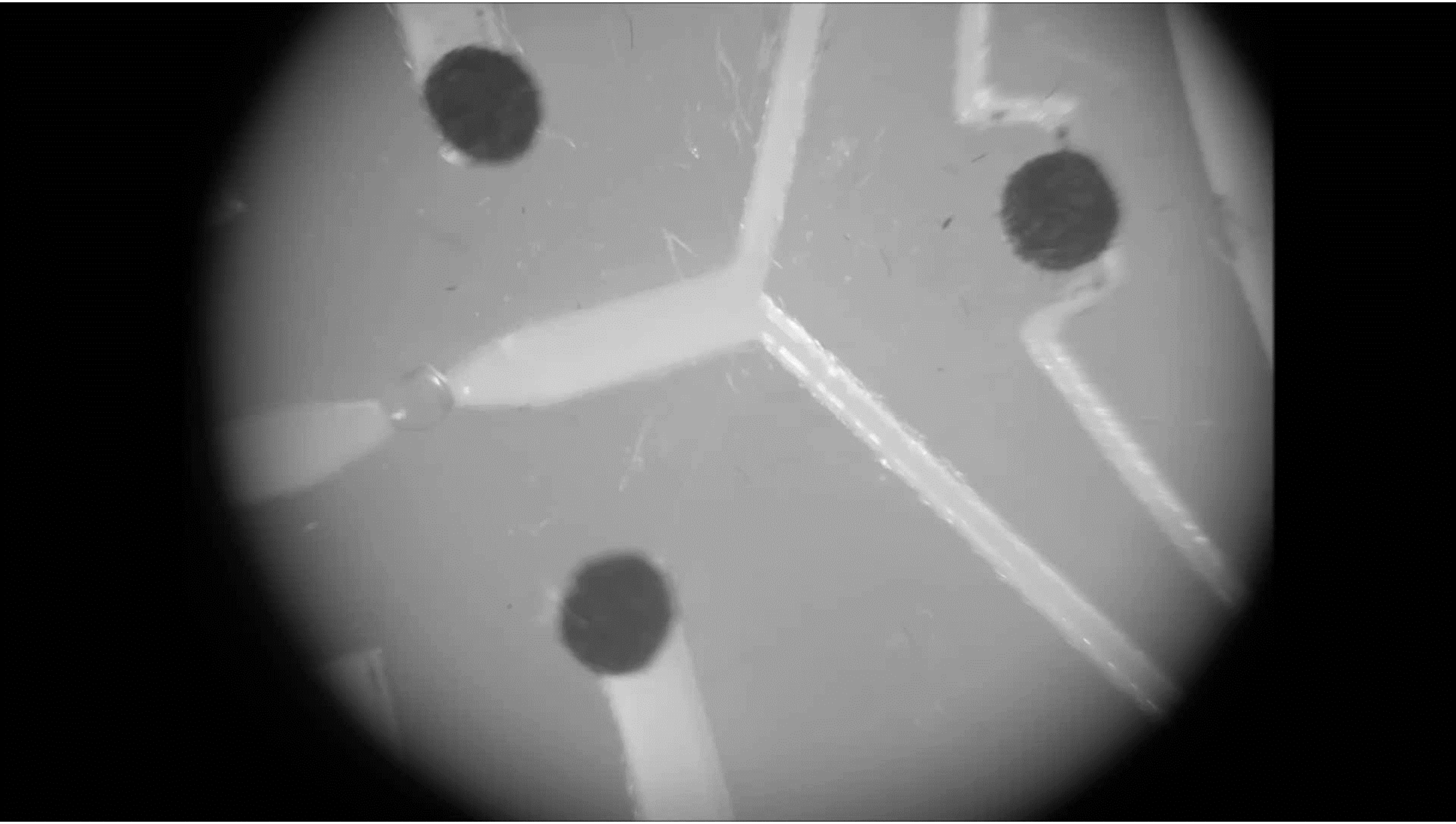
MCF-7 cell grasping



With Santosh Bhargav

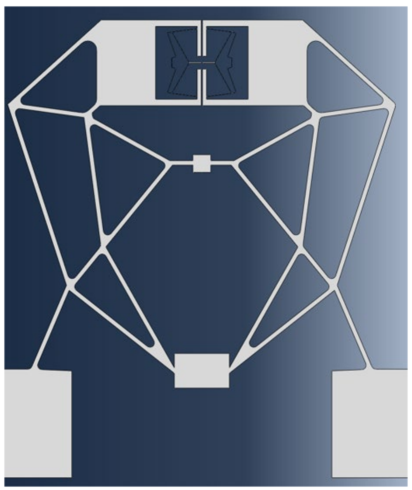
Force estimated to deform the zerbafish embryo by 150 μm is 1.2 mN. Thus the bulk stiffness is about 8 N/m

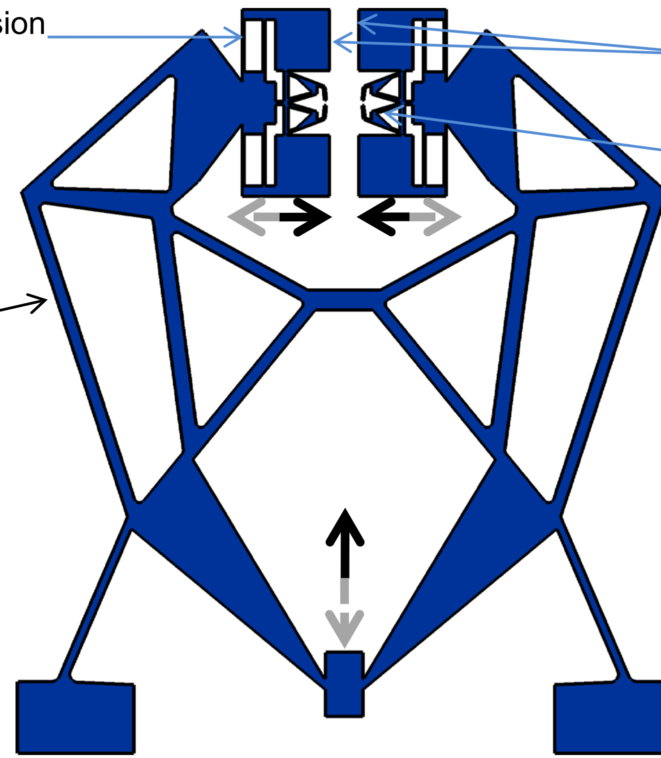
Squeezing a zebrafish egg… for mechanical characterization



