Experiment

Be careful with
the magnets!!
They are very
Strong!!!

Keep them away
From your computer
And credit cards

2.76 / 2.760 Lecture 3: Large scale

Flexure experiment

Constraints

Micro-fabrication

Micro-physics scaling

Assignment

Experiment

(1) What is the smallest displacement you can "really" measure with the probes? It is smaller than the ticks….

(2) What metrology/measurement issues must be dealt with?

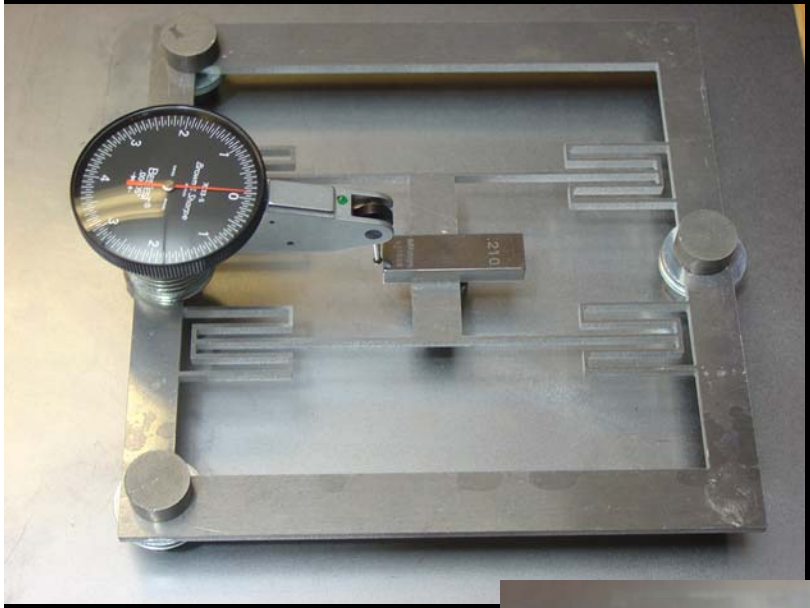
(3) Estimate the effect of actuator angular misalignment on parasitic error. Do an order of magnitude estimate. Use your finger…

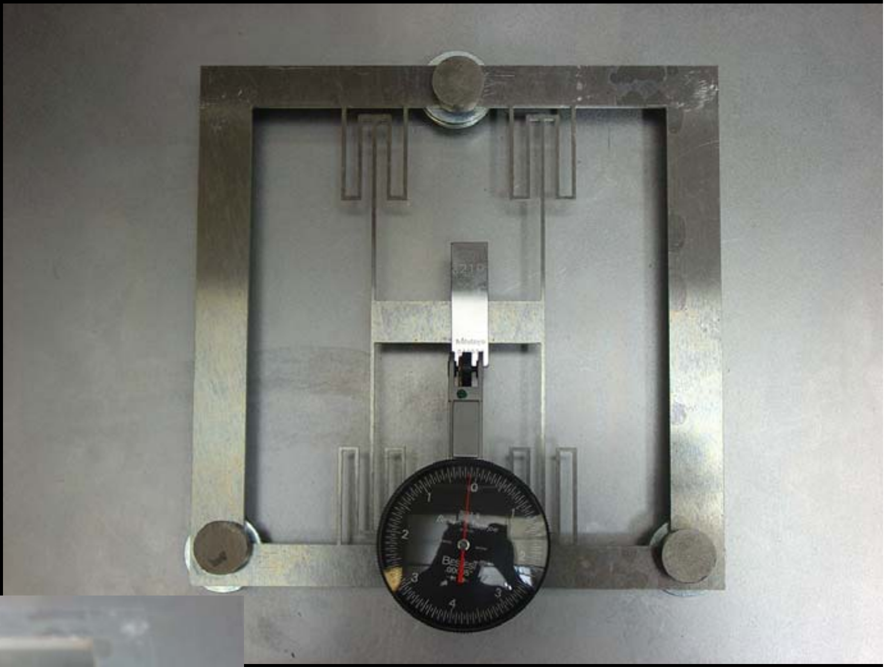
(4) How should you design a constraint between the actuator and the flexure to mitigate angular misalignment?

(5) How effective would this constraint be? What are the important design variables? Use CoMeT…

Time Limit: 30 minutes
Email results to me when time is called

Experiment





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Discussion

Metrology/measurement issues

Actuator angular misalignment on parasitic error

Effectiveness of constraint between actuator-flexure

Purpose of today

$$
\begin{Bmatrix} O_{Macro} \\ O_{Meso} \\ O_{Micro} \\ O_{Nano} \end{Bmatrix} =
\begin{bmatrix}
f_{11}\left(SR_{\frac{Macro}{Macro}}\right) & f_{12}\left(SR_{\frac{Meso}{Macro}}\right) & f_{13}\left(SR_{\frac{Micro}{Macro}}\right) & f_{14}\left(SR_{\frac{Nano}{Macro}}\right) \\
f_{21}\left(SR_{\frac{Macro}{Meso}}\right) & f_{22}\left(SR_{\frac{Meso}{Meso}}\right) & f_{23}\left(SR_{\frac{Micro}{Meso}}\right) & f_{24}\left(SR_{\frac{Nano}{Meso}}\right) \\
f_{31}\left(SR_{\frac{Macro}{Micro}}\right) & f_{32}\left(SR_{\frac{Meso}{Micro}}\right) & f_{33}\left(SR_{\frac{Micro}{Micro}}\right) & f_{34}\left(SR_{\frac{Nano}{Micro}}\right) \\
f_{41}\left(SR_{\frac{Macro}{Nano}}\right) & f_{42}\left(SR_{\frac{Meso}{Nano}}\right) & f_{43}\left(SR_{\frac{Micro}{Nano}}\right) & f_{44}\left(SR_{\frac{Nano}{Nano}}\right)
\end{bmatrix} \cdot
\begin{Bmatrix} I_{Macro} \\ I_{Meso} \\ I_{Micro} \\ I_{Nano} \end{Bmatrix}
$$

Finish mechanical gain factors to make big machines work with little machines

Micro-scale flow/interface dominators

- Micro-scale fabrication
- Micro-scale surface/volume physics

Constraints

Constraint-based design

Constraint-based compliant mechanism design

STEP 1: Design requirements
Motion path, stiffness, load capacity, etc…

STEP 2: Motion path decomposition
Arcs, lines, rotation pts. sub-paths

STEP 3:Kinematic parametric concepts
Motions, constraint metric, symmetry, etc.

STEP 4:Constraint-motion addition rules
Serial, parallel, hybrid

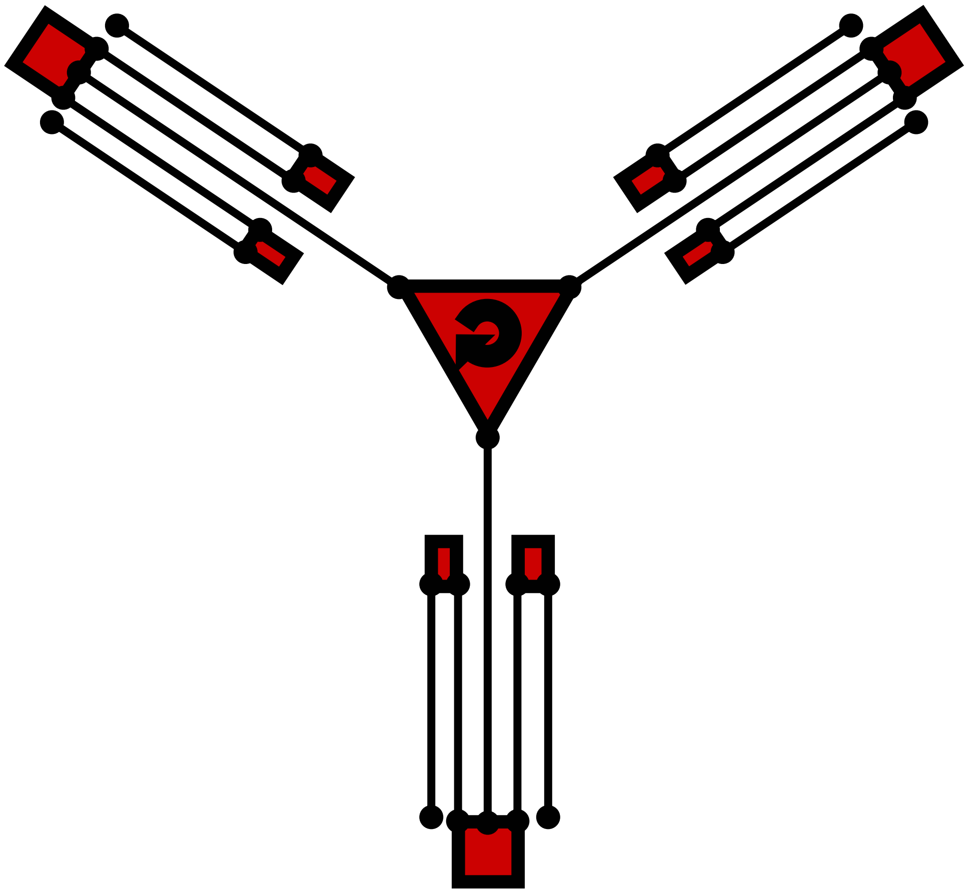
STEP 5: Topology concept generation
Path & constraint driven

STEP 6: Concept selection phase I
Path errors & over constraint

STEP 7: Size and shape optimization
Stiffness, load capacity, efficiency, etc…

STEP 8: Concept selection phase II
Direct comparison with design requirements

Photo removed for copyright reasons.
Compliant test rig for automotive steering column.



Exact constraint

At some scale, everything is a mechanism

Exact constraint: Achieve desired motion

- ❑ By applying minimum number of constraints
- ❑ Arranging constraints in optimum topology
- ❑ Adding constraints only when necessary

Visualization is critical, this is not cookbook

For now:

- ❑ Start with ideal constraints
- ❑ Considering small motions
- ❑ Constraints = lines

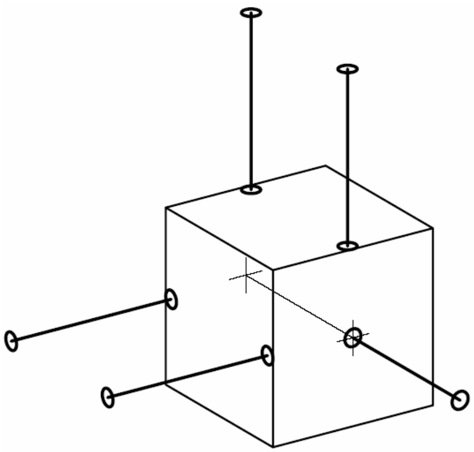


Figure: Layton Hales PhD Thesis, MIT.

Constraint fundamentals

Rigid bodies have 6 DOF

DOC = # of linearly independent constraints

DOF = 6 - DOC

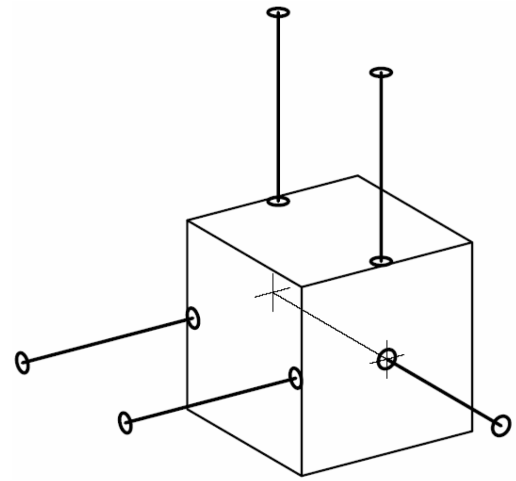


Figure: Layton Hales PhD Thesis, MIT.

A linear displacement can be visualized as a rotation about a point which is "far" away

Statements

Points on a constraint line move perpendicular to the constraint line

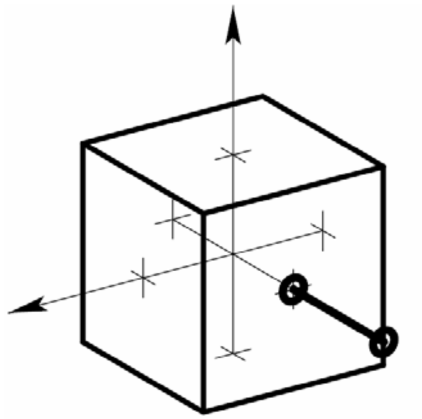
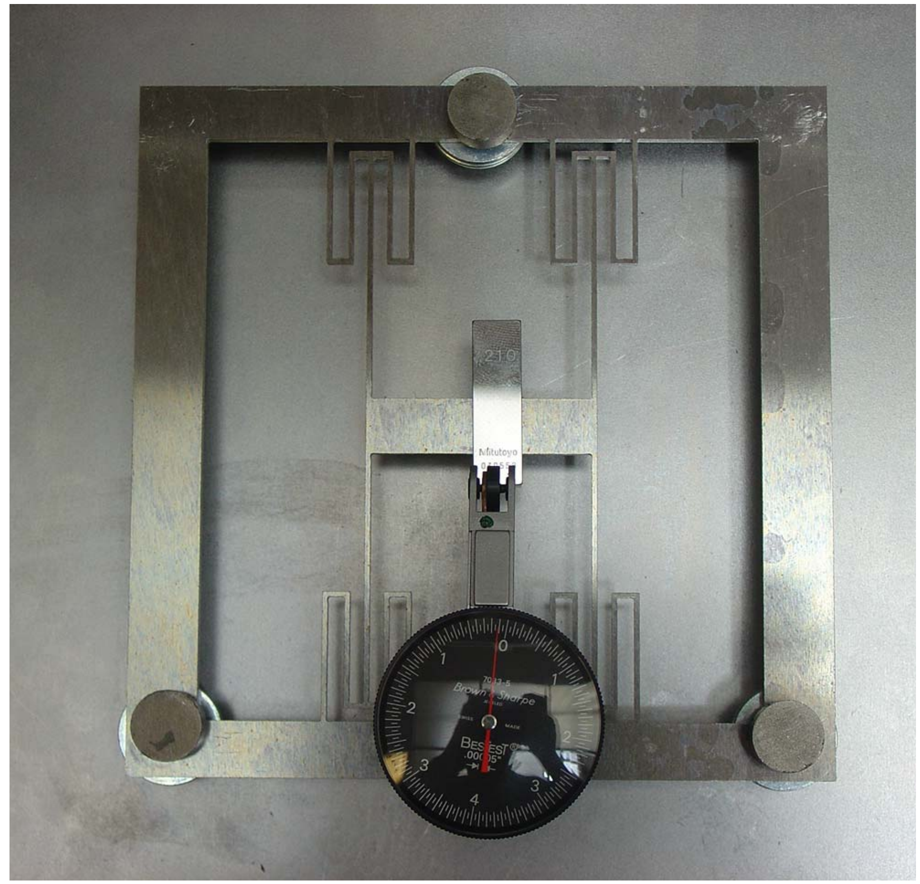


Figure: Layton Hales PhD Thesis, MIT.

