Rapid Efficient Design of Next Generation High Precision Machines
Process Rules for Design

8th Asia Pacific Conference on Optics Manufacture (APCOM2023)
& 3rd International Forum of Young Scientists on Advanced Optical Manufacturing (YSAOM2023)

Alexander H. Slocum
Walter M. May and A. Hazel May Professor of Mechanical Engineering
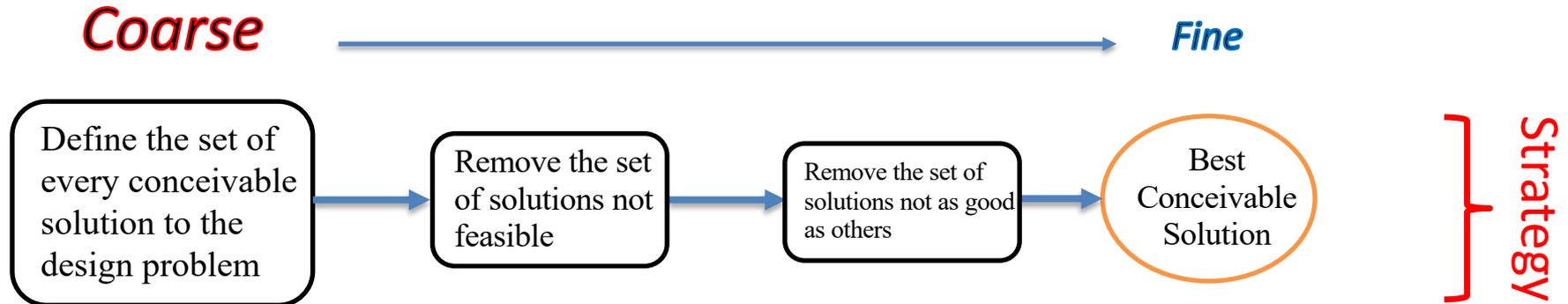Massachusetts Institute of Technology
slocum@mit.edu
http://pergatory.mit.edu
@ahslocum

8/2/23

As I look at presentation titles for this conference, I ask myself:

"What have I learned about precision machine design in the last four decades that is most useful for next generation precsion manufacture of optics?"

2

8/2/23

Deterministic Design = Good Process

Coarse → *Fine*

| Define the set of every conceivable solution to the design problem | → | Remove the set of solutions not feasible | → | Remove the set of solutions not as good as others | → | Best Conceivable Solution |

Strategy

- Broadly encourage all ideas, keep the good and cast out the bad
  - Ideas can be broad (Strategies) or specific (Concepts)
    - *Strategy: a general approach*
      - Move the tool using linear motion axes
    - *Concepts: specific implementations*
      - X axis (left-right motion) + Y axis (in-out motion) + Z axis (up-down motion)
- Use "FRED PARRC" and FUNdaMENTAL principles to generate and compare ideas
- Use PREP process to prevent bias, ensure breadth of thought

Concepts

8/2/23

Deterministic Design Process "Rules"
One for each day of the week!

8/2/23

# Rule 1: Nature Does Not CARE
(*C*reate *A*rbitrary *R*andom *E*xcuses)
so learn FUNdaMENTAL Principles (FPs)

Mechanical FPs
- Occam's Razor
- Newton's Laws
- Conservation of Energy
- Saint-Venant's Principle
- Golden Rectangle
- Abbe's Principle
- Maxwell & Reciprocity
- Self-Principles
- Stability
- Symmetry
- Parallel Axis Theorem
- Accuracy, Repeatability, Resolution
- Sensitive Directions & Reference Features
- Structural Loops
- Preload
- Centers of Action
- Exact Constraint Design
- Elastically Averaged Design
- Stick Figures
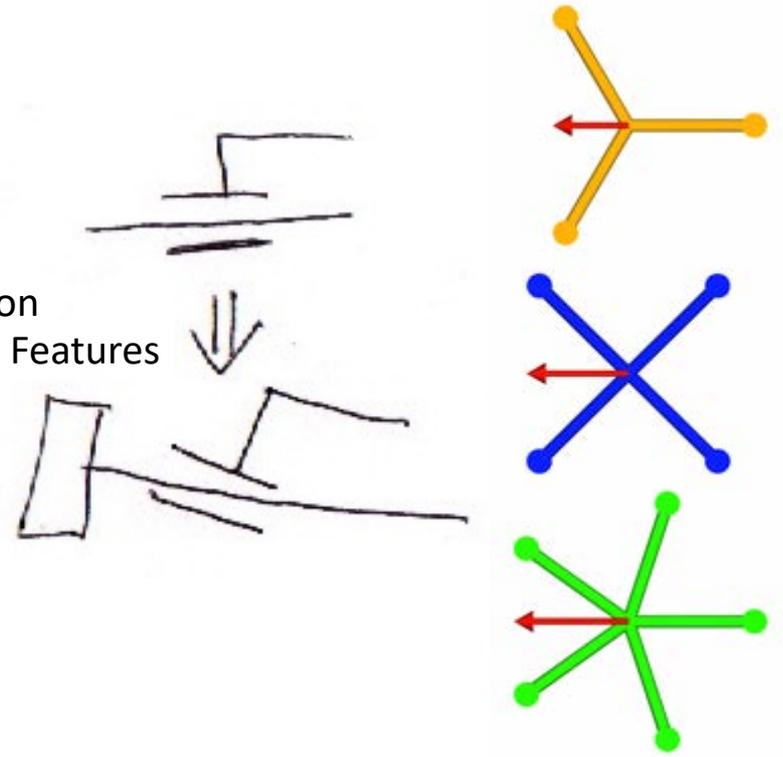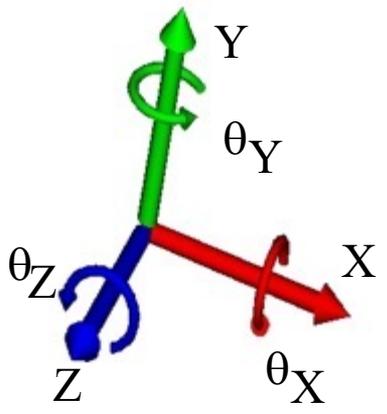
Rule 2: Apply FPs to Deterministic Design Cycle:

Organize thoughts… Be free to *hop* about… Catalyze creativity…

Seven Elements for Creative Realization of Engaged Thinking for Success (SECRETS)
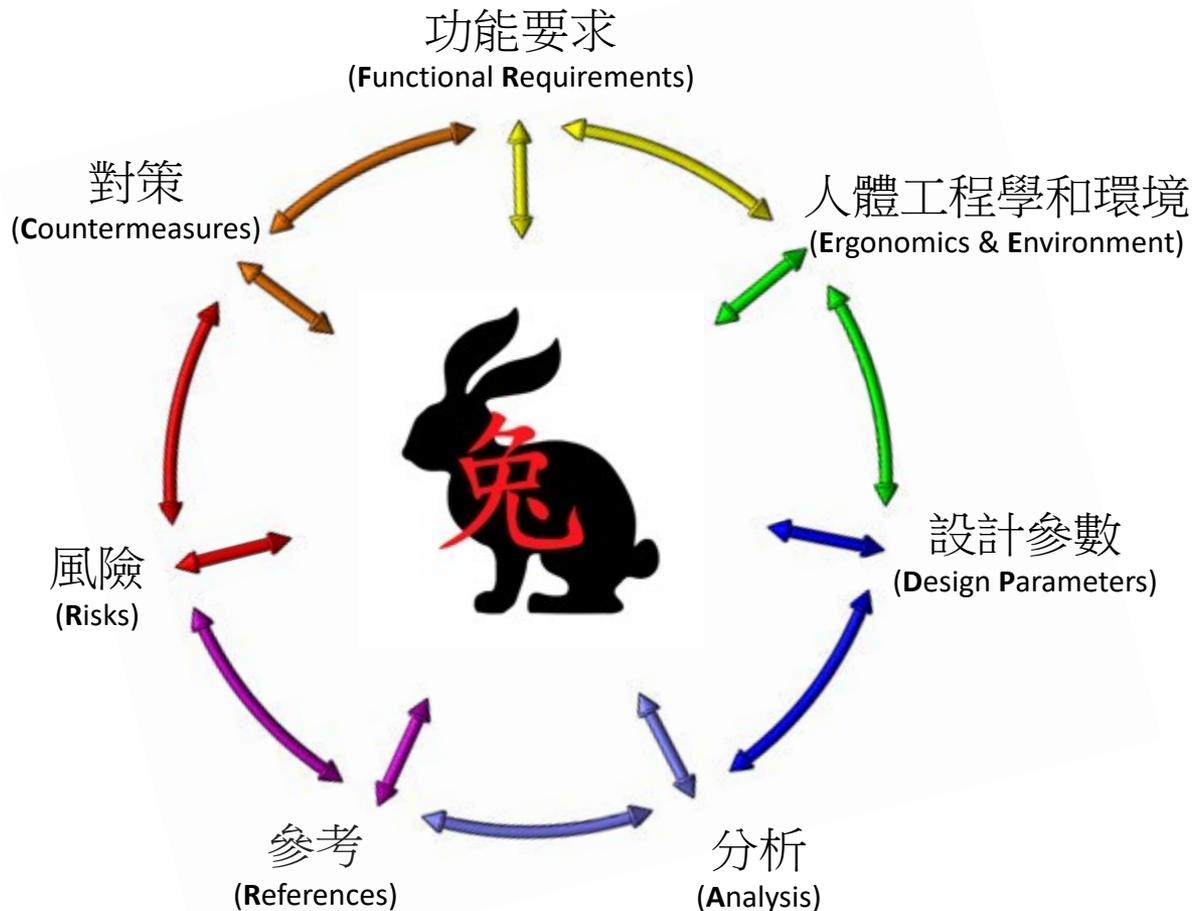
Rule 3: Teamwork Rules!