Tuning stiffness… by combining

Gripper + DaCM =>
Stiffness tuning + GA

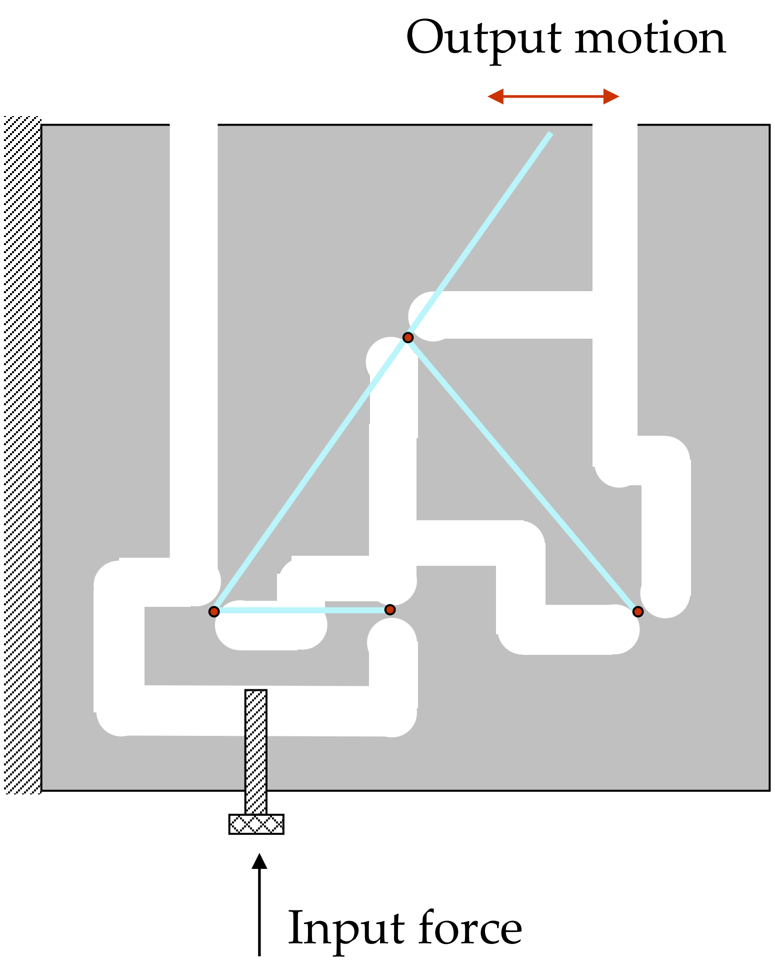




With Santosh Bhargav

Stretch too…

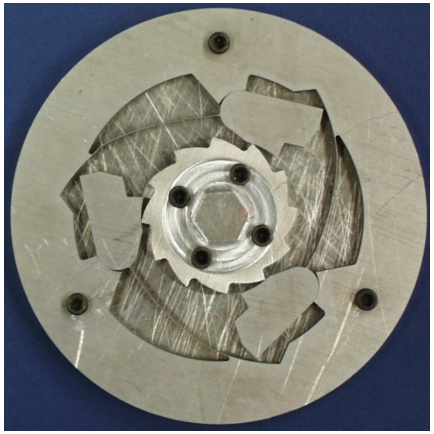
No more rubbing the wrong way



- Ease of manufacture – reduced or no assembly
- Ability to withstand overloads – "I bend but I break not."
- Less or no friction and wear
- No backlash problem – more precision

Prefer hinges to sliders, flexures to either.
- M. J. French

Real applications



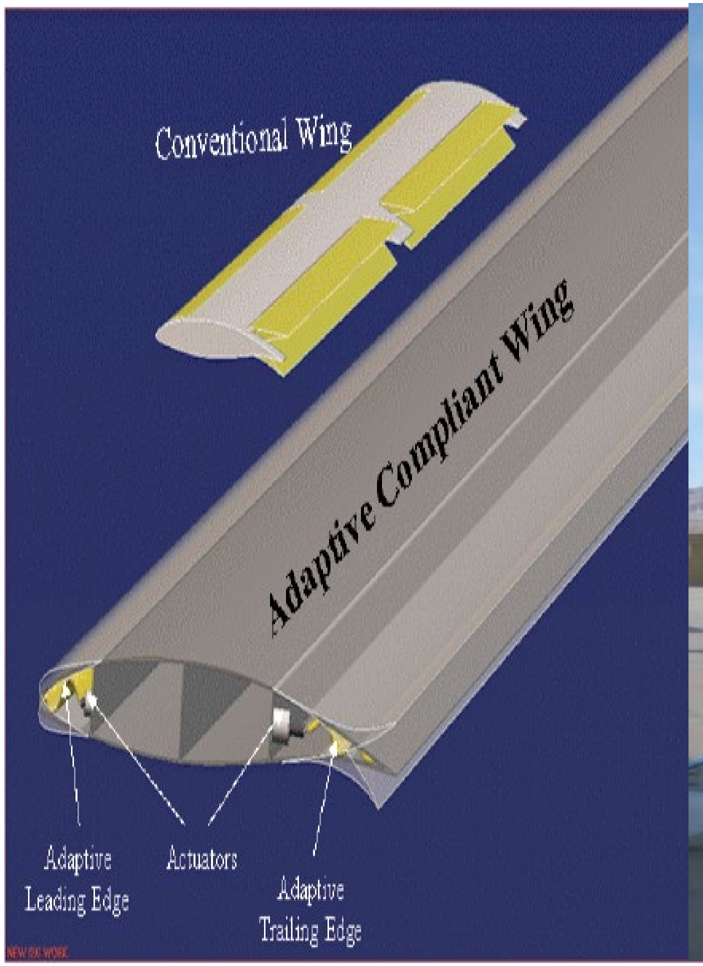
- Ease of manufacture – reduced or no assembly
- Ability to withstand overloads – “I bend but I break not.”
- Less or no friction and wear
- No backlash problem – more precision
- Aesthetics made easier
- Economy of material and less cost for better performance