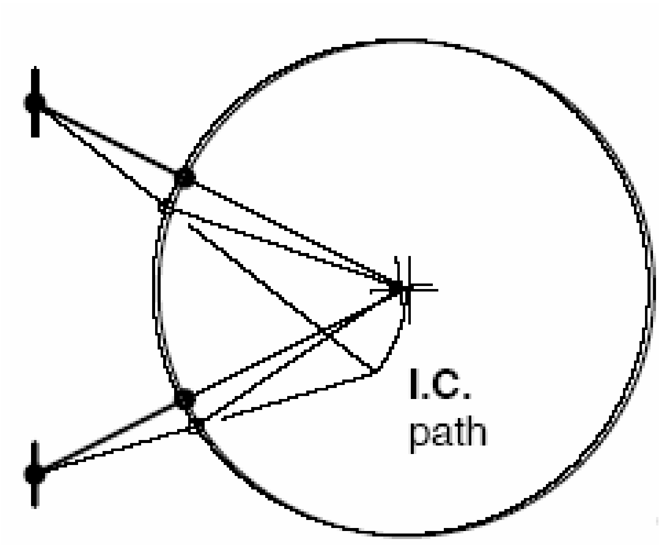
Constraints along this line are equivalent

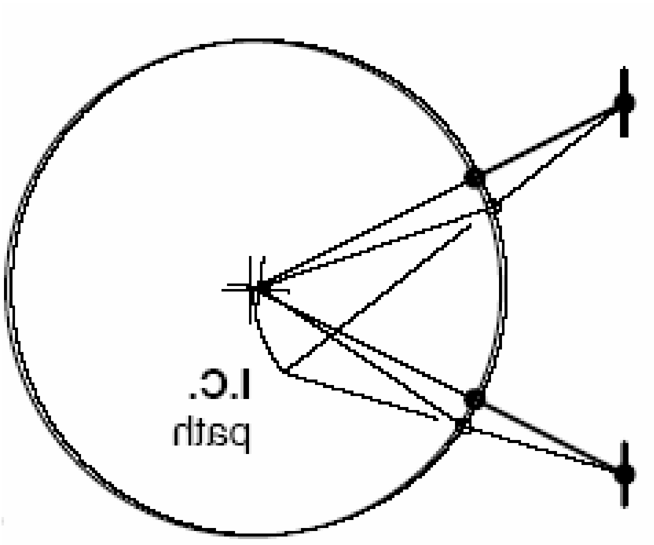
Diagrams removed for copyright reasons.
Source: Blanding, D. L. *Exact Constraint: Machine Design using Kinematic Principles*. New York: ASME Press, 1999.



Statements

Intersecting, same-plane constraints are equivalent to other same-plane intersecting constraints

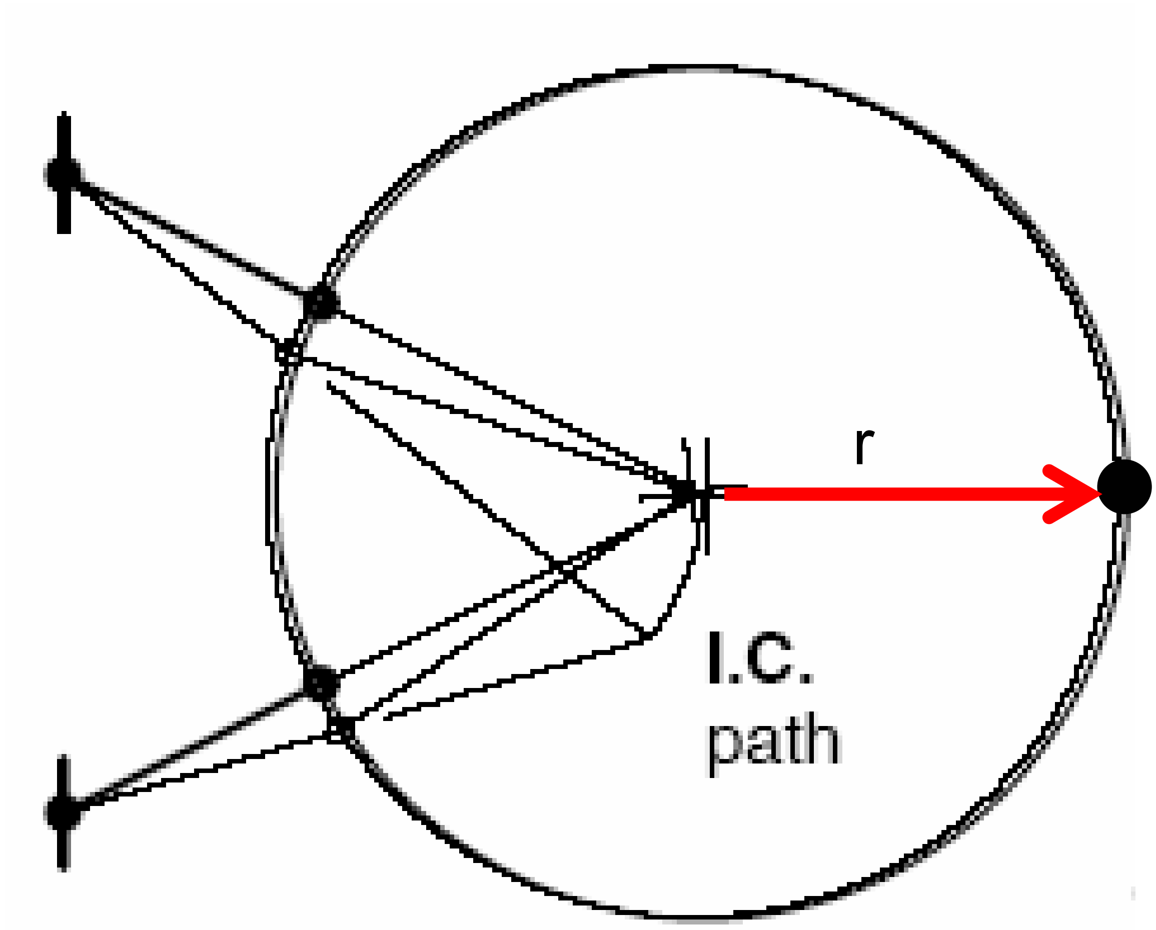




Instant centers are powerful tool for visualization, diagnosis, & synthesis

Abbe error

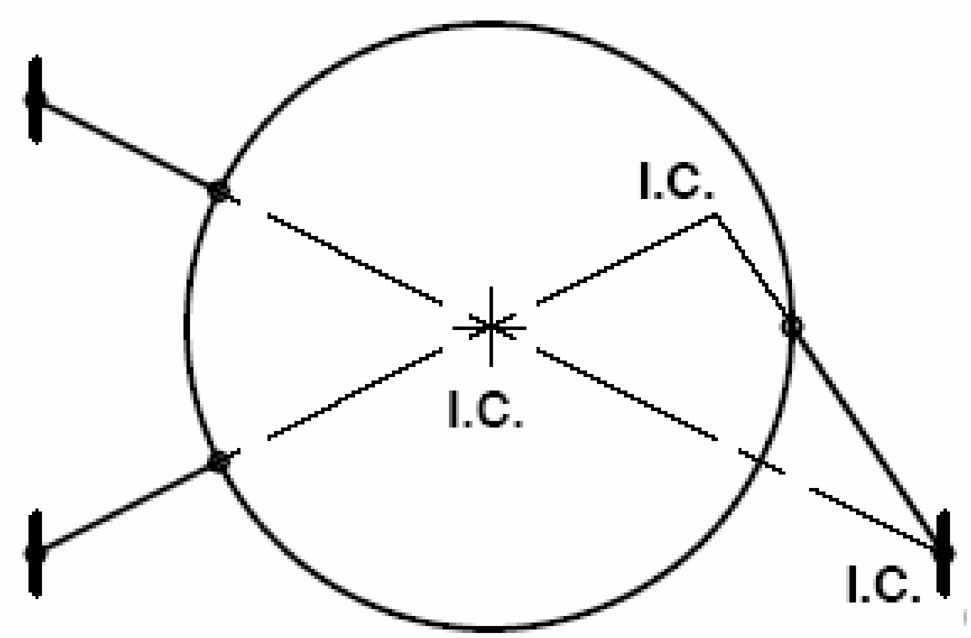
Error due to magnified moment arm



Statements

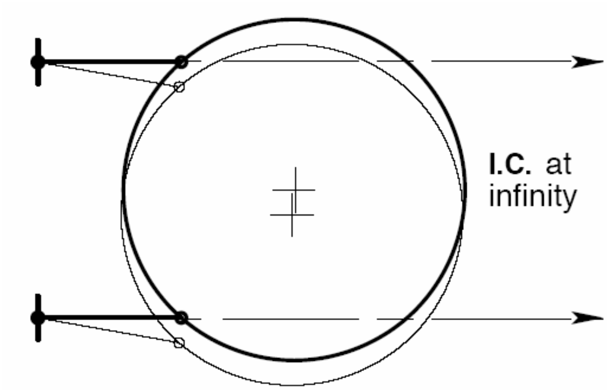
Constraints remove rotational degree of freedom

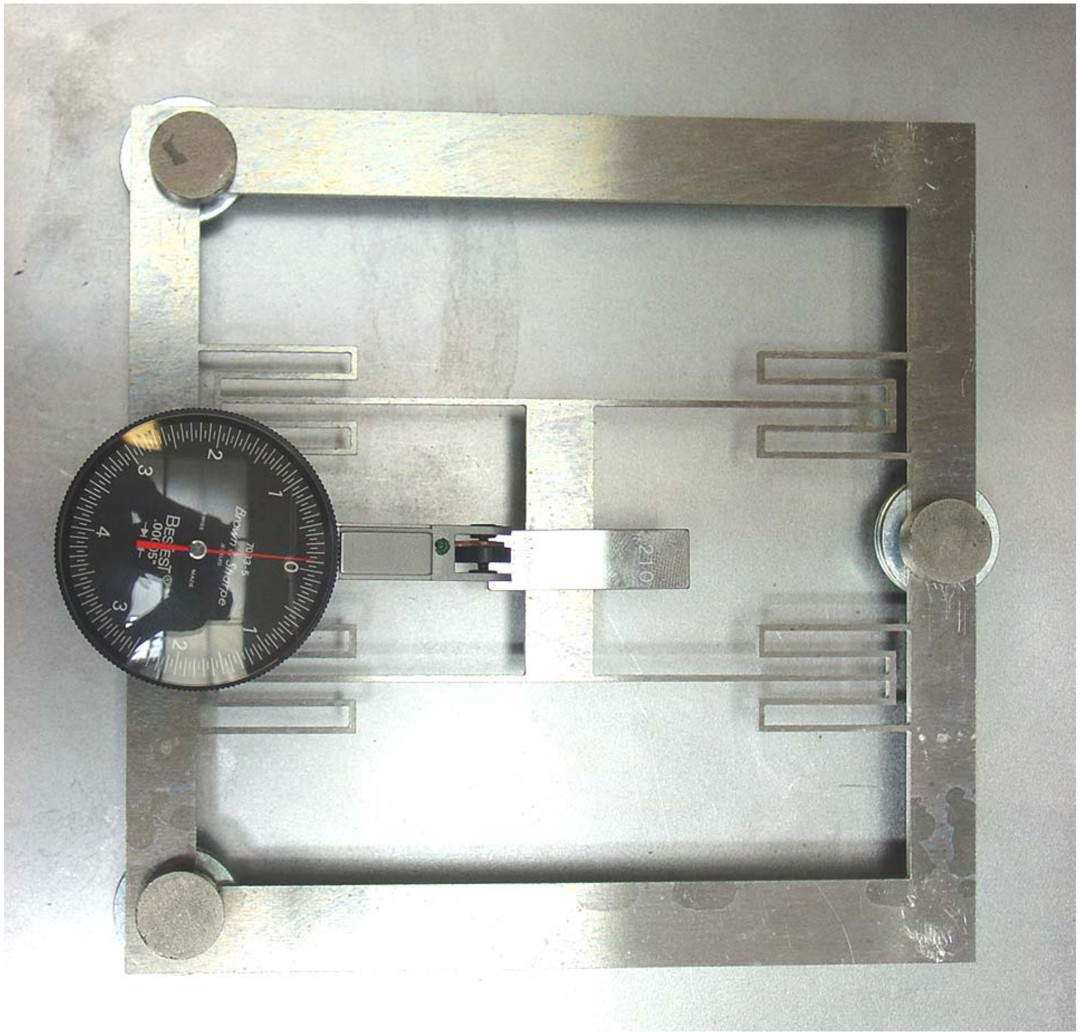
Length of moment arm determines the quality of the rotational constraint