- Aesop's Fable: *The Bundle of Sticks*

- Teams are critical!

- Individuals are critical!

- Solve Challenges with PREP process
  - Individuals then think and write/sketch ideas in notebooks
    - Including apply PREP to identifying problem to be solved!
  - Notebooks traded and everyone reviews each others work and writes constructive comments…
  - THEN brainstorm!

Reference: Graham, M, Slocum, A, Moreno Sanchez R., "Teaching high school students and college freshman product development by Deterministic Design with PREP", ASME Journal of Mechanical Design (Special Issue on Design Engineering Education), July 2007, Vol. 129, pp 677-681, [DOI: 10.1115/1.2722334].

個人想法

沉默的同行評審

討論和頭腦風暴

同行評審評價過程

8/2/23

❤️*Passion* ❤️ *Rule 4: Never Stop Being a Kid!*

- YES you CAN have family, career, & creative fun!

  – Big sheets of paper

  and crayons…

  - Create together!
    Top secret design development!

Gen1
Gen3
Gen2
Guard Units

"Enthusiasm is one of the most powerful engines of success. When you do a thing, do it with all your might. Put your whole soul into it. Stamp it with your own personality. Be active, be energetic, be enthusiastic and faithful and you will accomplish your object. Nothing great was ever achieved without enthusiasm". **Ralph Waldo Emerson**

Rule 5: *Mind AND Body*

- *Exercise Body and Mind*
- *To* stay healthy and smart!
  - Better blood flow to brain….
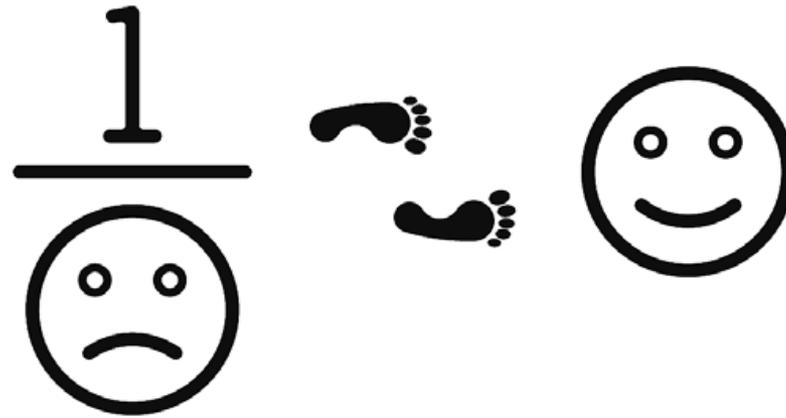 - Do it with friends, family
  - Never too young
  - Never too old

Rule 6: Be Prepared….

- Maintain library of things, processes, analysis …
  - Constantly cycle through what you see, apply FREDPARRC
  - Update library…
- Go to conferences, make friends and exchange ideas!
- Try not to generalize, you are often wrong

8/2/23
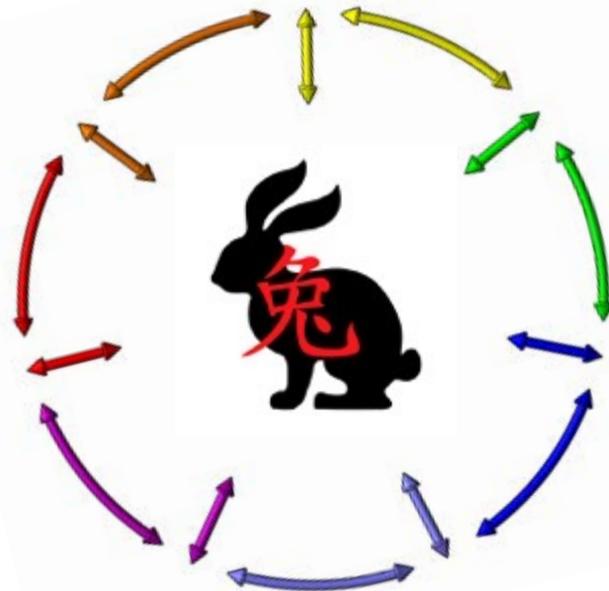
Rule 7: Reciprocity rules!

"Problems" motivate "Solutions"

8/2/23

Getting Started

8/2/23

Error Apportionment: A Precision Roadmap

- Use the product specification to drive the error budget

- Before starting to sketch ideas for a new machine:

  - Find level of performance required of each axis and components

    - This saves time thinking about ideas that are not likely viable

- *IF the errors of most concern can be dealt with, a design concept may be worth further investigation*

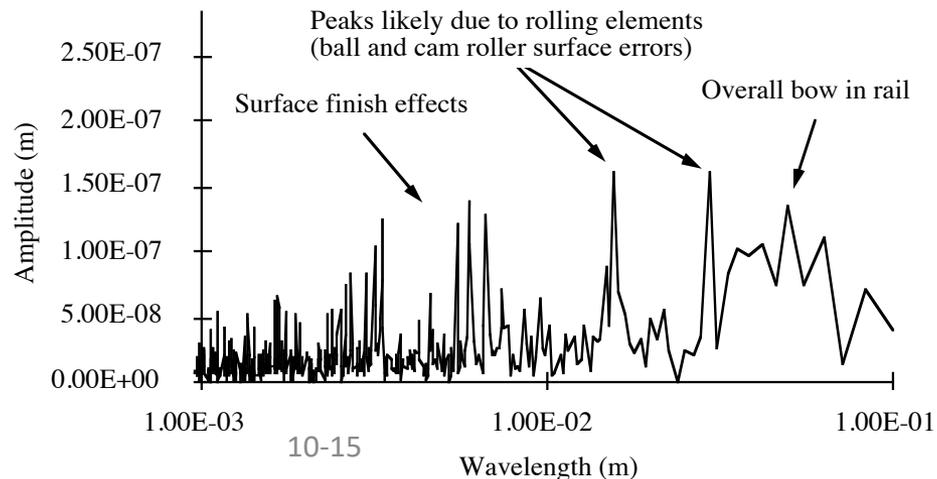| Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes. By Alex Slocum, last modified AHS 2014.04.09								
Enter numbers in **BOLD**, Results in **RED**								
Number of axes, N	**3**							
Total allowable error, dtot (microns)	**100**	what the customer wants from their machine						
				Apportion of error within each axis (amount allocated to each of X, Y, Z directions) to be determined by sensitive directions				
				Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
Source of error	Factor (f)	Apportion of error (dtot/f)	Apportion of error per axis	1	0.1	0.2	0.2	0