Over-running and one-way clutches

Prof. Larry Howell
Brigham Young University

Gahring and Ananthasuresh

Mission-adaptive compliant wings



Prof. Sridhar Kota, University of Michigan

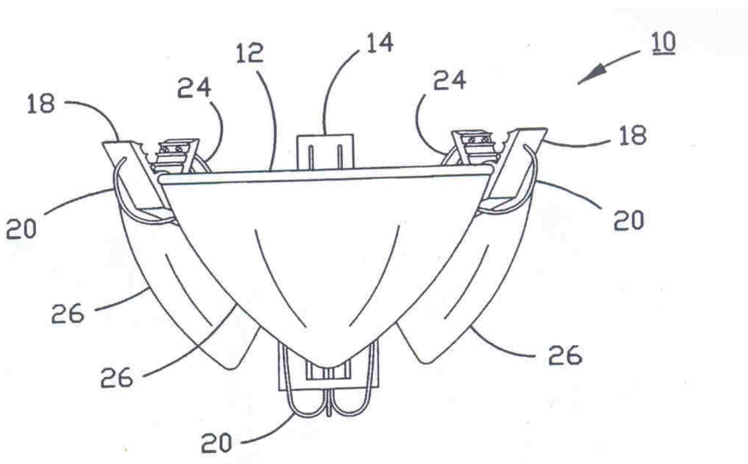
Morphing wing surface

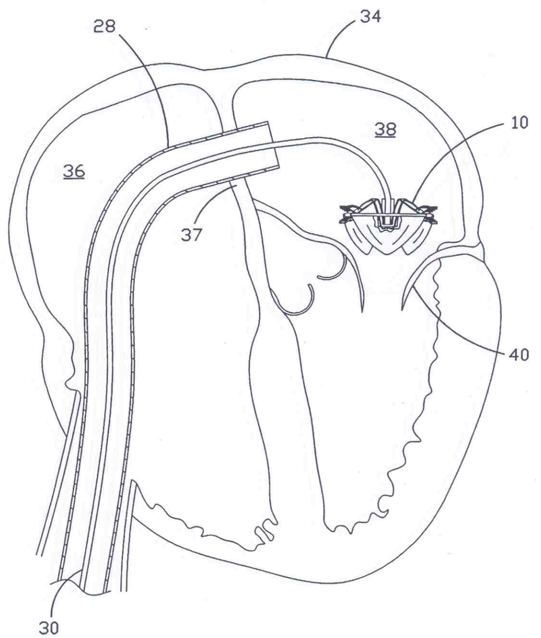
WITH ELASTIC DESIGN, flexible, morphing surfaces can replace rigid wing flaps (*1*), windshield wiper frames can be molded from single pieces of material (*2*), and one chunk of plastic can do the work of a conventional stapler's nearly two dozen parts (*3*).