Statements

Parallel constraints may be visualized/treated as intersecting at infinity





Basic elements

Bars

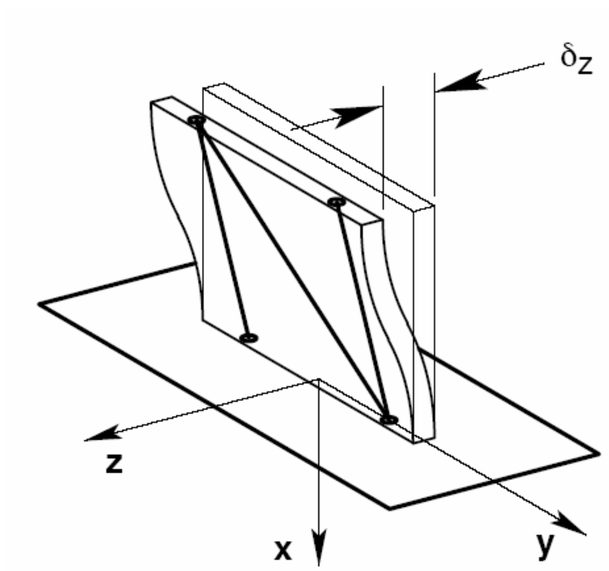
Beams

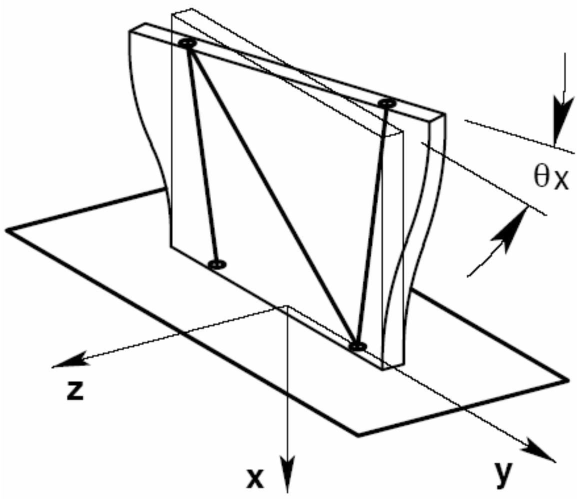
Plates

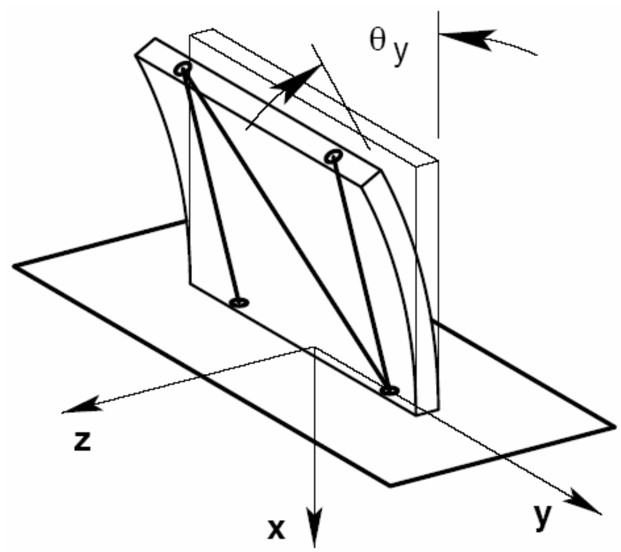
Diagrams removed for copyright reasons.
Source: Blanding, D. L. *Exact Constraint: Machine Design using Kinematic Principles*. New York: ASME Press, 1999.

Notch Hinge

Examples







Do you really get δz?

Figures: Layton Hales PhD Thesis, MIT.

Examples

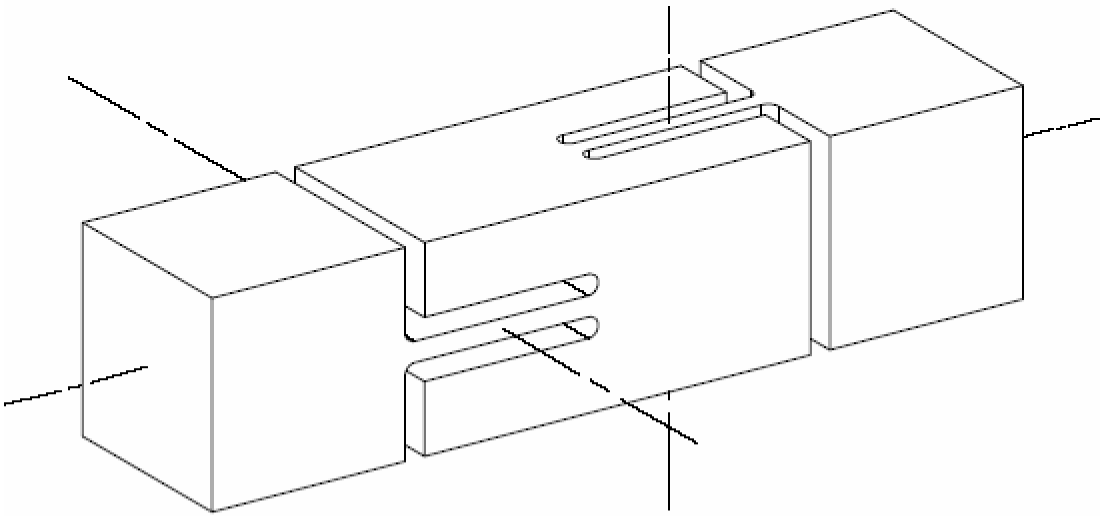


Figure: Layton Hales PhD Thesis, MIT.

Series: Add DOF

Follow the serial chain

Pick up every DOF

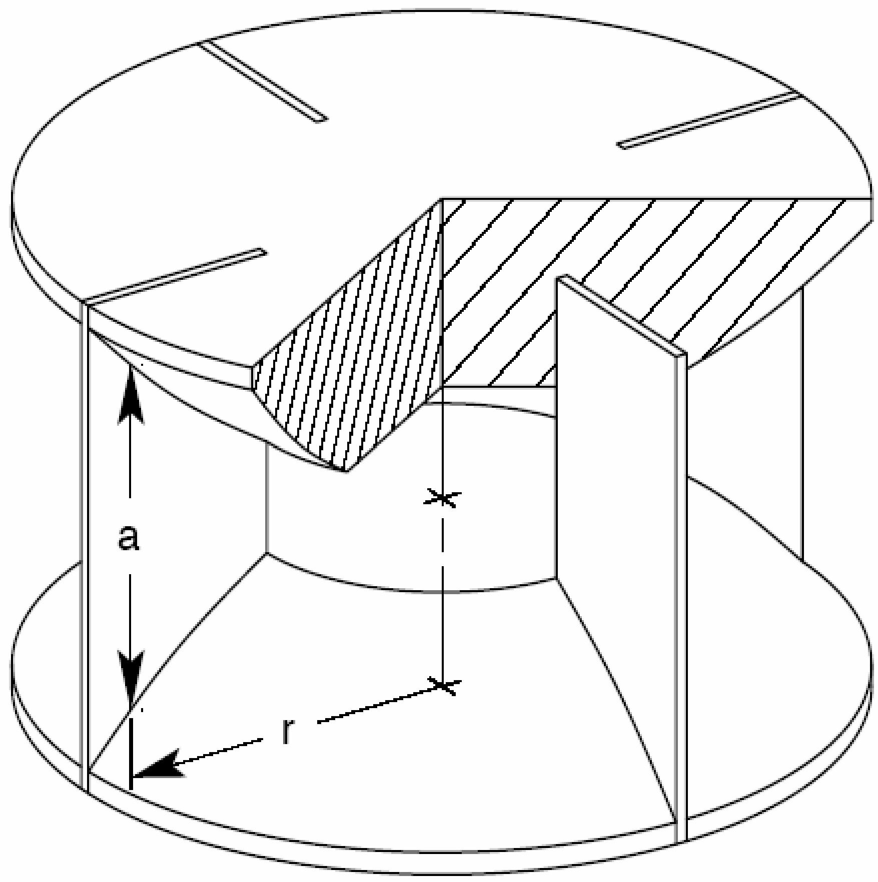
Differentiate series by Load path

Shared load path = Series

This could be 5 DOF

Depends on blade length

Examples



Parallel: Add Constraints

Where there is a common DOF, then have mechanism DOF

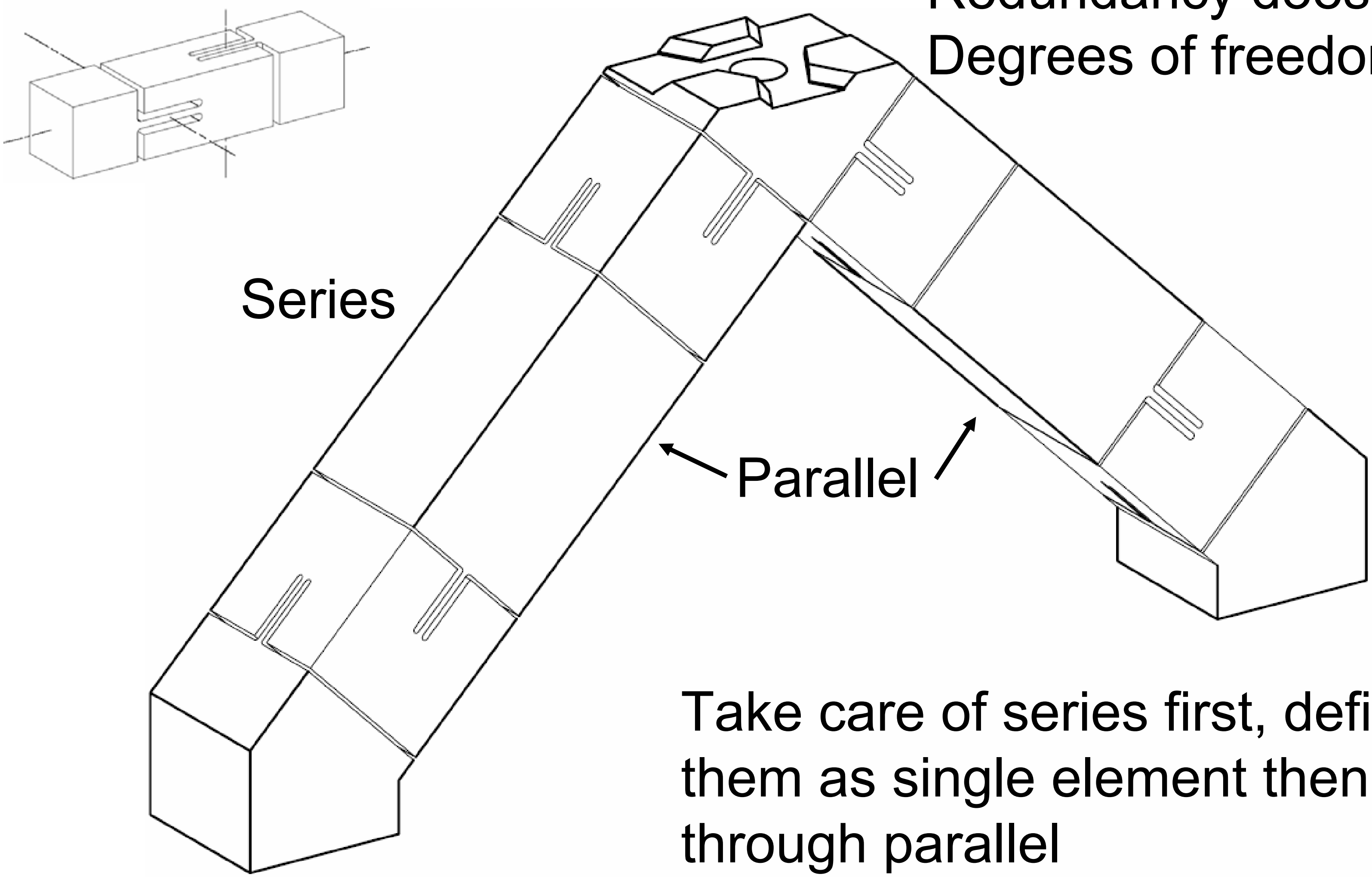
There are no conflicts in circumferential displacement To θz

Non-shared load paths = parallel

Figure: Layton Hales PhD Thesis, MIT.