• • •

8/2/23

Example: Error Apportionment Spreadsheet

|				Axis_error_apportionment_estimator.xls				
				To apportion errors between types and axes. By Alex Slocum, last modified AHS 2014.04.09				
Enter numbers in **BOLD,** Results in **RED**								
Number of axes, N	**3**							
Total allowable error, dtot (microns)	**100**	what the customer wants from their machine						
				Apportion of error within each axis (amount allocated to each of X, Y, Z directions) to be determined by sensitive directions				
				Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
Source of error	Factor (f)	Apportion of error (dtot/f)	Apportion of error per axis	1	0.1	0.2	0.2	0
				Based on linear sum of errors				
Geometric, fg	1.00	50	17	11	1	2	2	0
Thermal, ft	0.50	25	8	6	1	1	1	0
Load-induced (deflection), fl	0.50	25	8	6	1	1	1	0
Process, fp	0.00	0	0	0	0	0	0	0
				Based on Root Square Sum of errors				
Geometric, fg	1.00	82	47	45	5	9	9	0
Thermal, ft	0.50	41	24	23	2	5	5	0
Load-induced (deflection), fl	0.50	41	24	23	2	5	5	0
Process, fp	0.00	0	0	0	0	0	0	0
				Average (expected case) of Sum and RSS				
Geometric, fg	1.00	66	32	28	3	6	6	0
Thermal, ft	0.50	33	16	14	1	3	3	0
Load-induced (deflection), fl	0.50	33	16	14	1	3	3	0
Process, fp	0.00	0	0	0	0	0	0	0

8/2/23

Appropriate Elements

- The below also depends on loads and application… but as a starting illustration point:
  - Positioning Ability:
    - 100 microns: Sliding, rolling, flexure, fluid, air, magnetic (most anything)
    - 10 microns: Rolling, flexure, fluid, air, magnetic
    - 1 microns: Rolling (special) flexure, fluid, air, magnetic
   - 0.1 Microns: flexure, fluid, air, magnetic
  - Straightness of motion
    - 100 microns: Sliding, rolling, flexure, fluid, air, magnetic (most anything)
    - 10 microns: Sliding, Rolling, flexure, fluid, air, magnetic
    - 1 microns: Sliding, Rolling (special) flexure, fluid, air, magnetic
    - 0.1 Microns: Sliding, flexure, fluid, air, magnetic

Peaks likely due to rolling elements (ball and cam roller surface errors)

Surface finish effects

Overall bow in rail

8/2/23

Error Budgets

- Error Apportionment is the starting point for a detailed error budget

- As the concepts evolve based on first principles, a formal *error budget* should be created and updated

- An error budget is used to keep track of all the error motions in a machine

  - Remember Abbe and sine errors and how they can amplify bearing angular errors!

- The *error budget* is a living document to revise after FEA and prototype testing

8/2/23

Models Enable Error Assessment
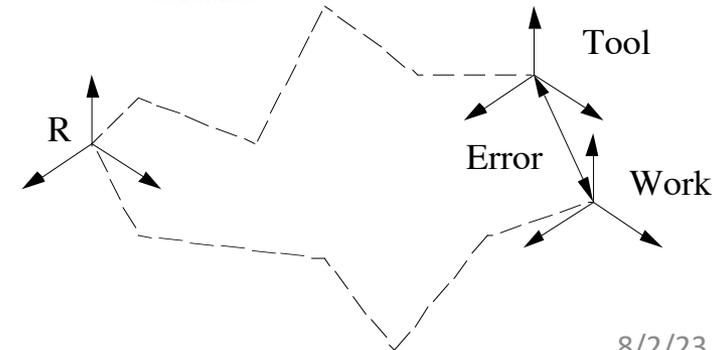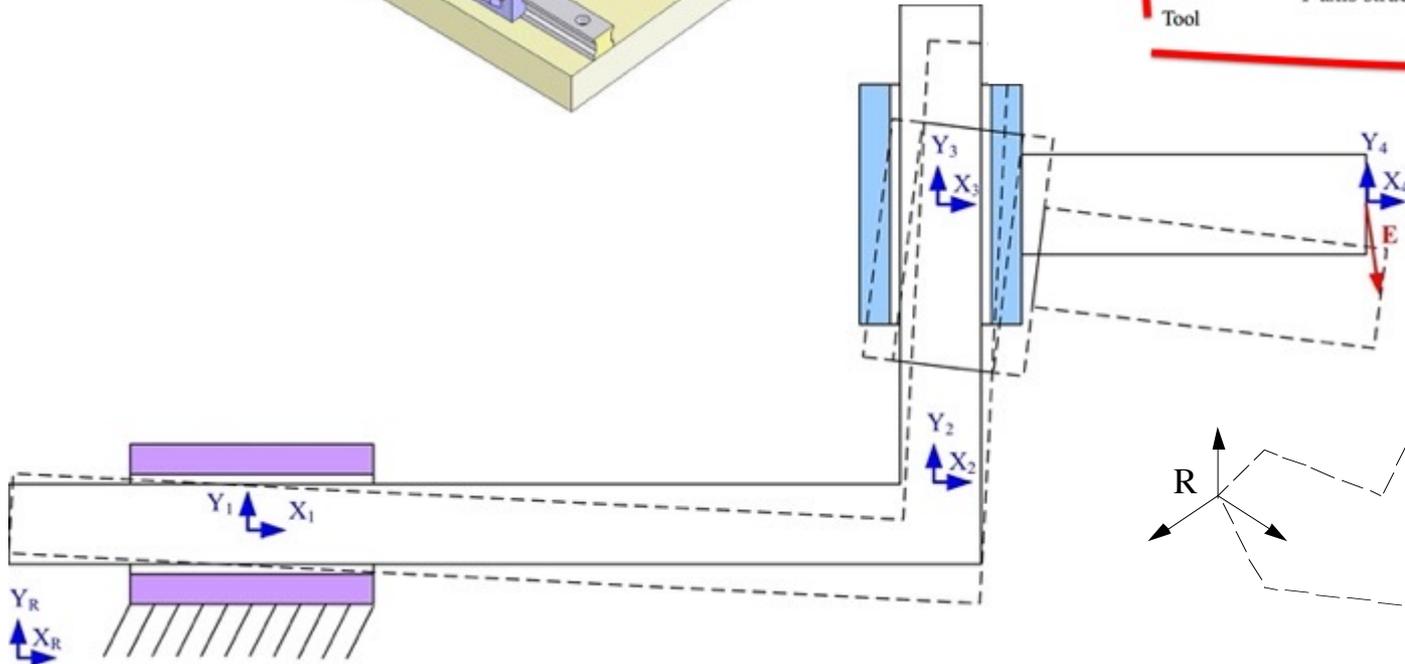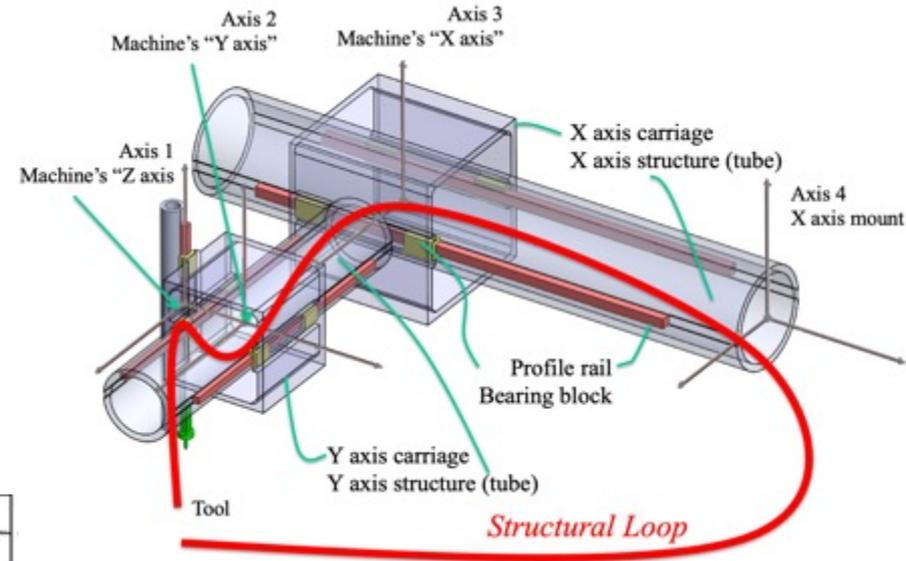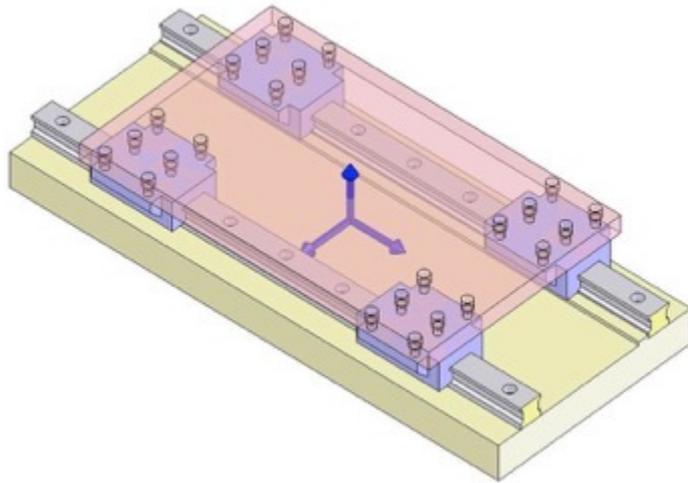
Sketch Strategies & Concepts