Shape-shifting Things to Come
Sridhar Kota

May 2014, ScientificAmerican.com

An artificial heart valve

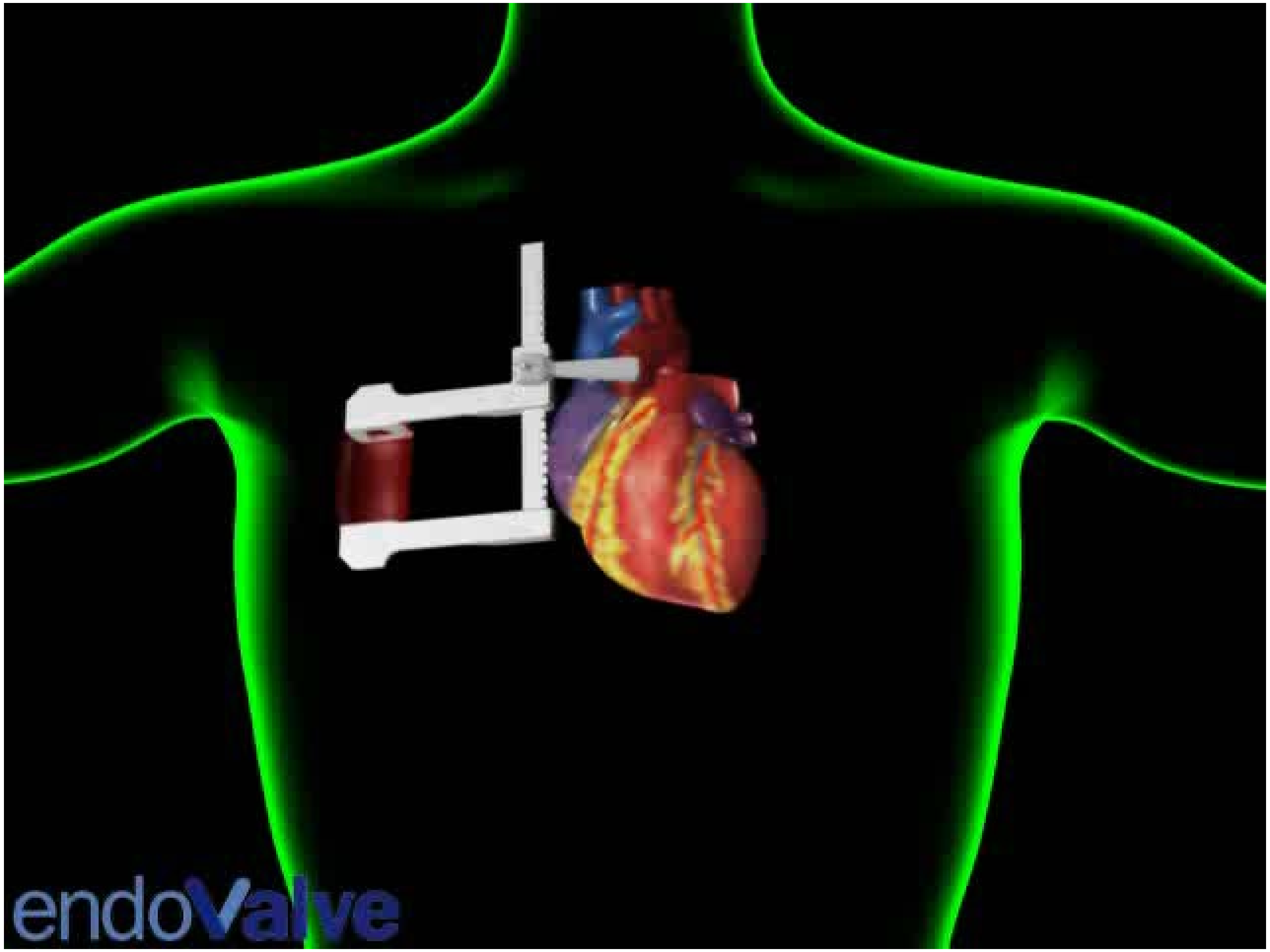




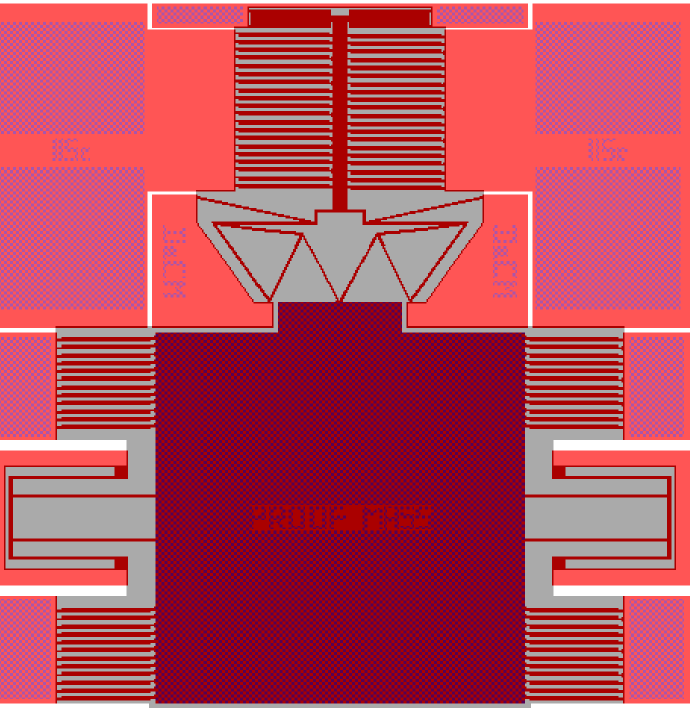
Currently under further development by Endovalve, Inc., USA

Patent

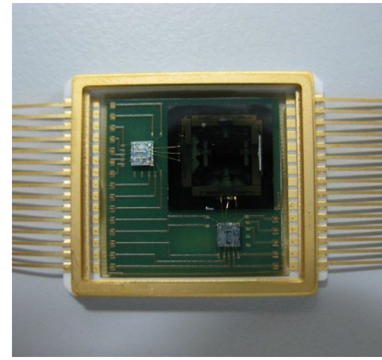
"Percutaneous Heart Valve," Patent application #. PCT/US2004/023211 dated 20th July, 2004 (H.C. Hermann and N. Mankame, G.K. Ananthasuresh)