Examples

Redundancy does not add Degrees of freedom

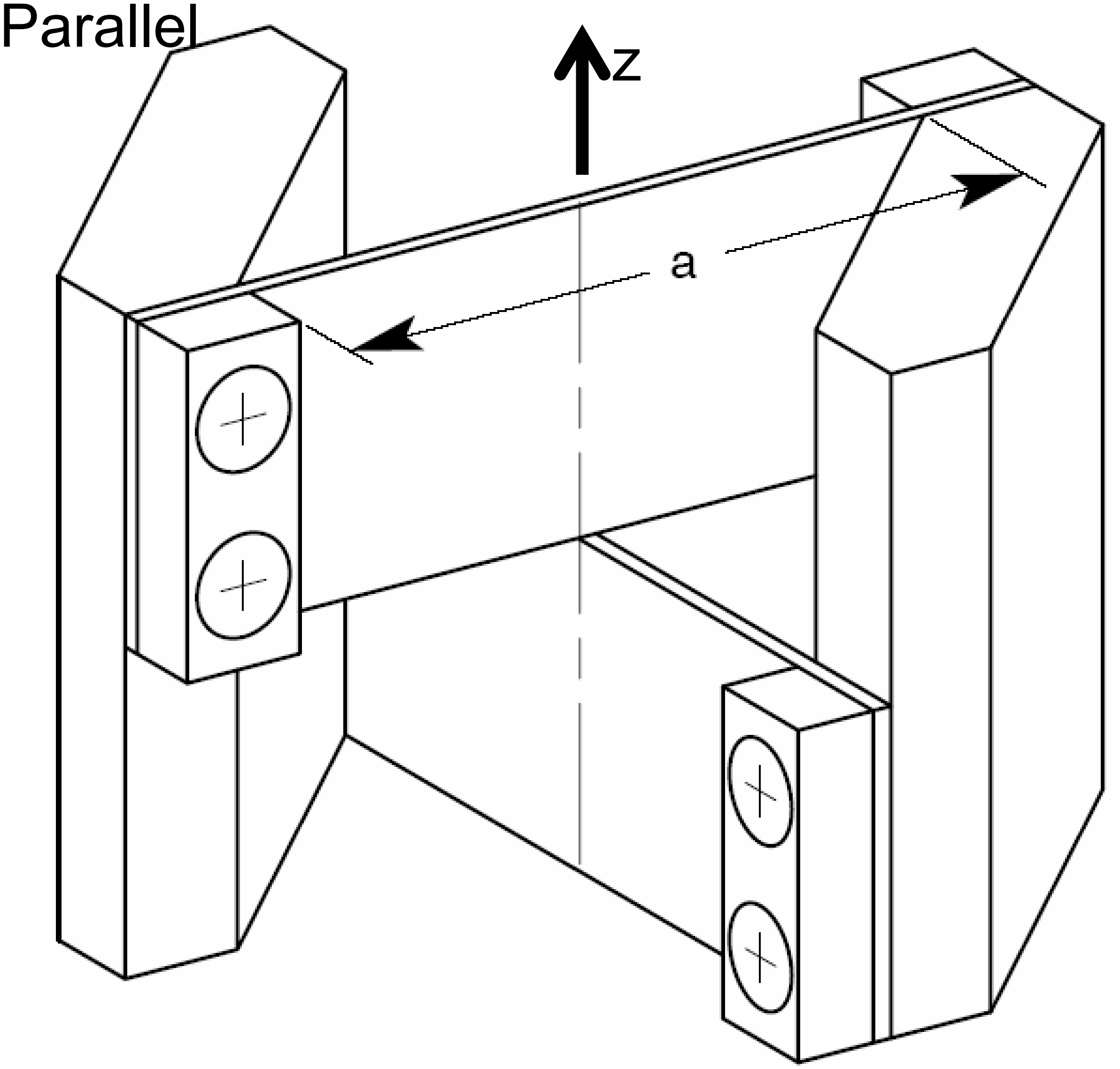


Take care of series first, define them as single element then go through parallel

Figure: Layton Hales PhD Thesis, MIT.

Examples

Parallel



Theta z is a common Degree of freedom

All others conflict

Figure: Layton Hales PhD Thesis, MIT.

Examples

Parallel

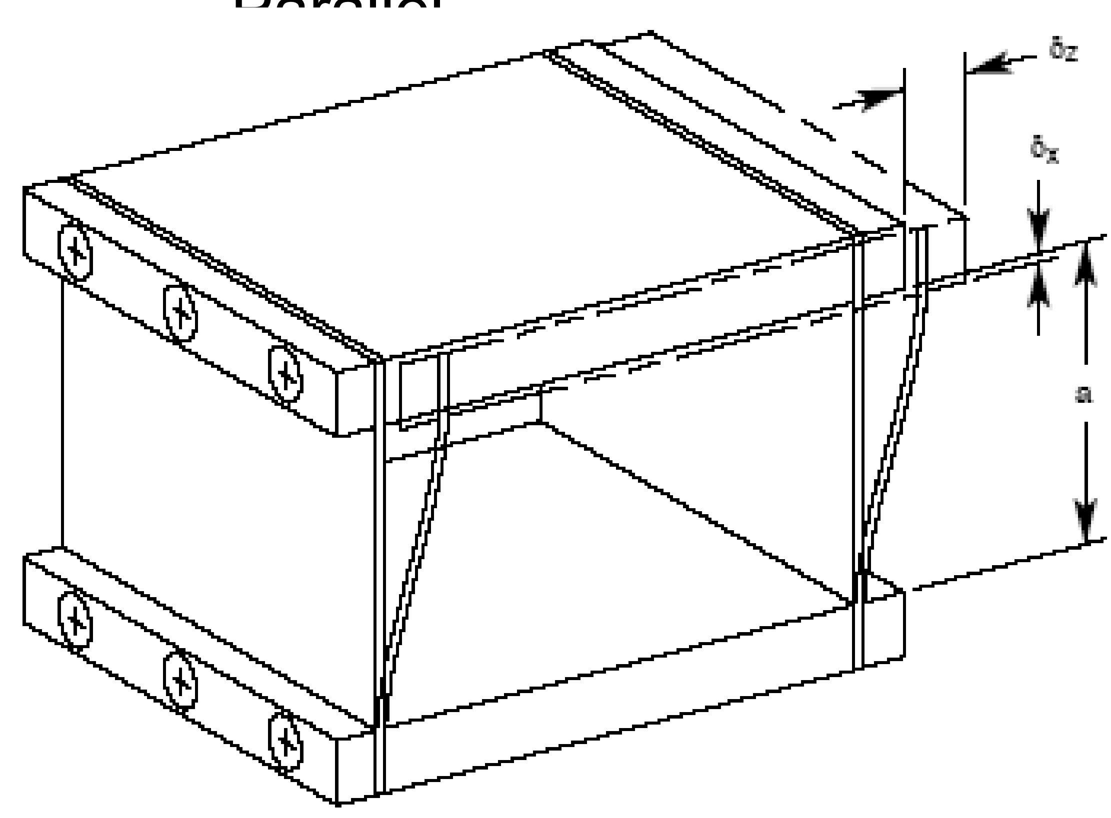


Figure: Layton Hales PhD Thesis, MIT.

δz is a common
Degree of freedom

All others conflict

Rotation arms cause
Conflict in out-of-plane
rotations

Over constraint

Flexures are often forgiving of over constraint

Over constraint = redundant constraint

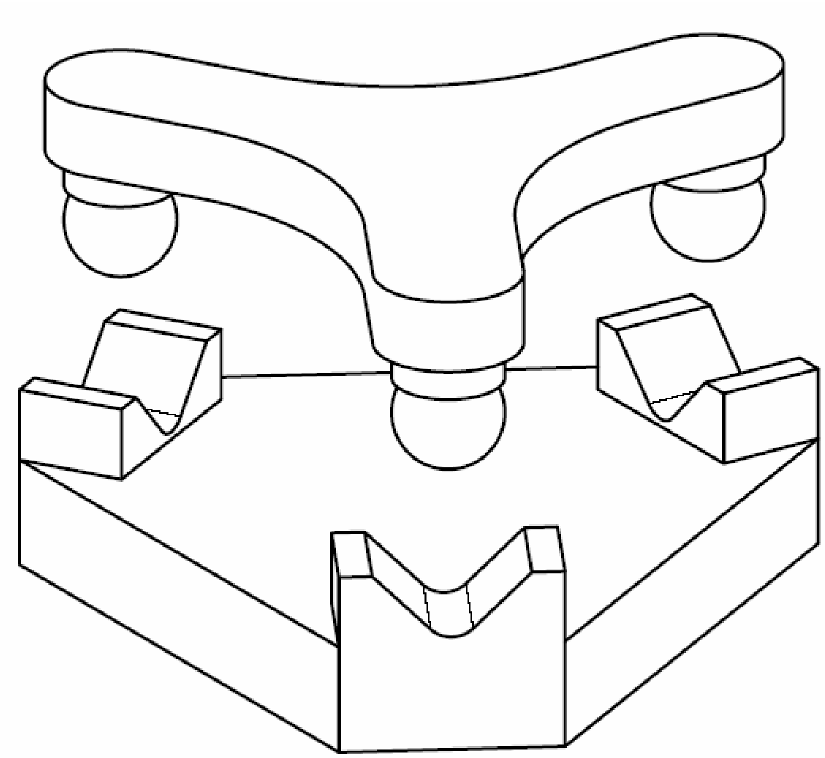
Identifying over constraint

- How much energy is stored?

General metric relating constraint stiffness to motion along constraint

$$\frac{K_{\parallel}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\parallel}} \rightarrow CM_k \cdot CM_{\delta} << 1$$

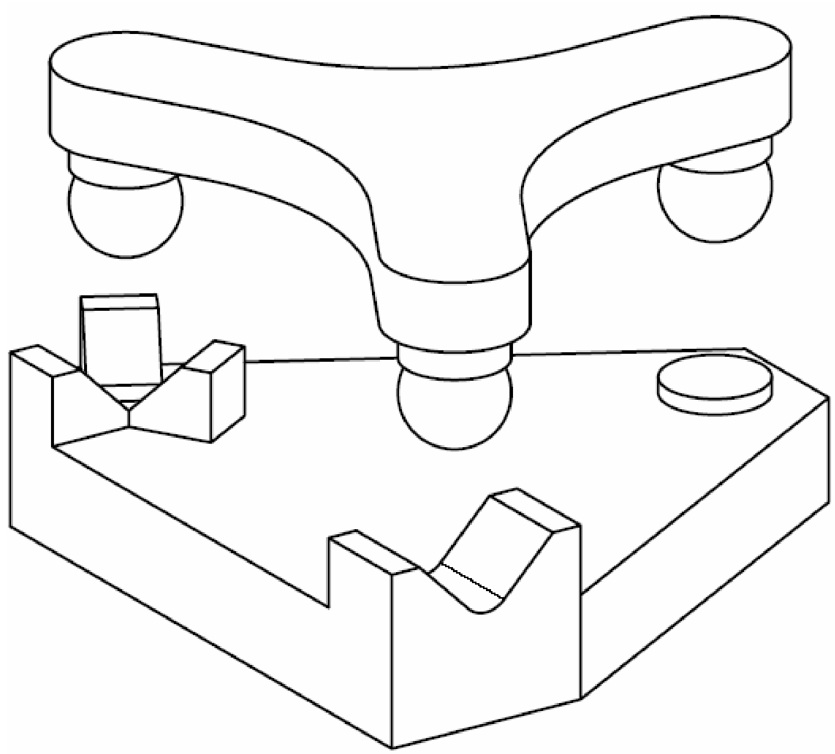
Extension: Fixtures



Maxwell

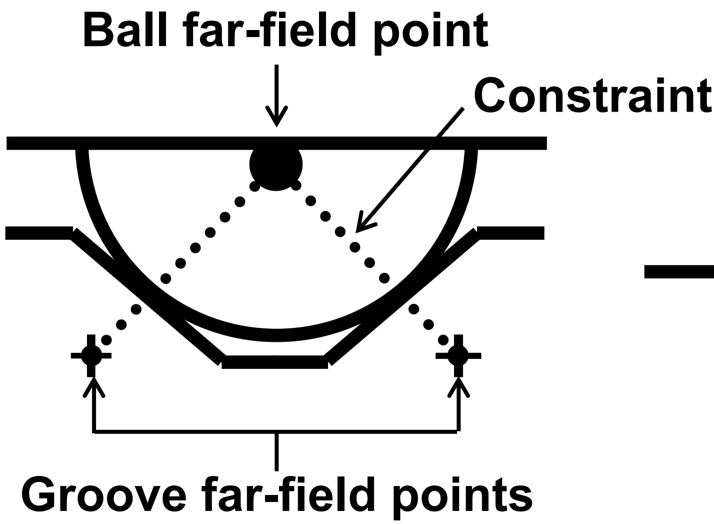
You will need to build a Passive fixture for your STM

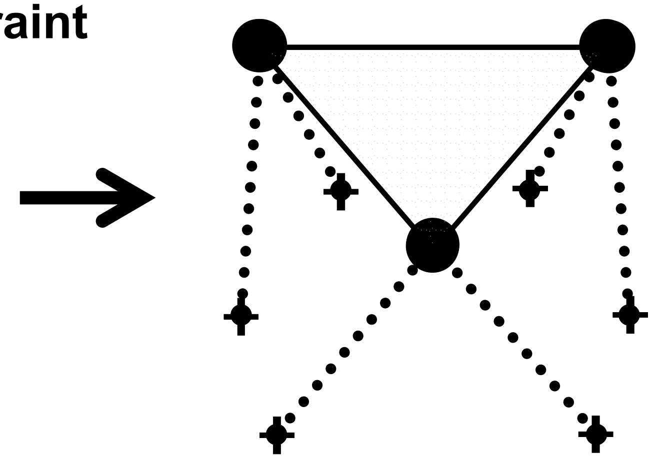
Kelvin



Figures: Layton Hales PhD Thesis, MIT.

Fixtures as mechanisms





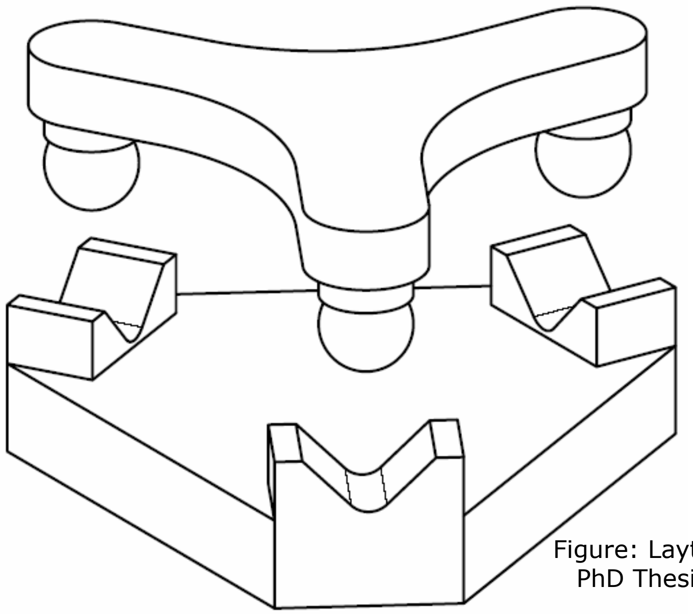


Figure: Layton Hales
PhD Thesis, MIT.