- Linear, Rotary, Hybrid
- Sketch as stick figures
- Enables first principle beam equations, system of springs…
- Same for thermal errors: steady state series parallel resistors and masses (inductors)
  - Extremely valuable as you transition your design to FEA (coarse to fine)
- Identify structural loop to guide analysis…

8/2/23
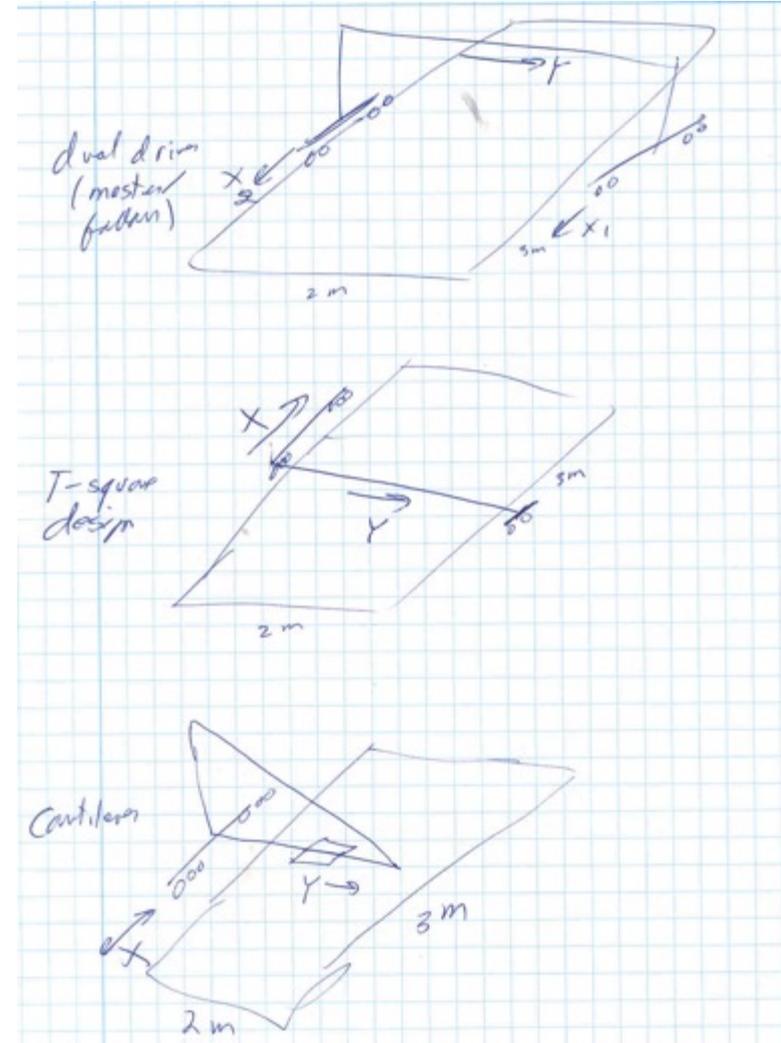
Identify Structural loops

- Guides error apportionment and error budgets

- Topology guide

- Heps to define metrology loops

- If you cannot measure it, you cannot make it

- Attack hardest axis first...

Structural Loop

Axis 2
Machine's "Y axis"

Axis 3
Machine's "X axis"

Axis 1
Machine's "Z axis"

X axis carriage
X axis structure (tube)

Axis 4
X axis mount

Profile rail
Bearing block

Y axis carriage
Y axis structure (tube)

Tool

Structural Loop

8/2/23
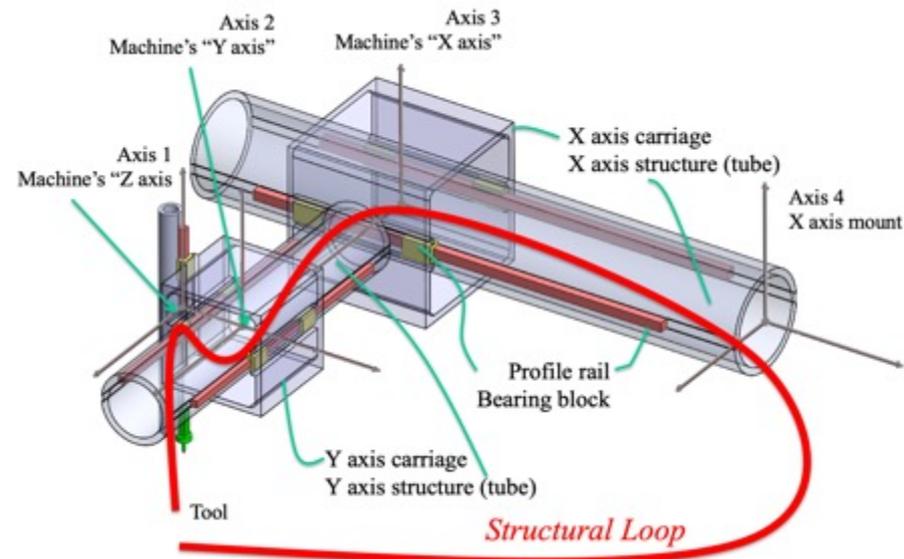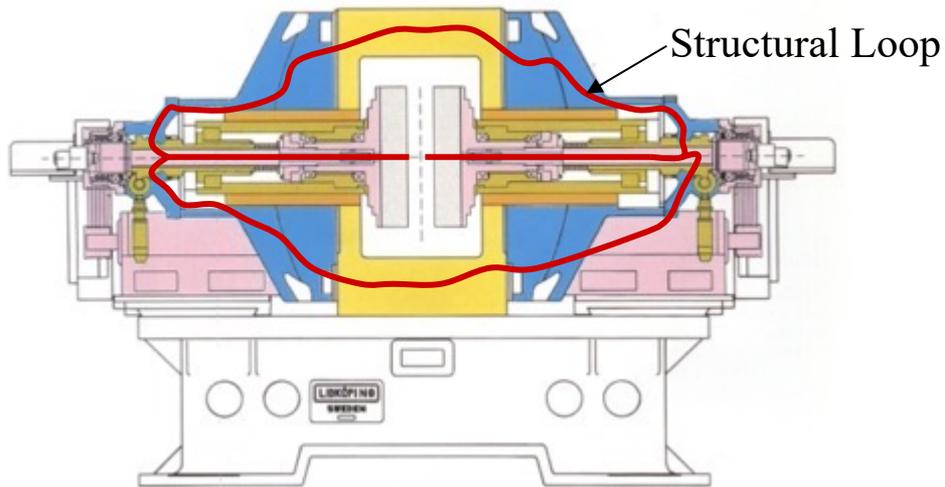
3D Structural Loops: Natural Geometries

- ## Closed structural loops good
  - – Enhanced by geometries that want to stay their shape

Figure 7.4.9 The Tetraform structural concept for machine tools and instruments developed by Lindsey. (Courtesy of the National Physical Laboratory.)