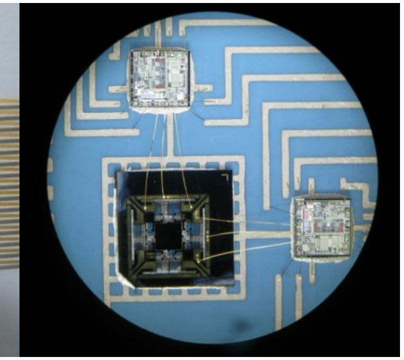

endoValve

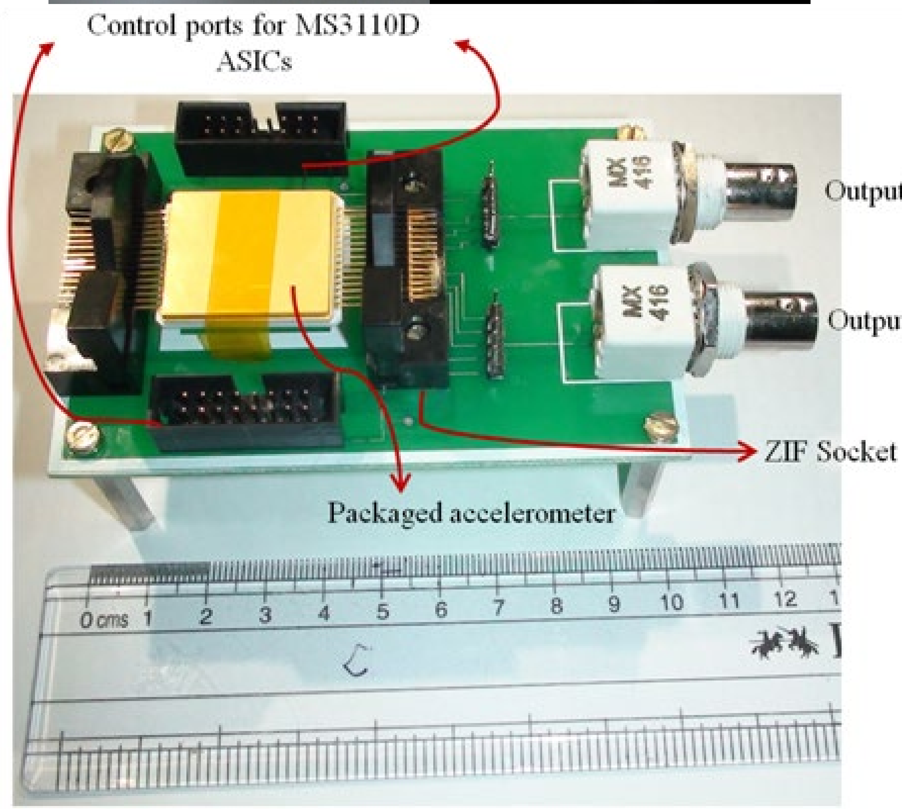
Improved micromachined accelerometers

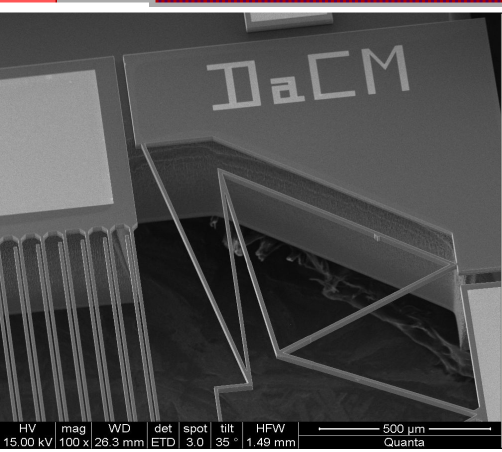


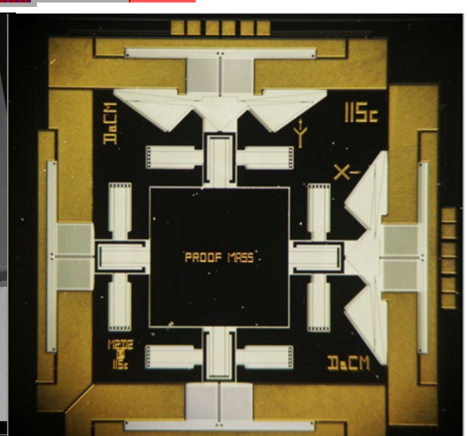
With Sambuddha Khan









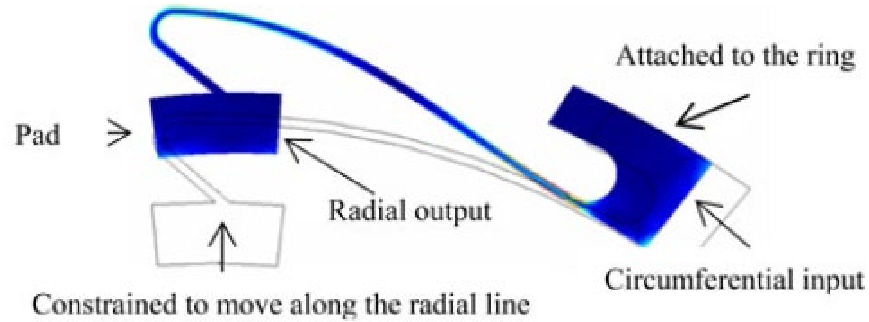


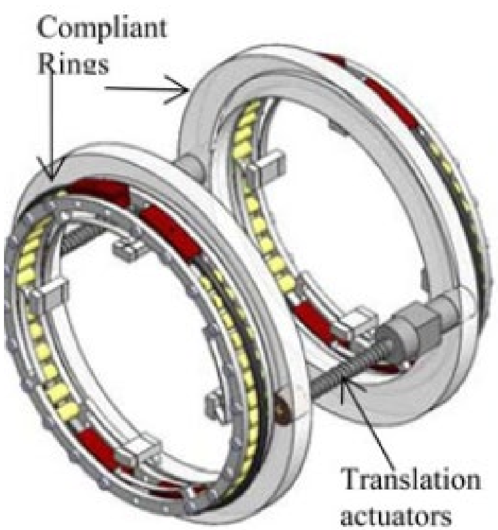
Ananthasuresh, IISc

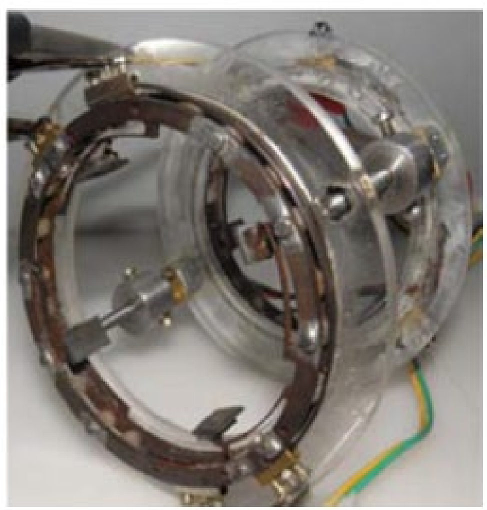
External pipe-crawler

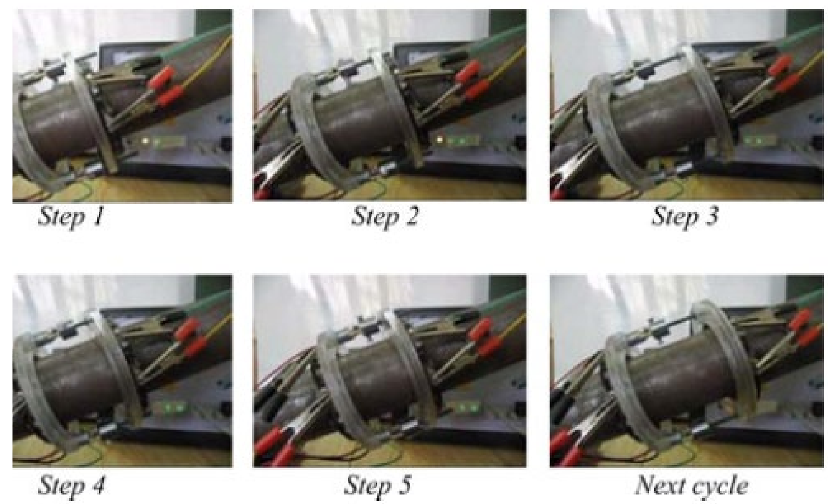
Inchworm concept

A compact ring-actuator





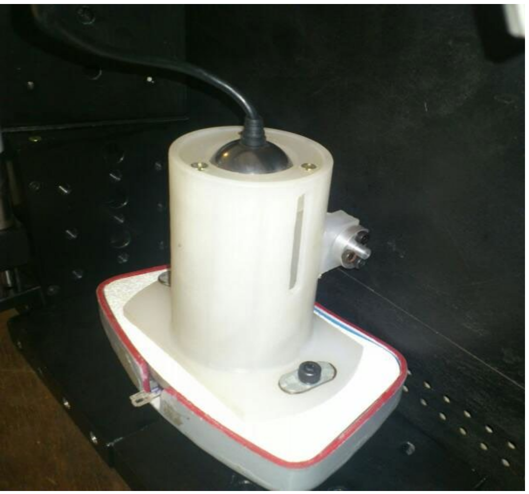


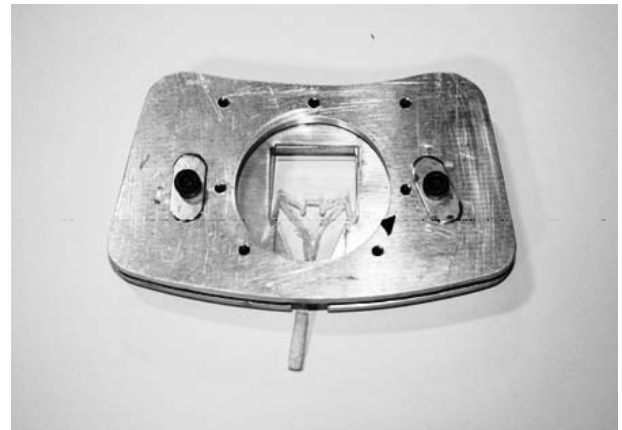


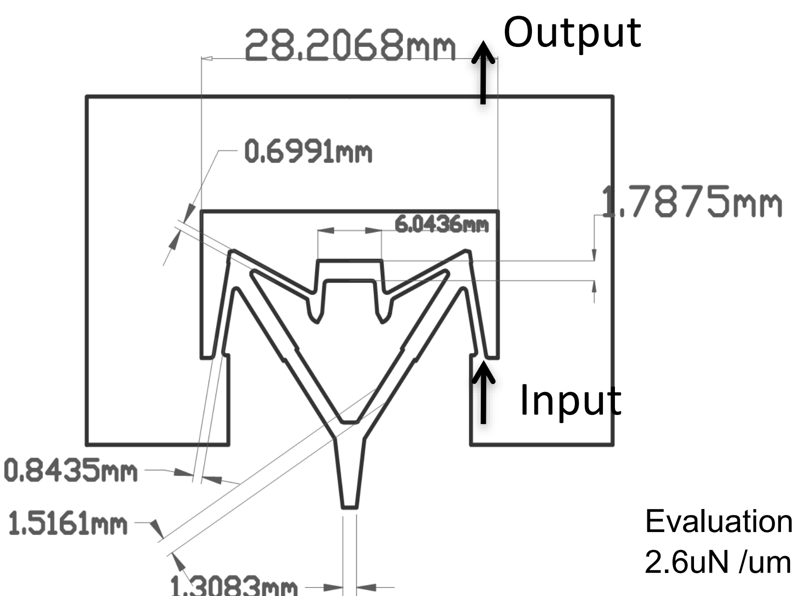
With Puneet Singh et al.

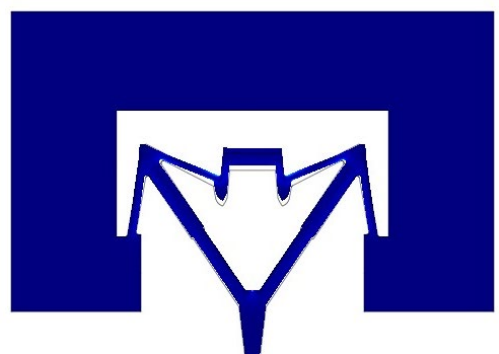
IEEE TRANSACTIONS ON ROBOTICS, VOL. 29, NO. 1, FEBRUARY 2013

Micron: a force sensor









Evaluation: effective stiffness of 26.N/m or 2.6uN /um

~2 μN resolution