Details of QKC element geometry

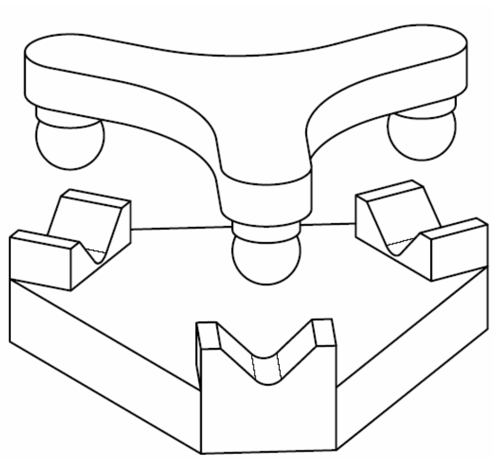
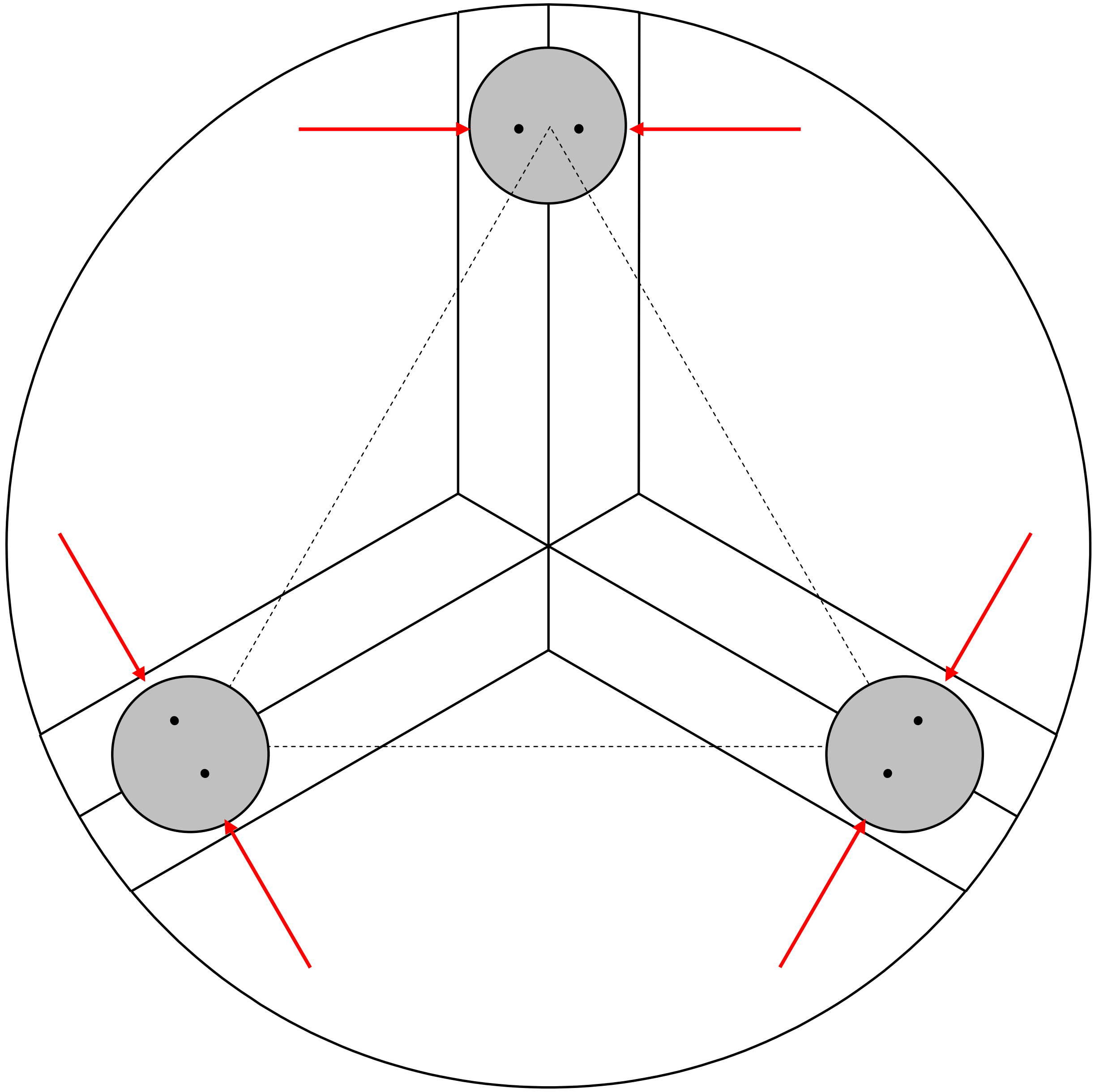
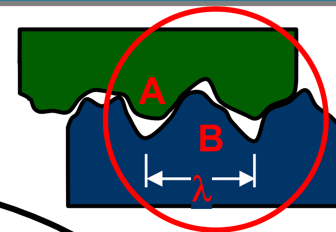


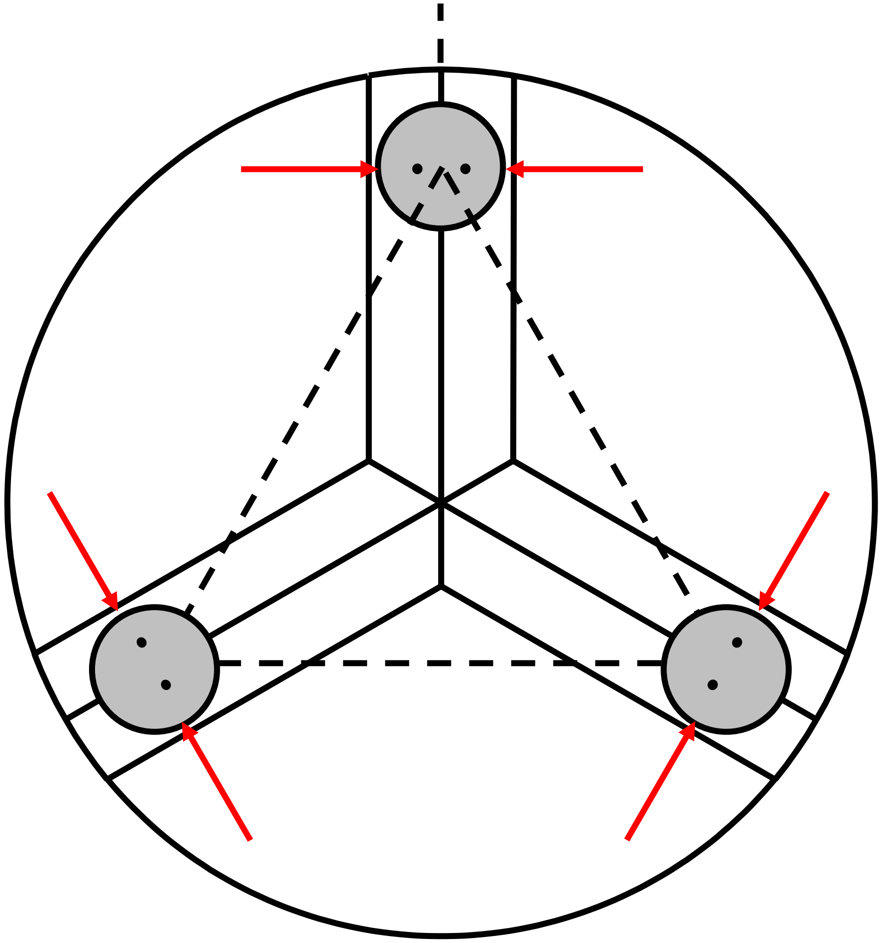
Figure: Layton Hales
PhD Thesis, MIT.



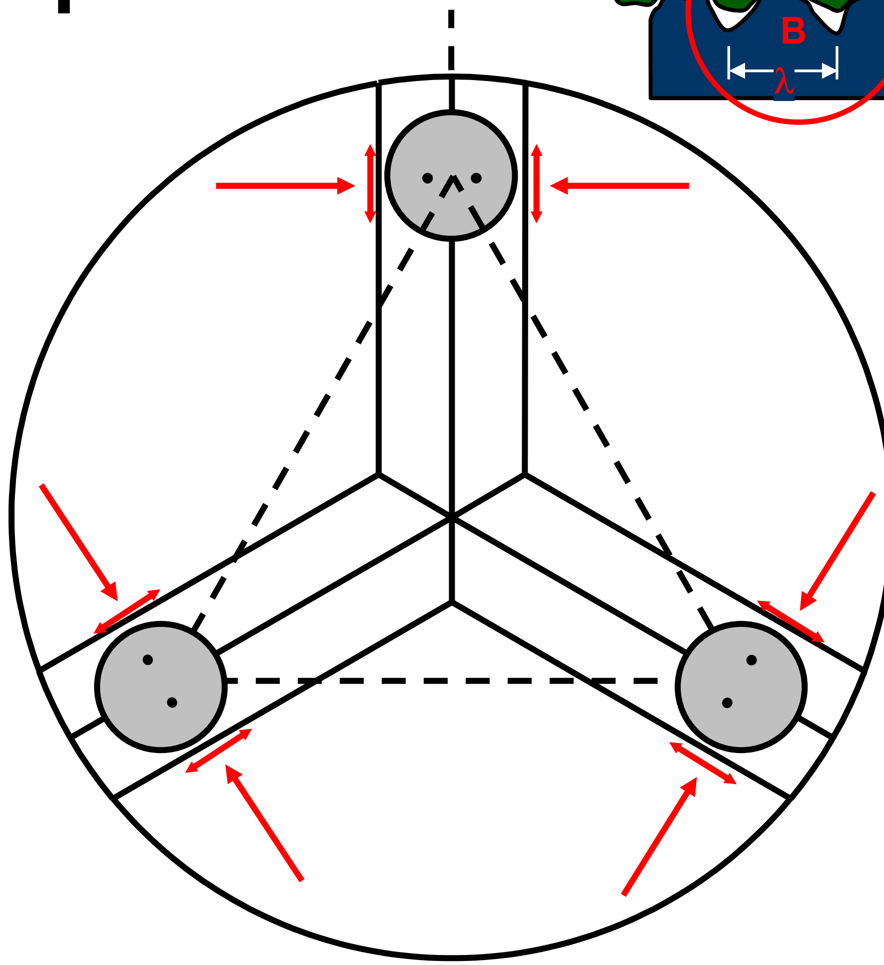
Consequences of friction

Are kinematic couplings perfect?