NPL's Kevin Lindsey's "Tetraform", UK patent 8,719,169
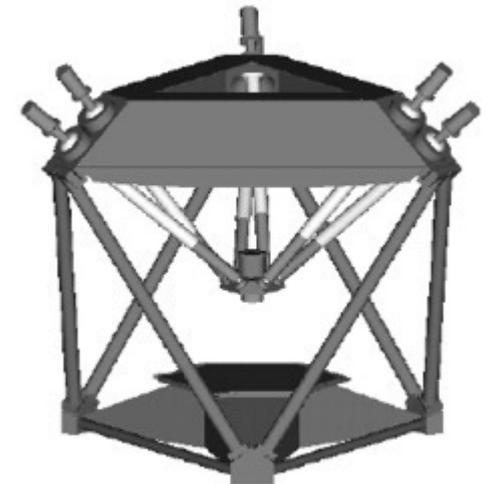
NIST Ingersoll octahedral- hexapod

8/2/23

Estimate Motion Axes' Error Motions

- Error motions of a carriage supported by a kinematic arrangement of bearings (exact constraint) can be determined "exactly"

- Error motions of a carriage supported by an elastically averaged set of bearings can be estimated by assuming the bearings act in pairs

  – Calculations are done using the "running parallelism" error information from the bearing supplier

    • Running parallelism number is usually a systematic (repeatable) error

    • Repeatability may typically be 10-20% of the running parallelism

Ideal path
High frequency straightness error ('Smoothness')
Straightness error
Lateral motion sensor's output trace
Nonperfect rollers
Nonperfect surface
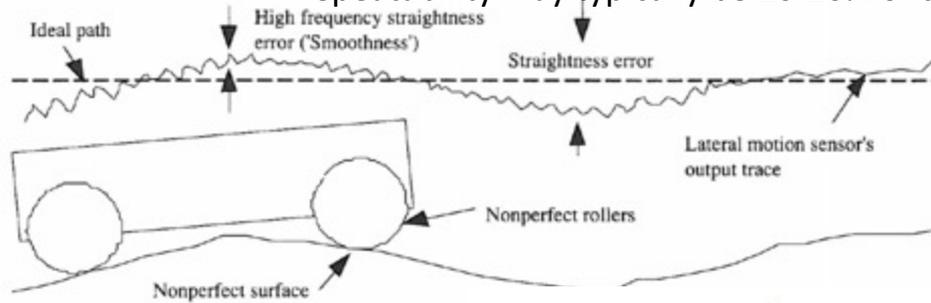
Horizontal Straightness: δ_y Assume all bearings move horizontally
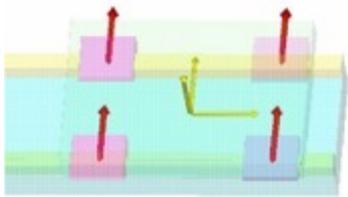
Vertical Straightness: δ_z Assume all bearings move vertically
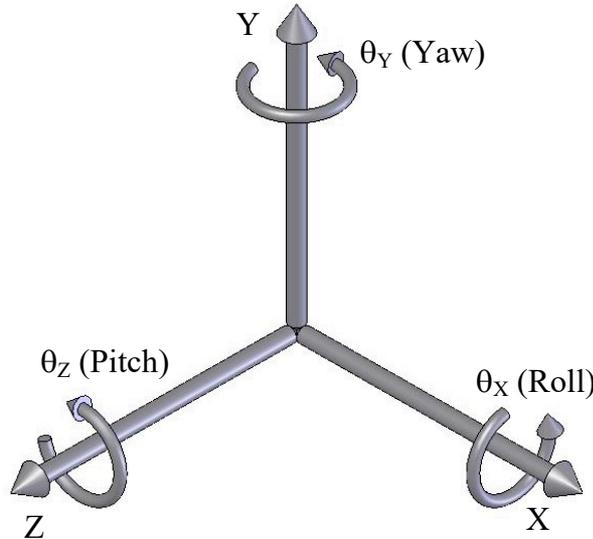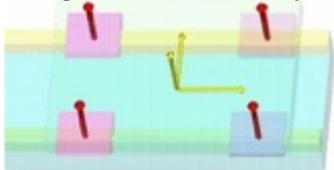
Roll: ε_x Assume all bearings on each rail move vertically in an opposite direction
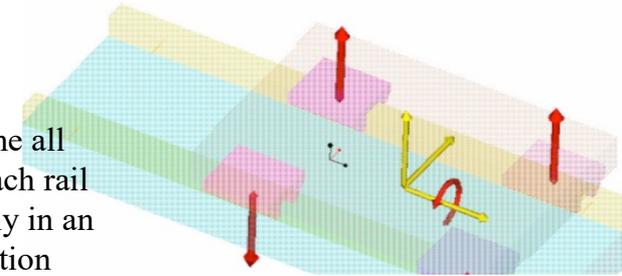
*Pitch:* ε_z Assume front and rear bearing pairs move in opposite vertical directions
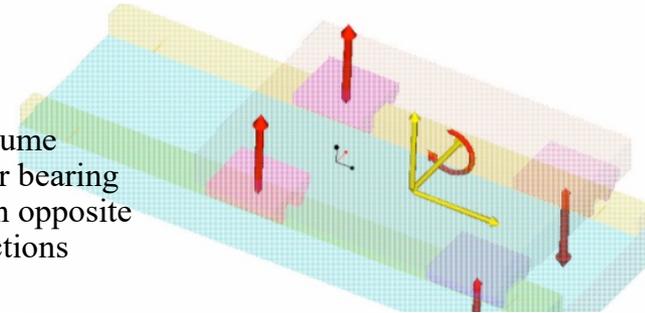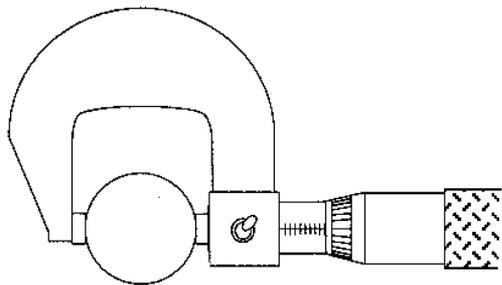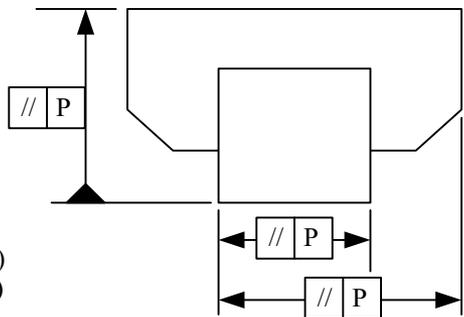
Yaw: ε_y Assume front and rear bearing pairs move in opposite horizontal directions

Y
θ_Y (Yaw)
θ_Z (Pitch)
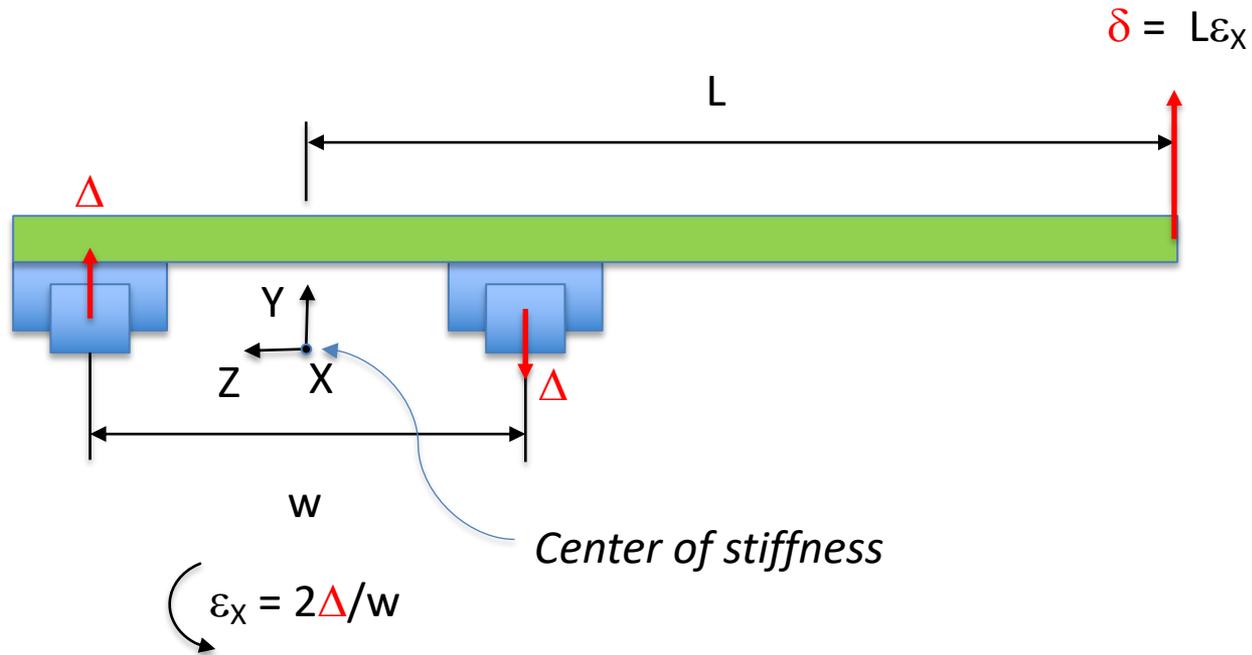θ_X (Roll)
Z
X
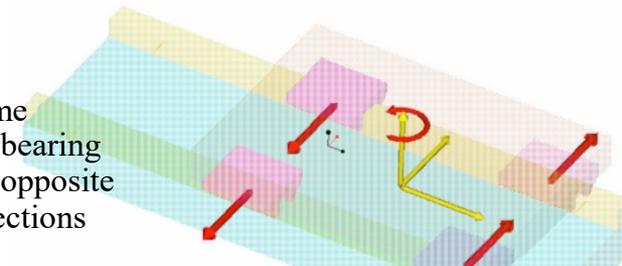
Estimate Bearing Error Motions