~ 1 mN range

Baichapur, Bhargav, Gulati, Maheswari, and Ananthasureh, 2012

MicroN

These are good wheels!

Flattening of tire
under loading

Non-pneumatic tire from IISc.

ME project report, G. Bhargav, 2008.

Flattening of tire under loading in *tweel*, an experimental design made by michelin and inspiration for this project

Tweel from Michelin.

Almost any type of motion

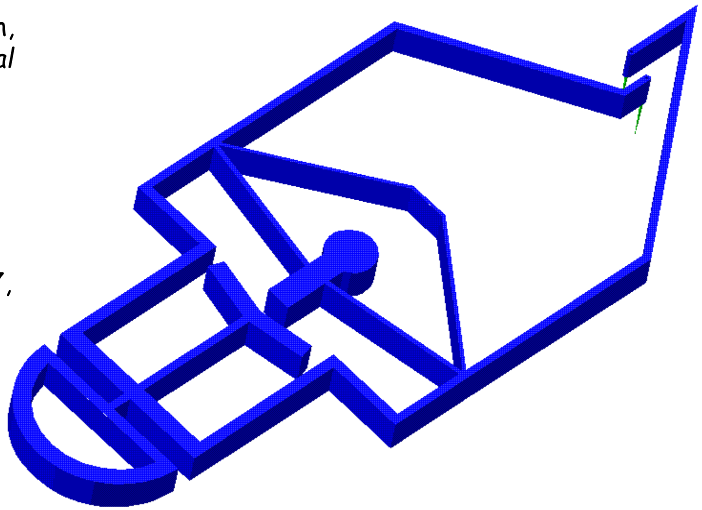
- Displacement amplification
- Curved paths
- Non-smooth paths
- Frequency tuning
- Constant-force
- Actuator characteristic modification
- Etc.

- Ease of manufacture – reduced or no assembly
- Ability to withstand overloads – "I bend but I break not."
- Less or no friction and wear
- No backlash problem – more precision
- Aesthetics made easier
- Economy of material and less cost for better performance
- Any type of motion