Ideal in-plane constraints

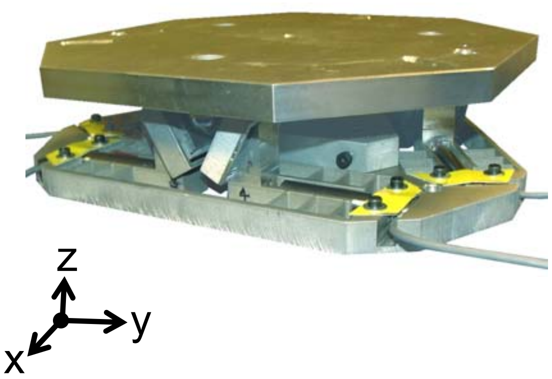


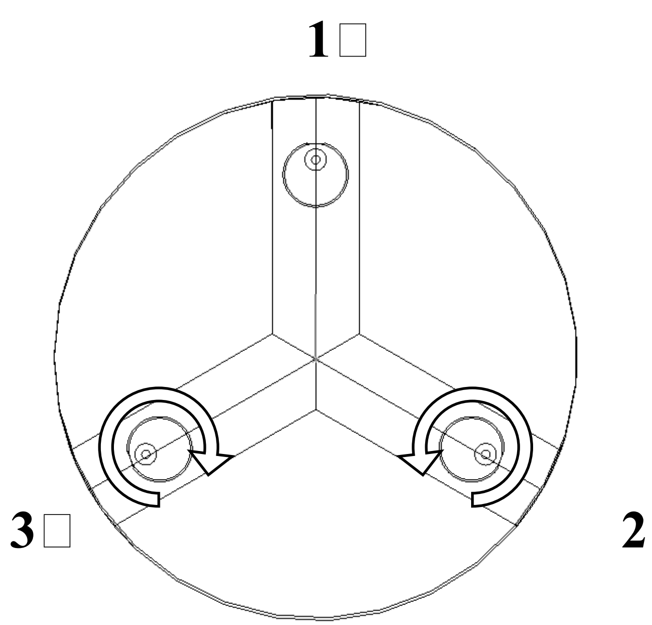
Real in-plane constraints

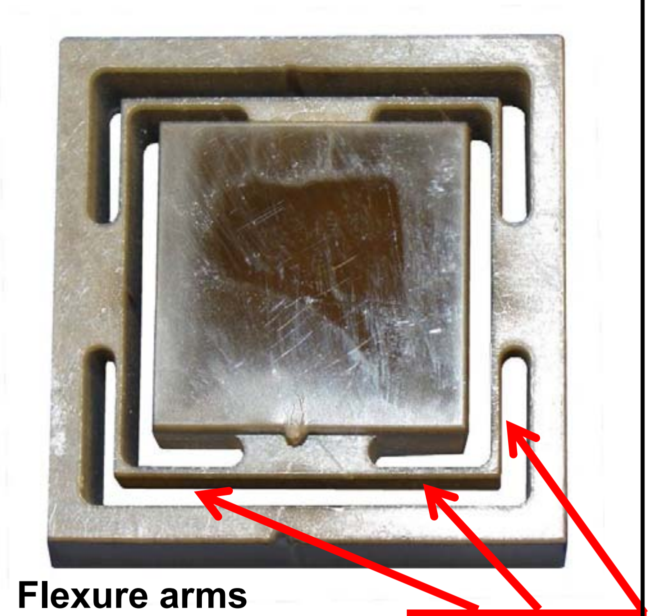
Flexure grooves reduce friction effect

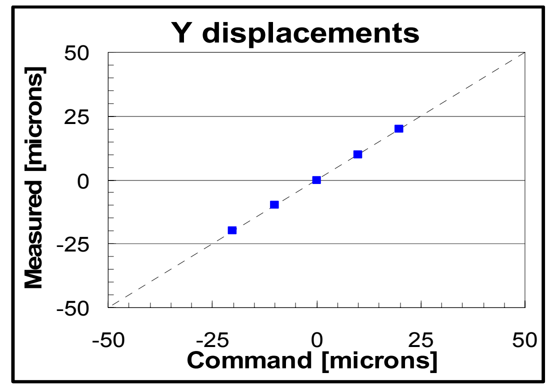
+

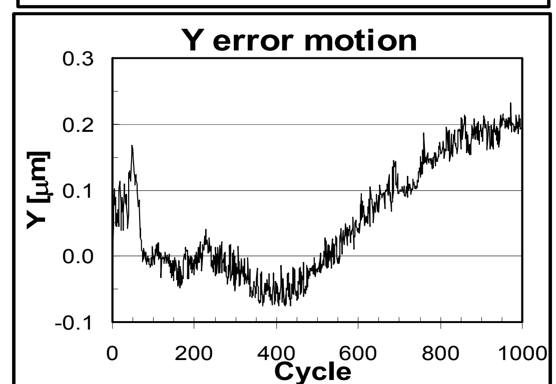
=



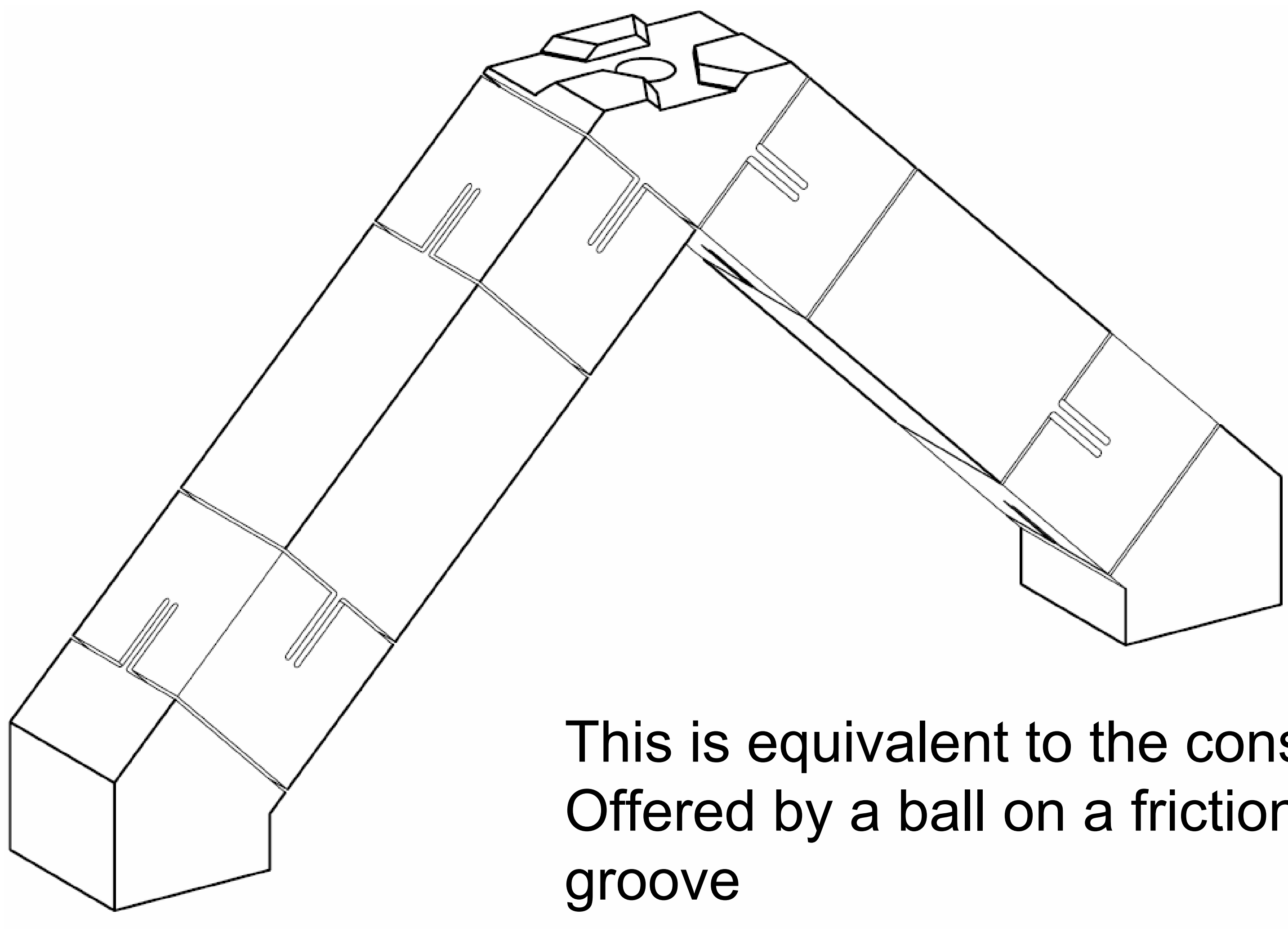








Orrr....



This is equivalent to the constraint
Offered by a ball on a frictionless
groove

Figure: Layton Hales PhD Thesis, MIT.

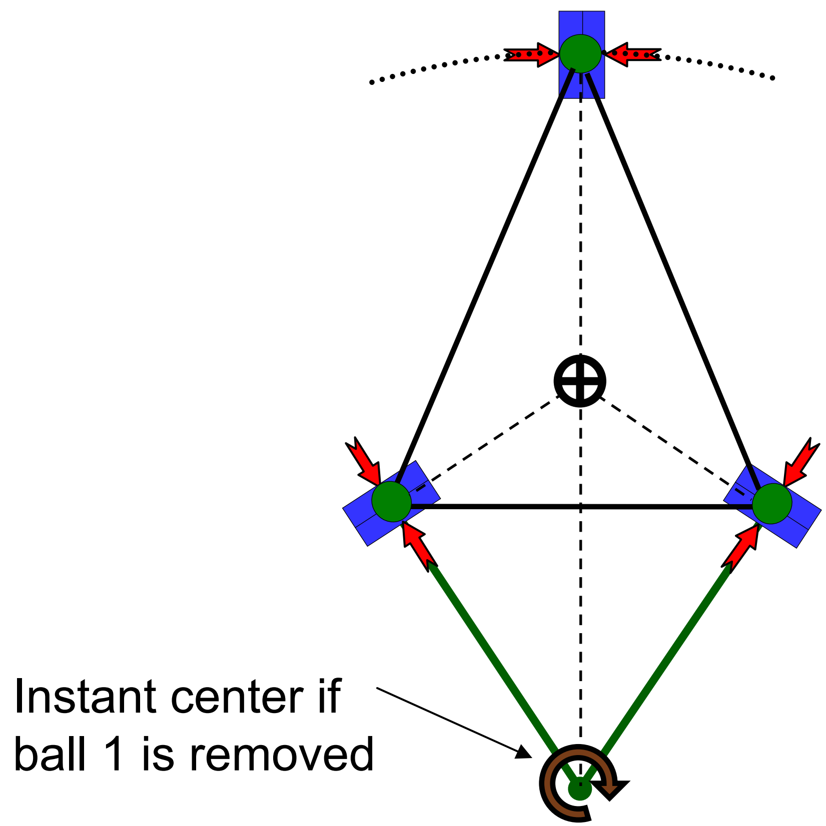
Instant center visualization example

Instant center can help you identify how to best constrain or free up a mechanism

$$\frac{K_{\parallel}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\parallel}} \rightarrow CM_{k} \cdot CM_{\delta} << 1$$

Diagram removed for copyright reasons.
Source: Alex Slocum, *Precision Machine Design*.

Poor **Good**



Examples

Is it a wise idea to put three balls in three cones while the balls are rigidly attached to a rigid part?

$$\frac{K_{\|}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\|}} \rightarrow CM_{k} \cdot CM_{\delta} << 1$$

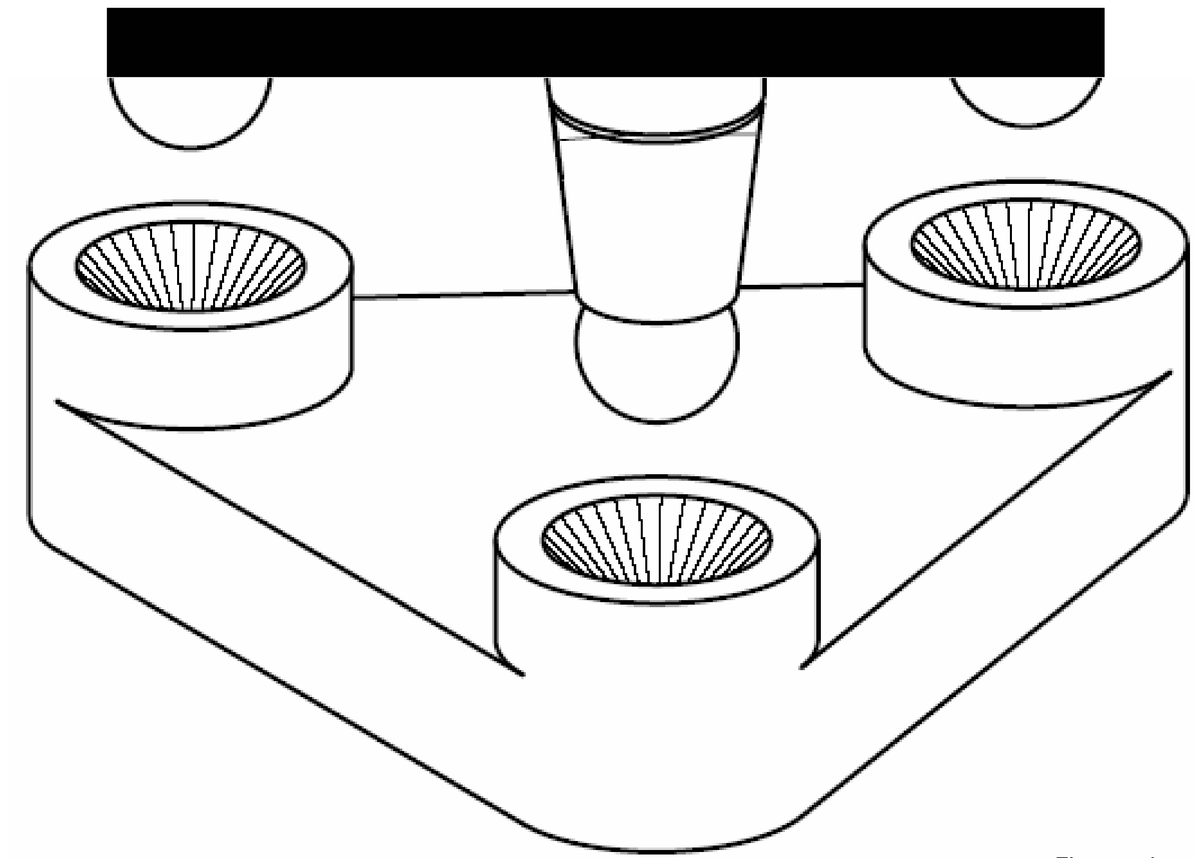
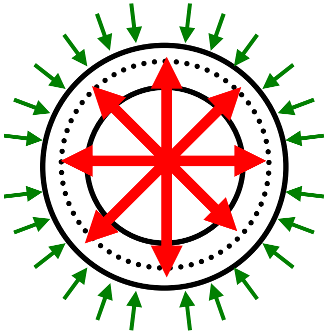


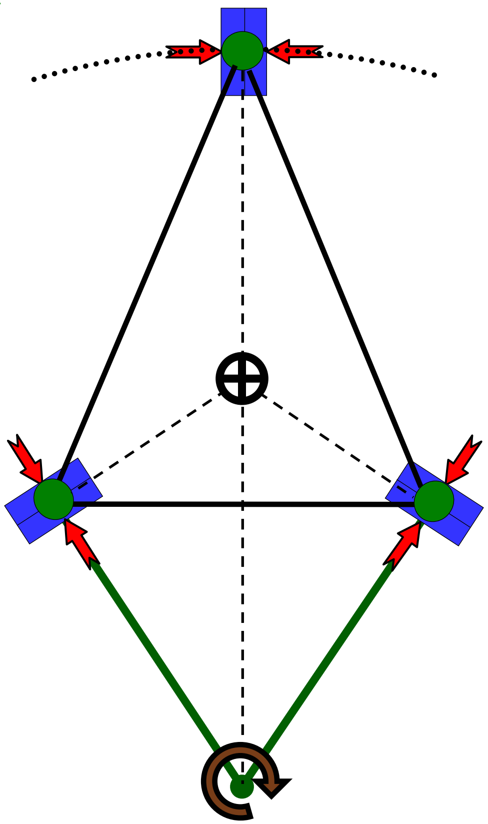
Figure: Layton Hales PhD Thesis, MIT.