- Bearings are not perfect, and when they move, errors occur in their motion
  - Think about manufacturing process to use for mounting the bearings to achieve the desired parallelism and flatness
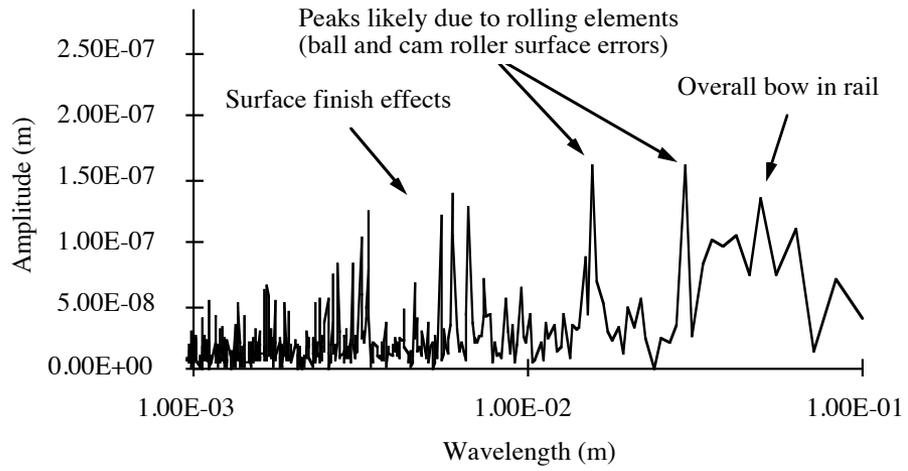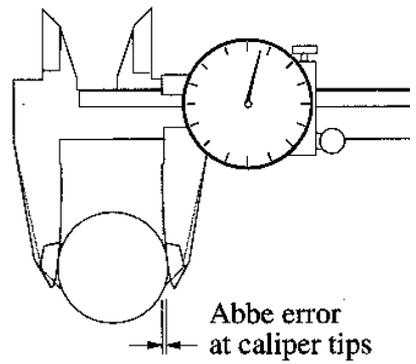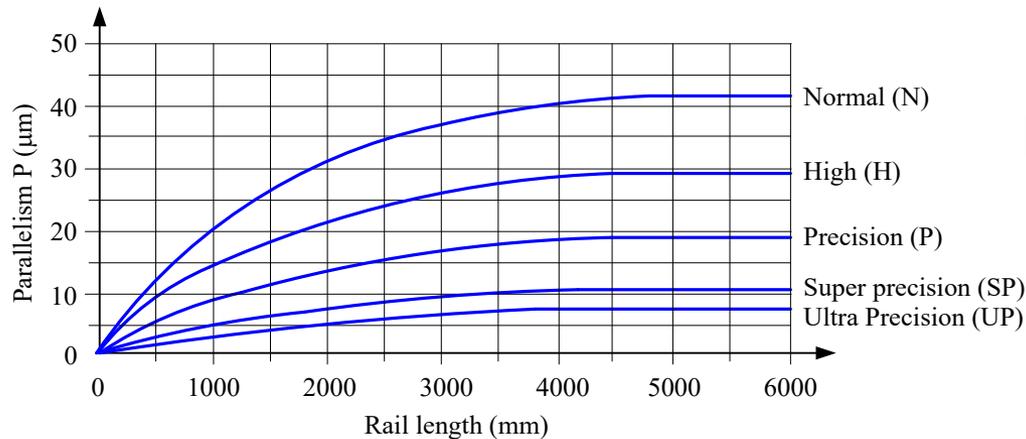
Example: Error Motions from Bearings

$$\delta = L\varepsilon_X$$

$$\varepsilon_X = 2\Delta/w$$

Center of stiffness

If error apportionment value can be met for the axis most distant from the tool point: Next step is look at structure deflection…

8/2/23

Case Study: 450 mm Silicon Wafer Grinding Machine

- How to back-grind next generation silicon wafers from 1300 μm to 50 μm in <1 minute?

8/2/23

Ground Wafer Specifications

- Total Thickness Variation (TTV) ≤0.5µm per 100wafers
- Wafer To Wafer variation (WTW) ≤1µm per 100wafers
- Flatness: 0.1µm per die (20mmx20mm)
- Parallelism of wafer faces: 0.6µm
- Surface roughness: Ra<10nm
- Final thickness: 10µm to several mm
- SEMI M76-0710 - Specification for Developmental 450 mm Diameter Polished Single Crystal Silicon Wafers
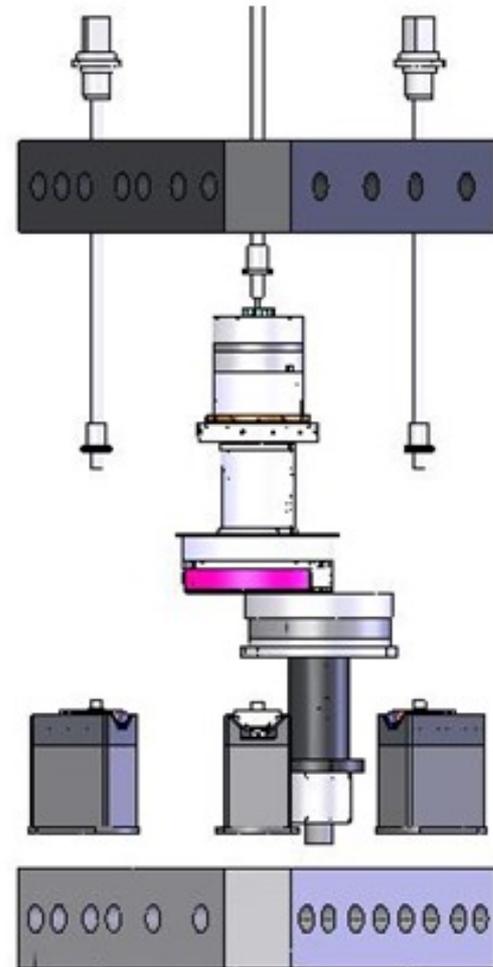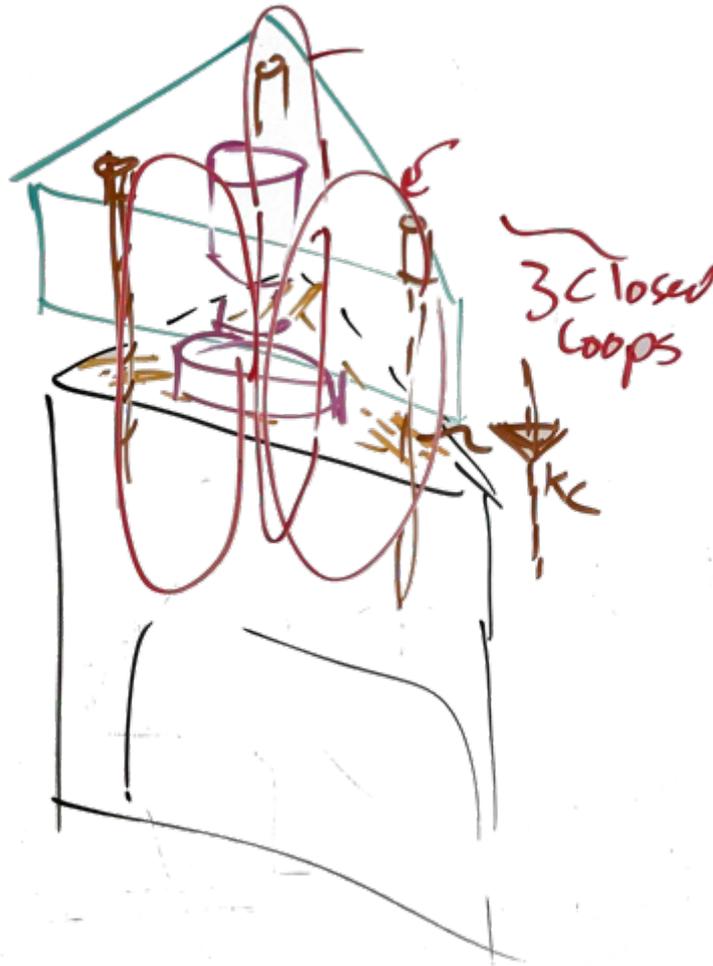
8/2/23