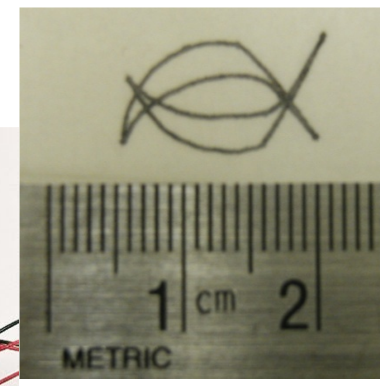
Non-smooth curved paths

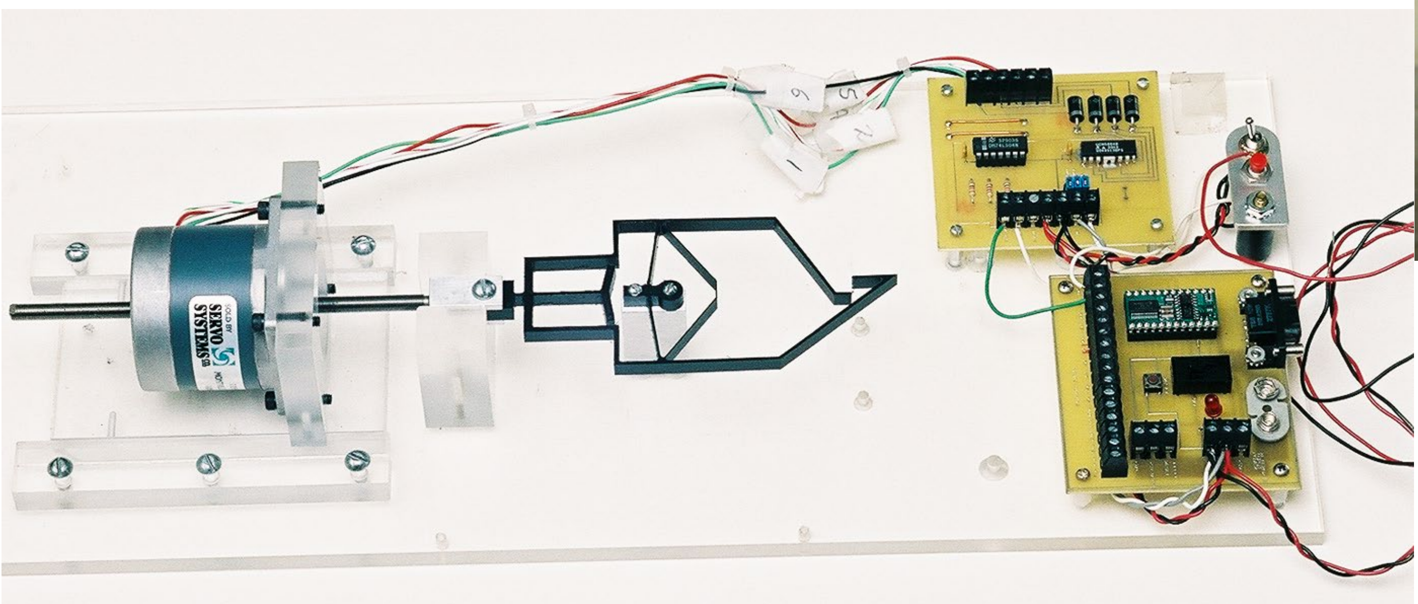
Mankame, N. and Ananthasuresh, G.K., *Journal of Mechanical Design*. 126(4), 2004, pp. 667-672.

Mankame, N. D. and Ananthasuresh, G. K., International Journal of Numerical Methods in Engineering, 69 (12), 2007, pp. 2564-2605.