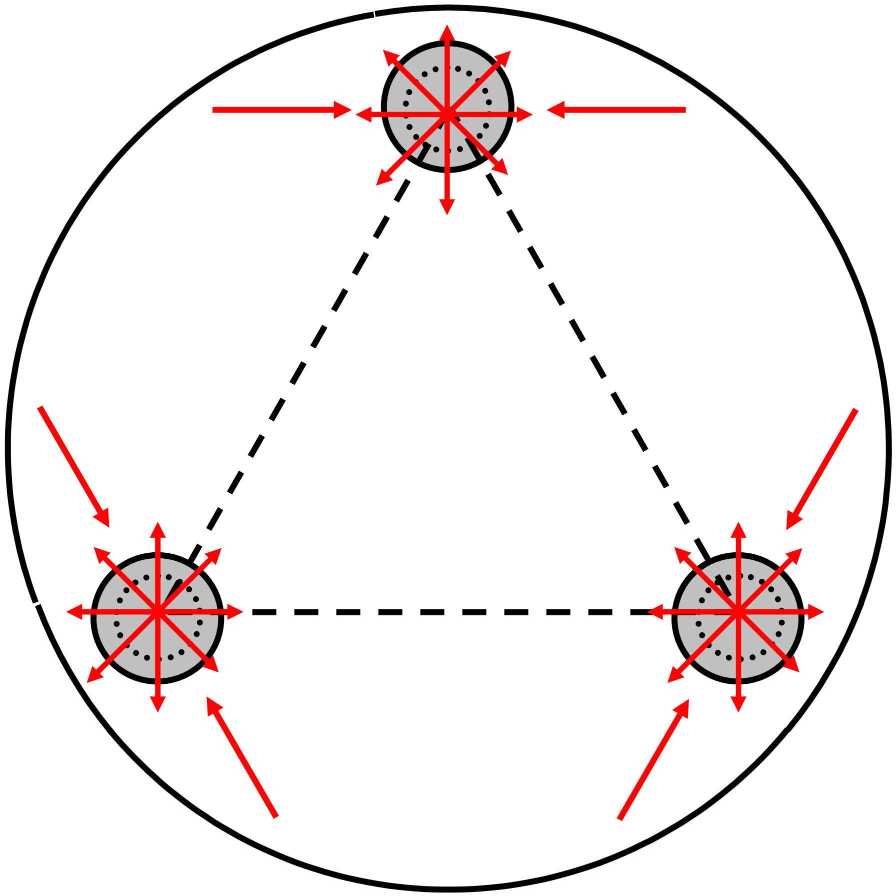
In-plane use of flexures

Three balls in three cones

What does the constraint diagram look like?







Use of flexures to avoid over constraint

Flexures provide a very low CM for each joint

- Energy stored due to over constraint is minimized
- Energy is channeled through continuously variable
- Is possible to reach a true minimum

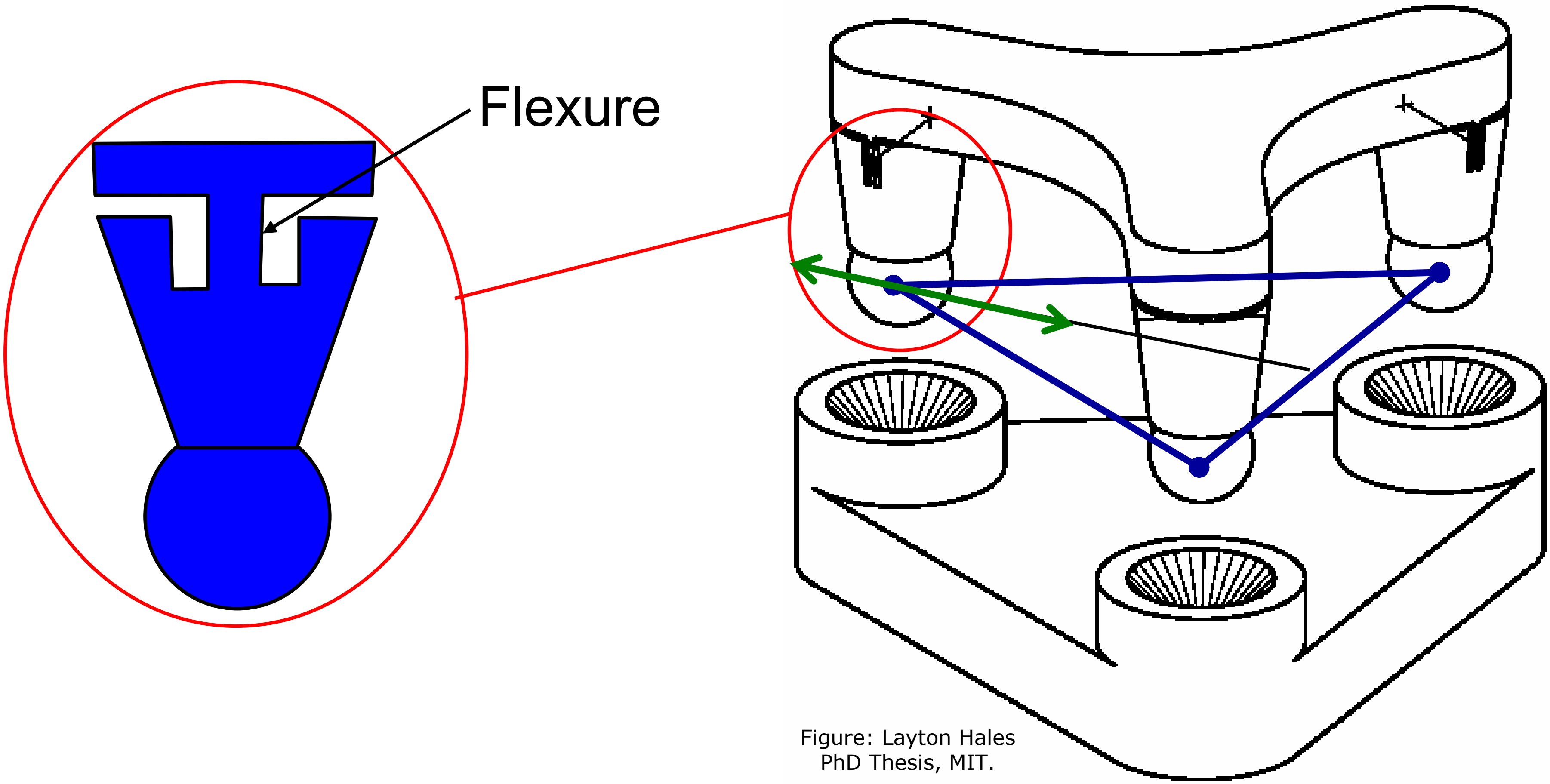
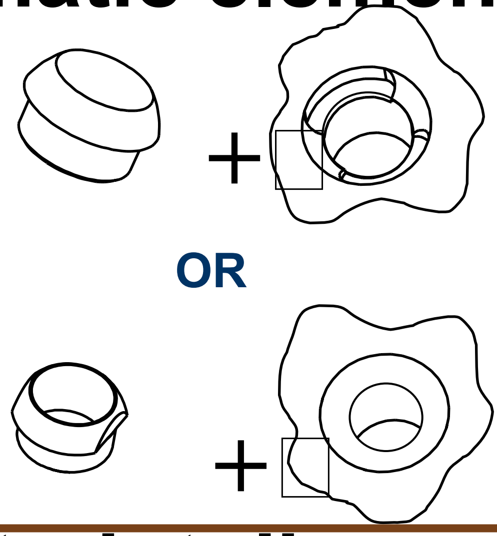


Figure: Layton Hales
PhD Thesis, MIT.

Low-cost couplings

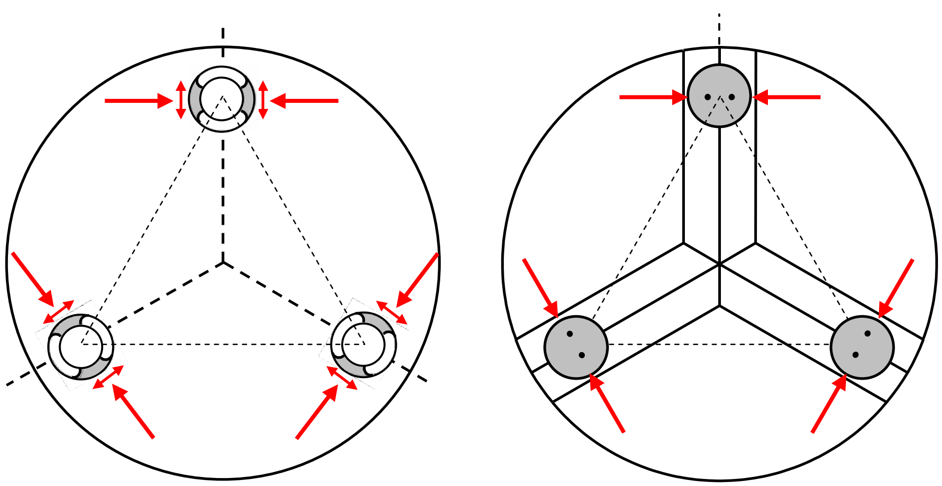
Kinematic elements



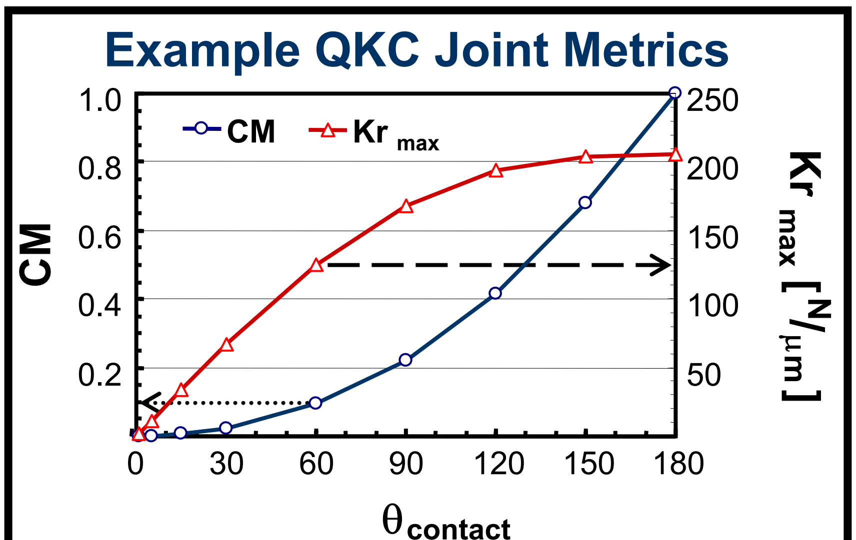
Manufacturing

Diagrams removed for copyright reasons.
"Cast + Form Tool = Finished"

