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

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

Metrology/measurement issues

Actuator angular misalignment on parasitic error

Effectiveness of constraint between actuator-flexure
Purpose of today

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

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

Figure: Layton Hales PhD Thesis, MIT.
Points on a constraint line move perpendicular to the constraint line

Constraints along this line are equivalent

Figure: Layton Hales PhD Thesis, MIT.

Diagrams removed for copyright reasons.
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
Parallel constraints may be visualized/treated as intersecting at infinity
Basic elements

Bars

Beams

Plates

Notch Hinge

Diagrams removed for copyright reasons.
Examples

Do you really get $\delta z$?

Figures: Layton Hales PhD Thesis, MIT.
Examples

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

Figure: Layton Hales PhD Thesis, MIT.
Parallel: Add Constraints

Where there is a common DOF, then have mechanism DOF

There are no conflicts in circumferential displacement To $\theta z$

Non-shared load paths = parallel

Figure: Layton Hales PhD Thesis, MIT.
Examples

Redundancy does not add Degrees of freedom

Series

Parallel

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

Figure: Layton Hales PhD Thesis, MIT.
Examples

Theta $z$ is a common Degree of freedom

All others conflict

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

Figure: Layton Hales PhD Thesis, MIT.
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

\[
\frac{K_{\parallel}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\parallel}} \rightarrow CM_k \cdot CM_\delta \ll 1
\]
Extension: Fixtures

You will need to build a Passive fixture for your STM

Maxwell

Kelvin

Figures: Layton Hales PhD Thesis, MIT.
Fixtures as mechanisms

- Ball far-field point
- Groove far-field points
- Constraint

Figure: Layton Hales
PhD Thesis, MIT.
Details of QKC element geometry

Figure: Layton Hales PhD Thesis, MIT.

2.76 Multi-scale System Design & Manufacturing
Consequences of friction

Are kinematic couplings perfect?

Ideal in-plane constraints

Real in-plane constraints
Flexure grooves reduce friction effect

1. Flexure arms

2. Flexure arm details

3. Flexure arm assembly

4. Y displacements graph

5. Y error motion graph
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

\[
\frac{K_\parallel}{K_\perp} \cdot \frac{\delta_\perp}{\delta_\parallel} \rightarrow CM_k \cdot CM_\delta \ll 1
\]

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

Poor □   Good □

Instant center if ball 1 is removed
Examples

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

\[
\frac{K_{||}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{||}} \rightarrow CM_{k} \cdot CM_{\delta} \ll 1
\]

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.

2.76 Multi-scale System Design & Manufacturing
Low-cost couplings

Kinematic elements

Manufacturing

Constraint diagrams

Metrics

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

Example QKC Joint Metrics
Case study: Duratec engine

Components

Block

Bedplate

Pinned joint
Assembly Bolts

Bedplate

Block

QKC

Photos by Prof. Martin Culpepper, courtesy of Ford Motor Company. Used with permission.
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

- **Deposition**
  - Oxidation or Deposition

- **Lithography**
  - Add resist
  - Transfer pattern
  - Remove resist

- **Etch**
  - Wet isotropic or Wet anisotropic or RIE

Wafers ➔ Devices

Bulk micromachining = Removal of the wafer

Surface micromachining = Add/remove layers
## MiHx fabrication

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