Importance: Economy

- Bigger wafers → Greater economy
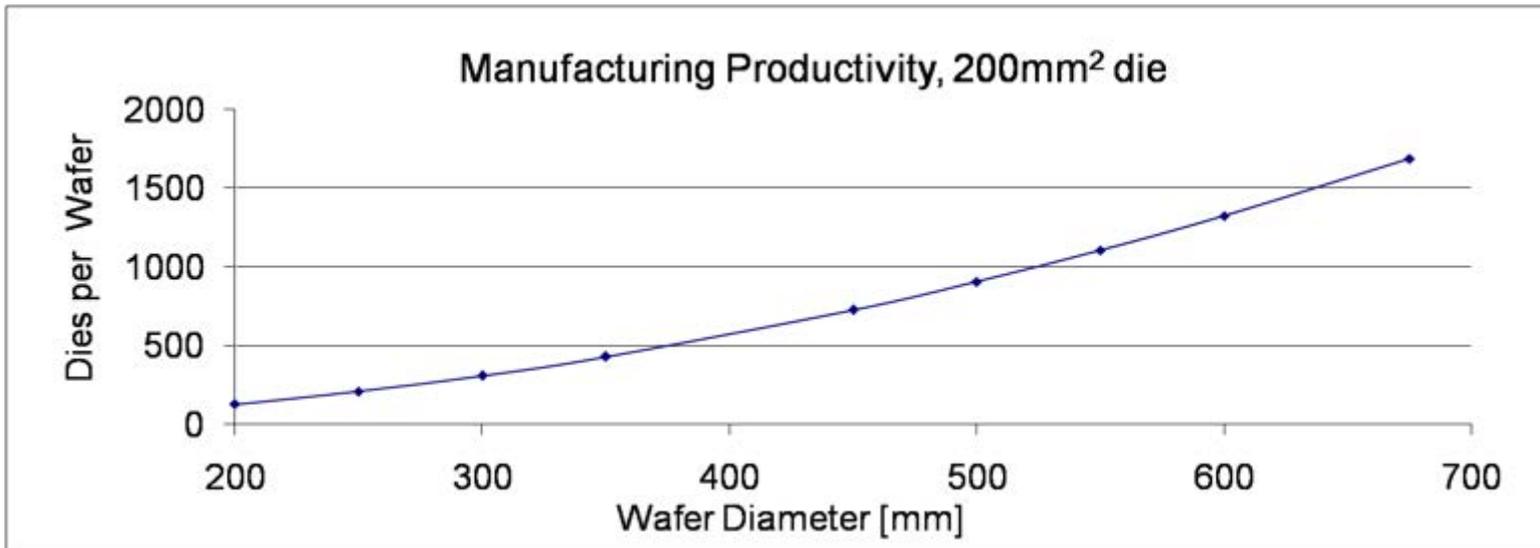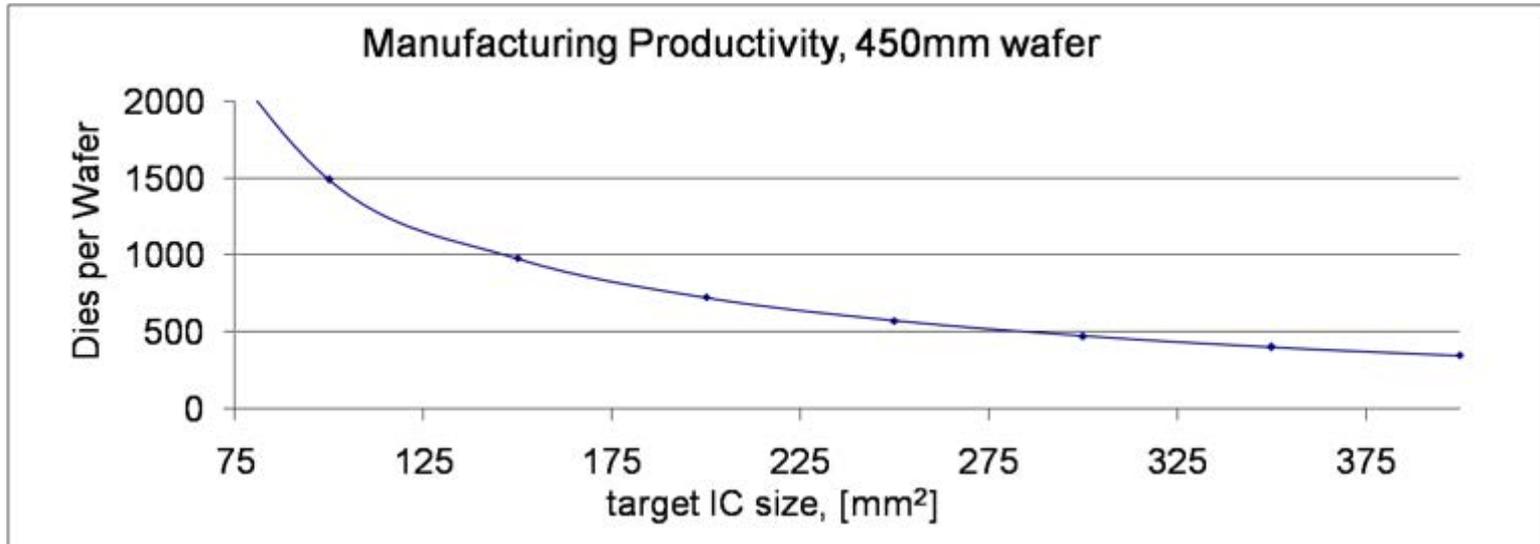
450 mm Wafer Grinding Machine

- Footprint to be minimized

- Stiffness to be maximized

- Cup grinding wheel to be controlled in Z
  - Pitch and roll nanoradian adjustable and set before grind

- 20 kW grinding power

8/2/23

# Early Design Sketch with Structural Loops

3 Closed Loops

8/2/23

Structure: Triangle most efficient

- Cast iron for ease of manufacture

- 1000N load applied at center (spindle grinding force)

- 1.5e-4mm deflection

- 6500 N/μm stiffness

- Even greater stiffness possible by bonding plate to bottom

- Damping by filling cavities with loose media

8/2/23
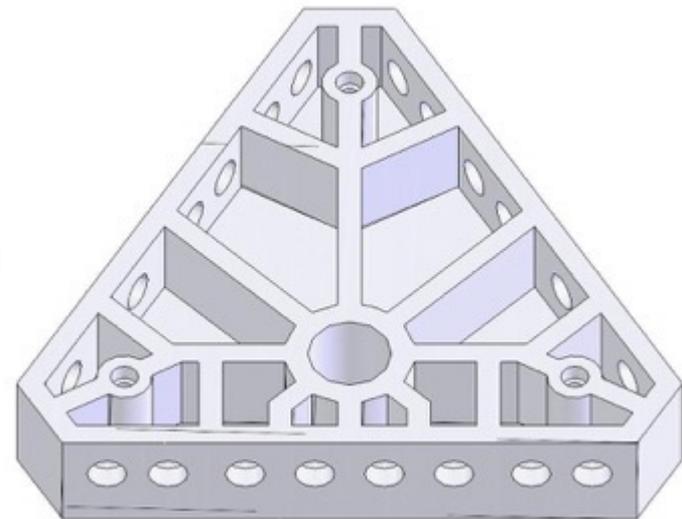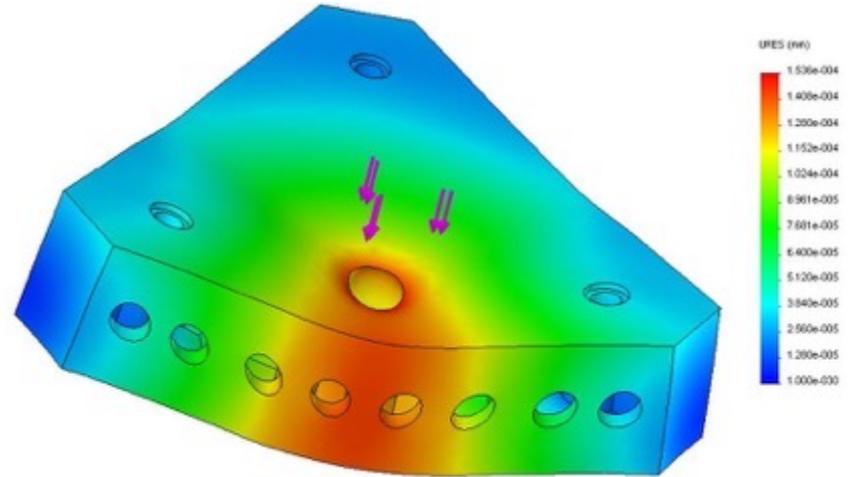
Z, ε_X, ε_Y: Adjustable Kinematic Coupling