Constraint diagrams



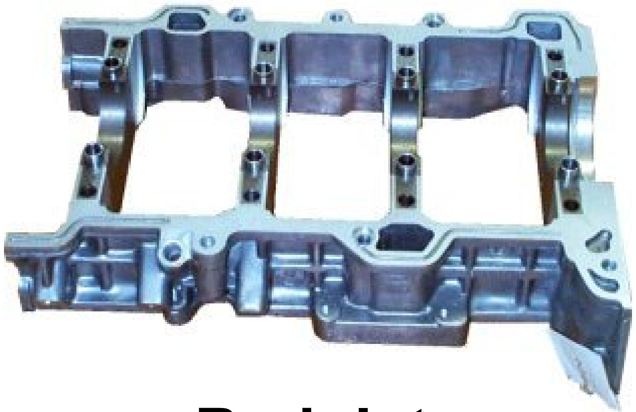
Metrics



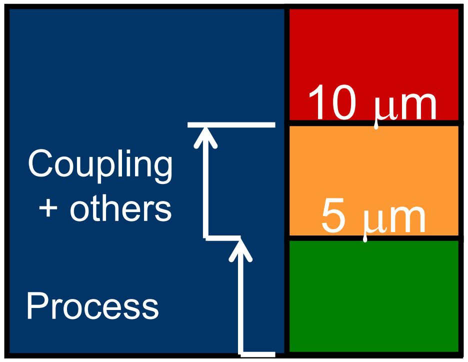
Case study: Duratec engine

Components

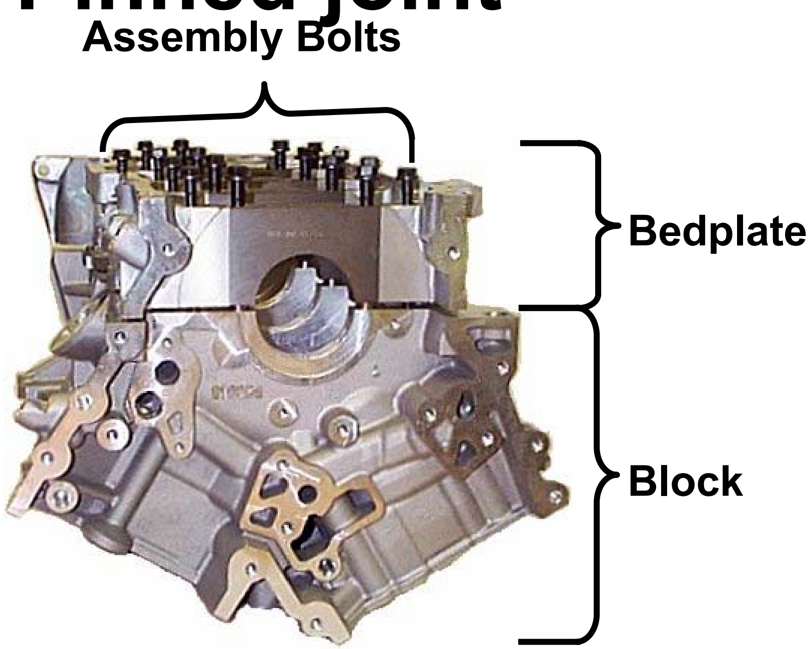
Block



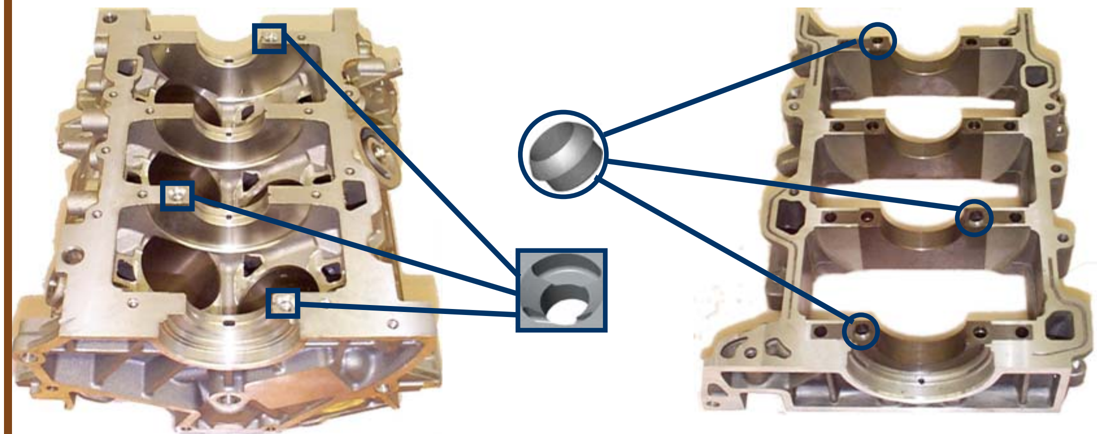
Bedplate



Pinned joint



QKC



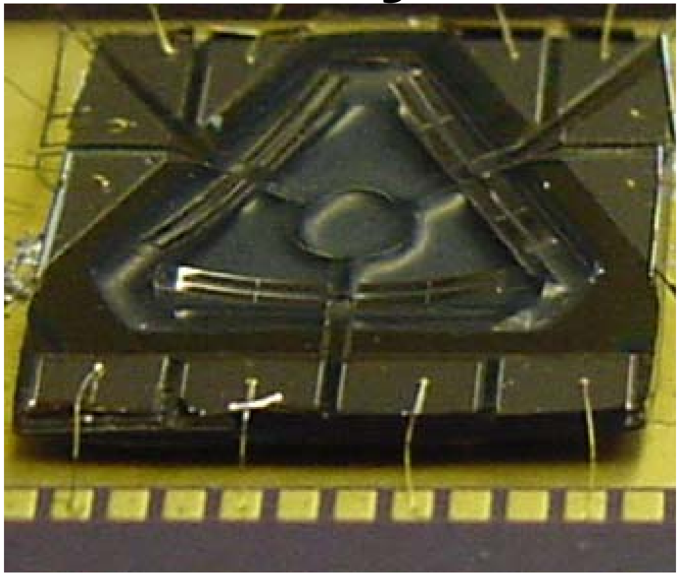
Micro-scale systems

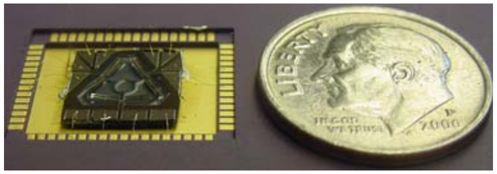
Micro-scale MuSS main challenges

Fabrication is fundamentally different

- ❑ Chemical
- ❑ Molecular
- ❑ Ballistic

- ❑ Finished geometry
- ❑ Possible geometries



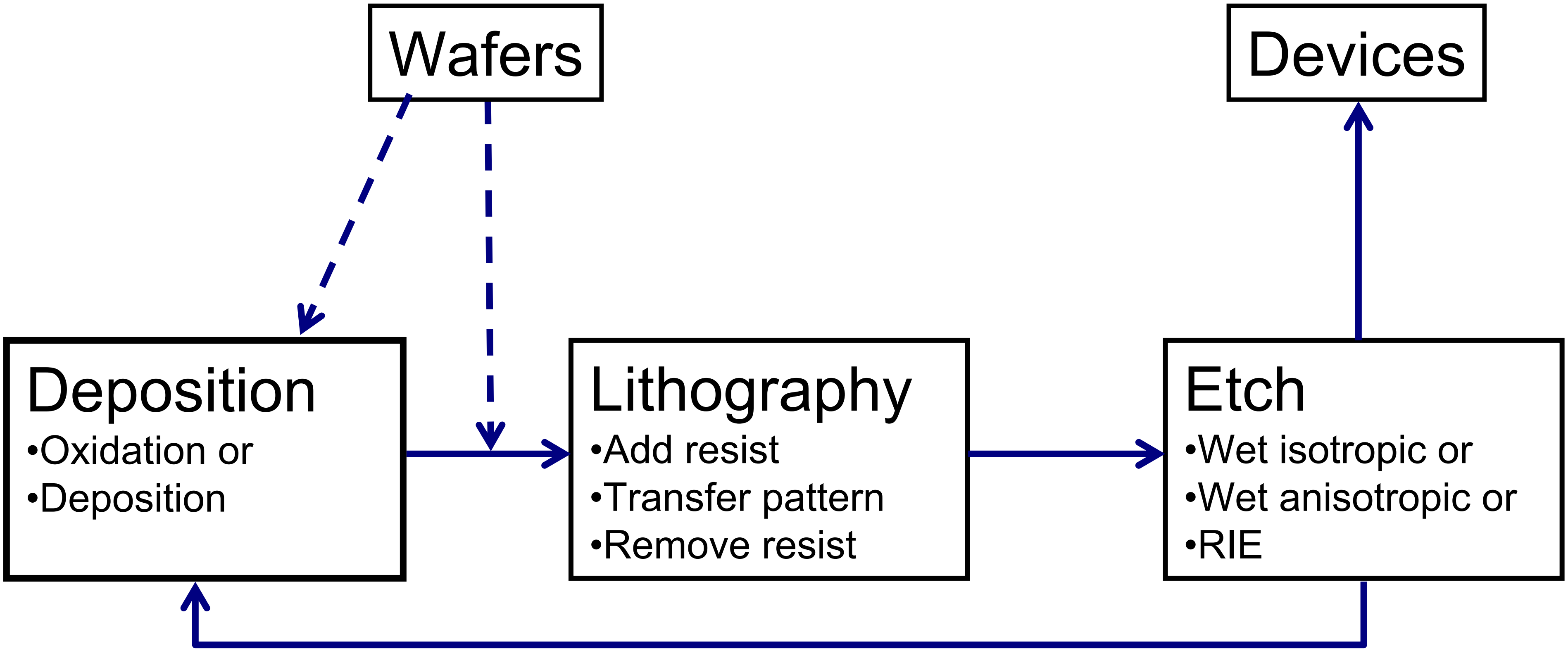


Physics “rounding” is no longer acceptable

- ❑ Surface forces
- ❑ Thermal time constants
- ❑ Strains

Micro-fabrication video

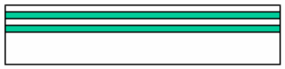
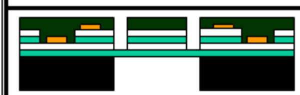
General process

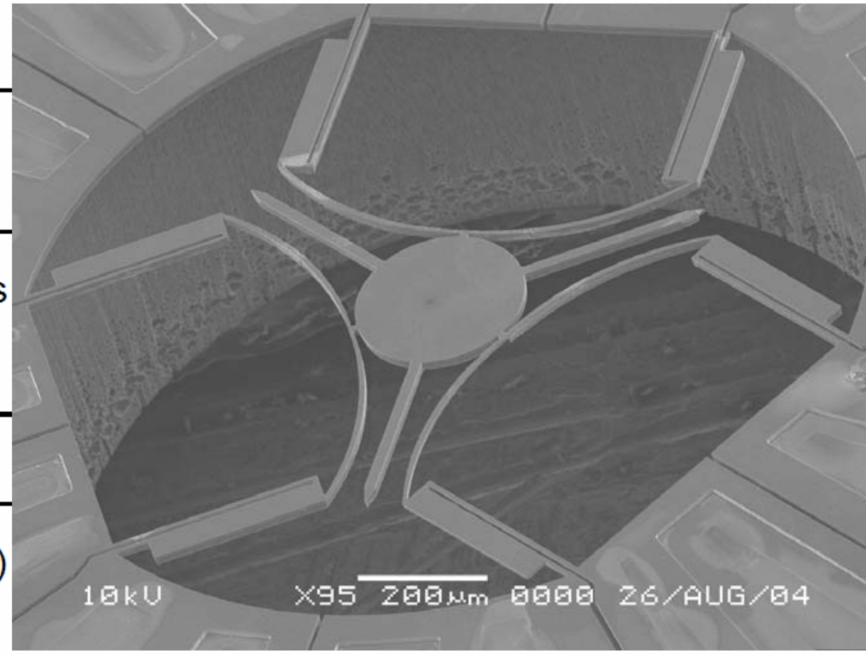


Bulk micromachining = Removal of the wafer

Surface micromachining = Add/remove layers

MiHx fabrication

Step	Recipe/Description
	Double deck SOIOI; Device layers @ 8 microns thickness; Oxide at 1 micron thickness
	Photoresist and pattern
	DRIE (Si) and BOE Oxide
	Pattern AL contacts at 350 nm thickness
	Photoresist and pattern
	DRIE (Si) and BOE Oxide and DRIE (Si)
	Pattern handle wafer; Mount to quartz wafer; DRIE backside etch
	Release with vapor HF
	Remove resist via plasma etch



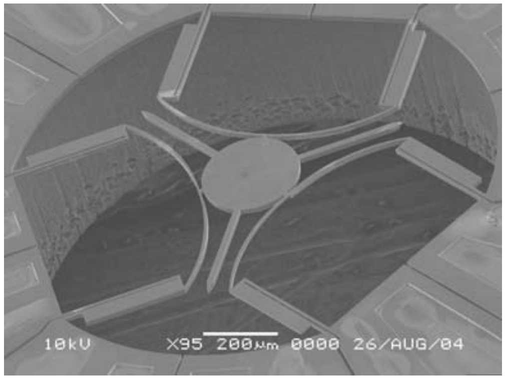
Micro-scale physics

For strong dependence on characteristic length, importance of phenomena decreases with characteristic dimension

- Gravity L^3
- Inertia L^3

For weaker dependence on characteristic length, phenomena become dominate at small scale

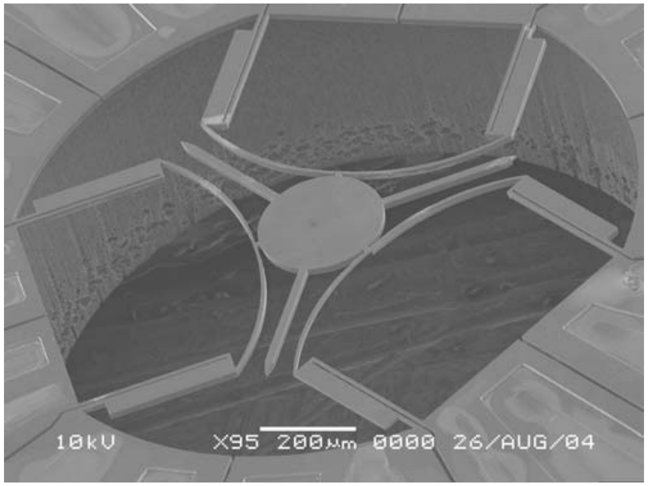
- Electrostatic L^2
- Surface tension L^2
- Thermal L

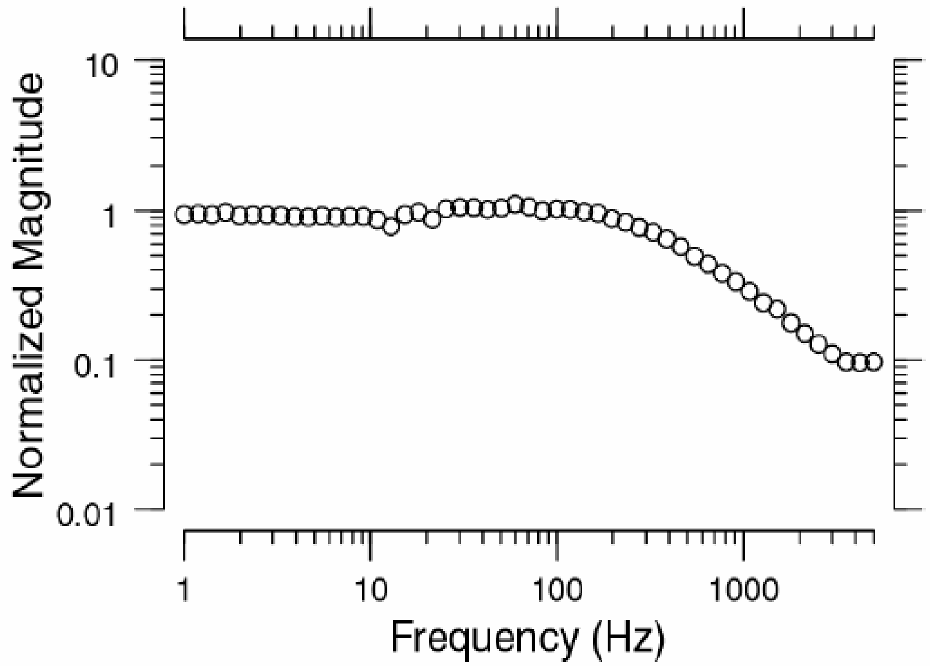


Thermal physics

Ratio of surface area to volume increases

Where does this help?





Where does this hurt?

Assignment

Design a mechanical filter system (may be more than one flexure which is capable of reducing actuator input by a factor of 100. The reduction is called the transmission ratio = output/input

Design constraints

- ❑ 5 x 5 envelope
- ❑ ¼ inch thick
- ❑ Flexures should be movable by hand
- ❑ Stress less than 20% of yield stress
- ❑ Actuator range = 0 – 150 microns
- ❑ Actuator resolution = 10 nanometers