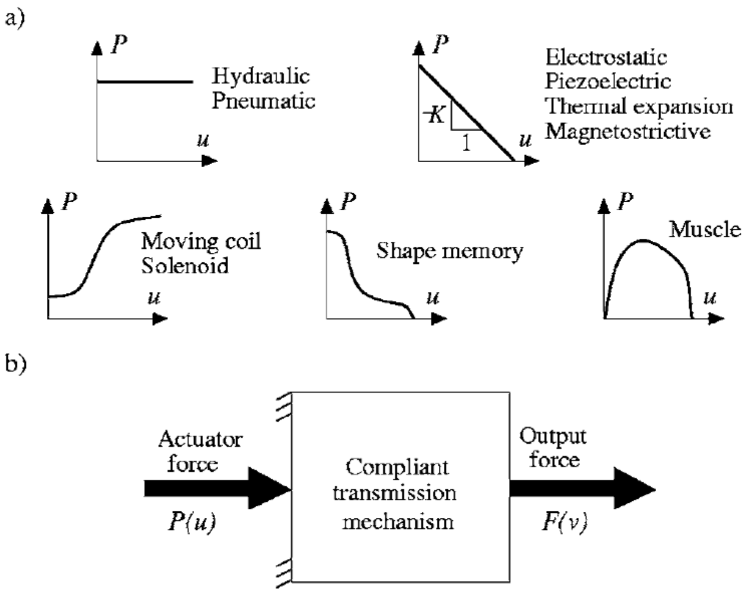
Movie

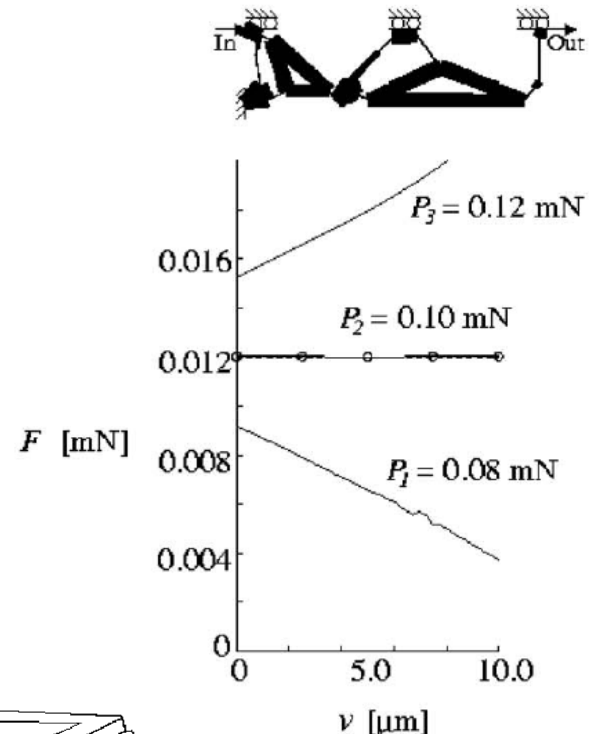


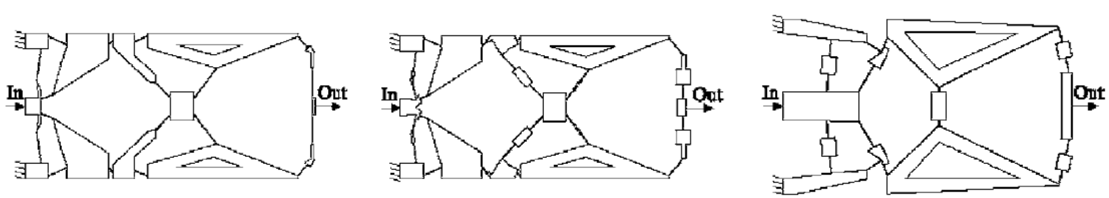


Non-smooth motion with smooth input using compliant mechanisms

Actuator characteristic modification



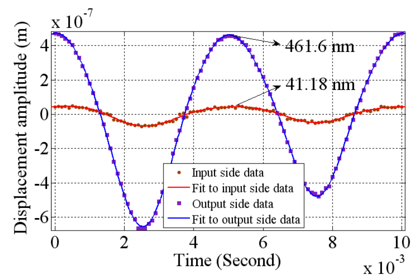


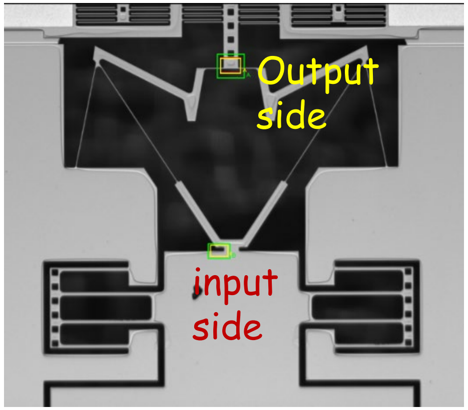


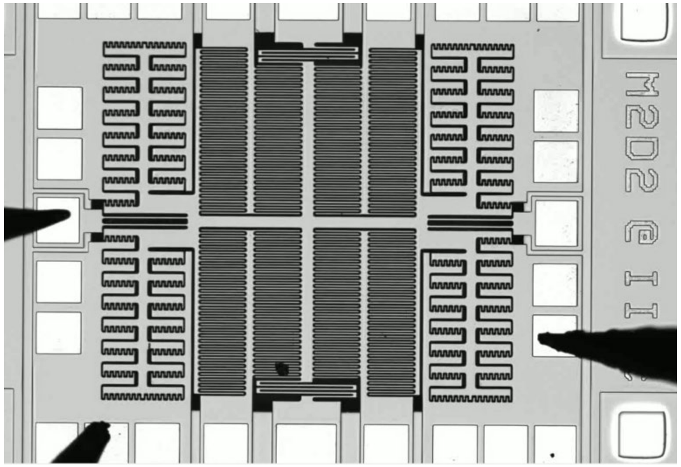
Pedersen, C. B. W., Fleck, N. A. and Ananthasuresh, G. K., *Journal of Mechanical Design*, 128(5), 2006, pp. 1101-1112.

Micromechaical signal processors

- Band-pass filters
- Switches and relays
- Amplifiers
- Frequency-translators
- Clocks

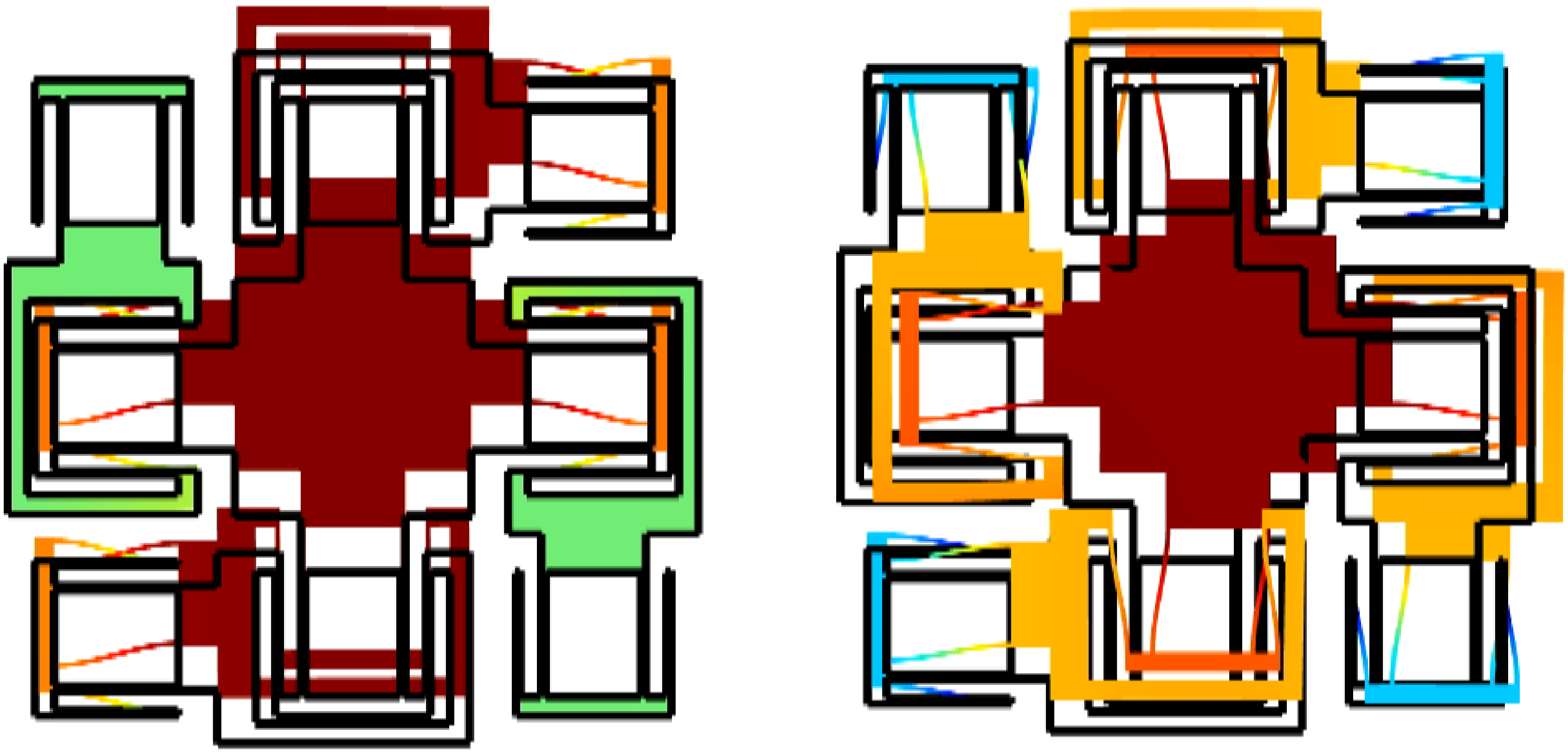






With Sambuddha Khan and Nirmit Dave

Separating x-y signals



Is compliant design difficult?

- Some people think so. It may be because…
  - you need to deal with elastic deformation.
  - you need to deal with elastic pairs and elastic segments as opposed to discrete rigid bodies.
- It is in fact easy once we pay attention to…
  - what benefits we can achieve with deformation
  - deformation mechanics in addition to kinematics

Models for analysis

- Empirical modeling of elastic pairs
- Elastica analysis of beam segments
- Pseudo Rigid-Body (PRB) modeling
- **Finite element analysis**
- Spring-Lever (SL) and Spring-Mass-Lever (SML) modeling
- Compliant ellipsoid modeling
- Non-dimensional maps

Synthesis methods

- Kinetostatic synthesis using PRB modeling
- **Topology and shape optimization**
- Selection and re-design
- Instant-centre method
- Design using building blocks
- Pragmatic design with non-dimensional maps
- Intuitive design using a kit