Coupling Stiffness	[N/nm]
Required	>5
Predicted at 26kN	6.5
Measured at 26kN	7.1
Scaled at 30kN	7.44
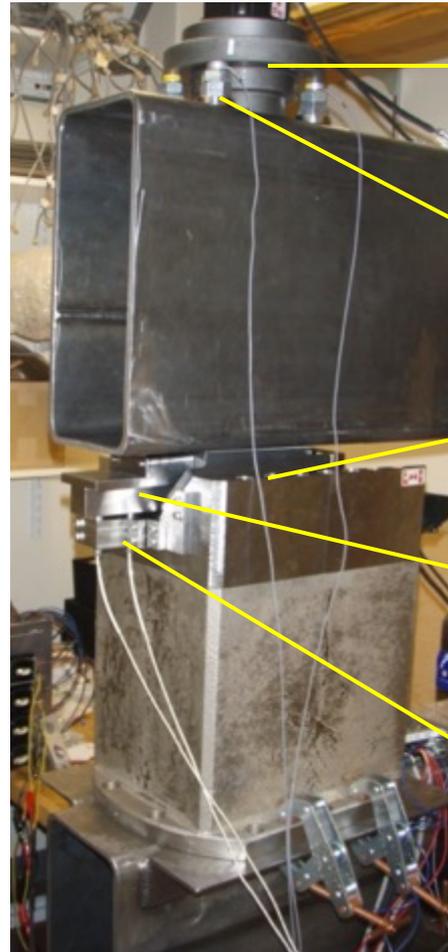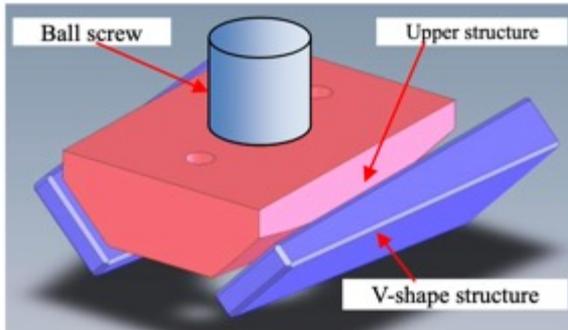
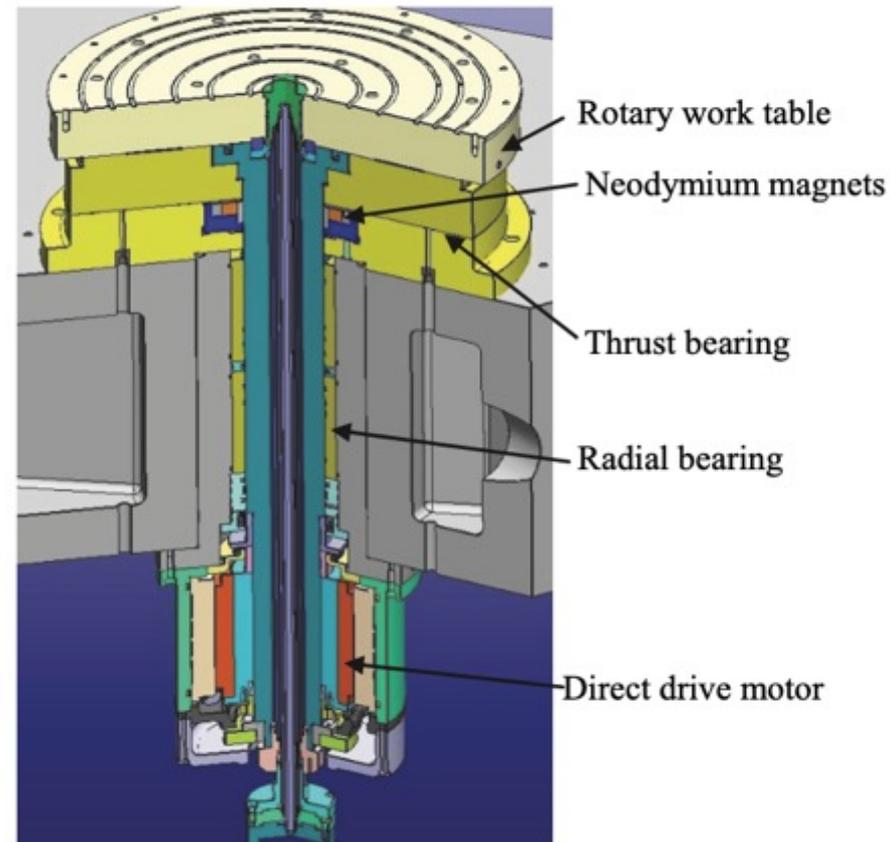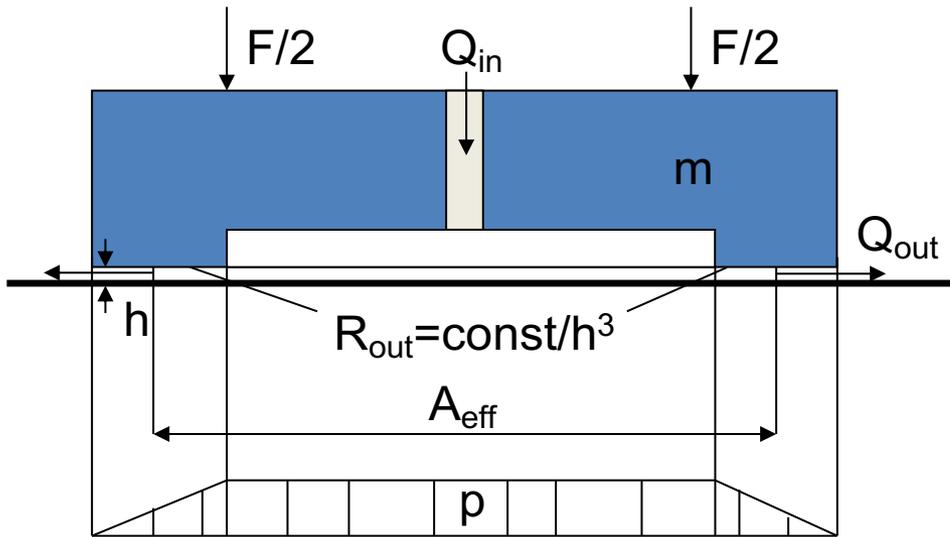Preload mechanism
(AC motor, harmonic drive, ball screw)

Four parallel load washers

Kinematic coupling contact pair

Capacitance probe target, mounted to male vee

Capacitance probes, mounted to female vee

Ball screw

Upper structure

V-shape structure

- Load washers for feedback
- Capacitance probes record displacement behavior of contacts

8/2/23

Workpiece Spindle

F/2 Q_{in} F/2

m

Q_{out}

h

$R_{out} = const/h^3$

A_{eff}

p

Rotary work table

Neodymium magnets

Thrust bearing

Radial bearing

Direct drive motor

- Water Hydrostatic bearings for cleanliness and high stiffness
  - Static stiffness via closed loop control
  - Dynamic stiffness via incompressible viscous flow
- Constant flow supply with magnet preload
  - One pump per pocket
    - *Servocontrol flow to each pocket by varying gear pump speed thus avoid clogging*
  - When the load increases the bearing gap decreases
  - Since the flow is kept constant the recess pressure increases.

31

8/2/23

Test Bearing

- Preload:
  - Magnetic preload: 6000N
  - Gravity preload: 2664N with shaft and 1800N without shaft
- 7µm minimum bearing gap
- Theoretical 1300N/µm @ 20µm bearing gap (assuming constant flow)
- Positive displacement pump supply (gear-type fuel pump)
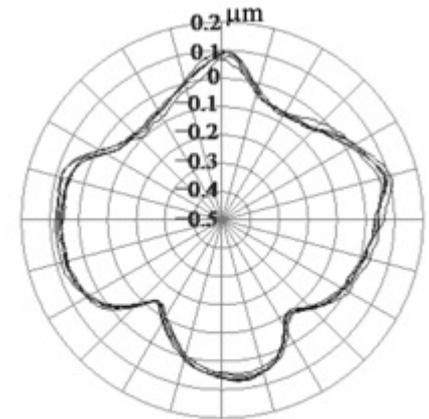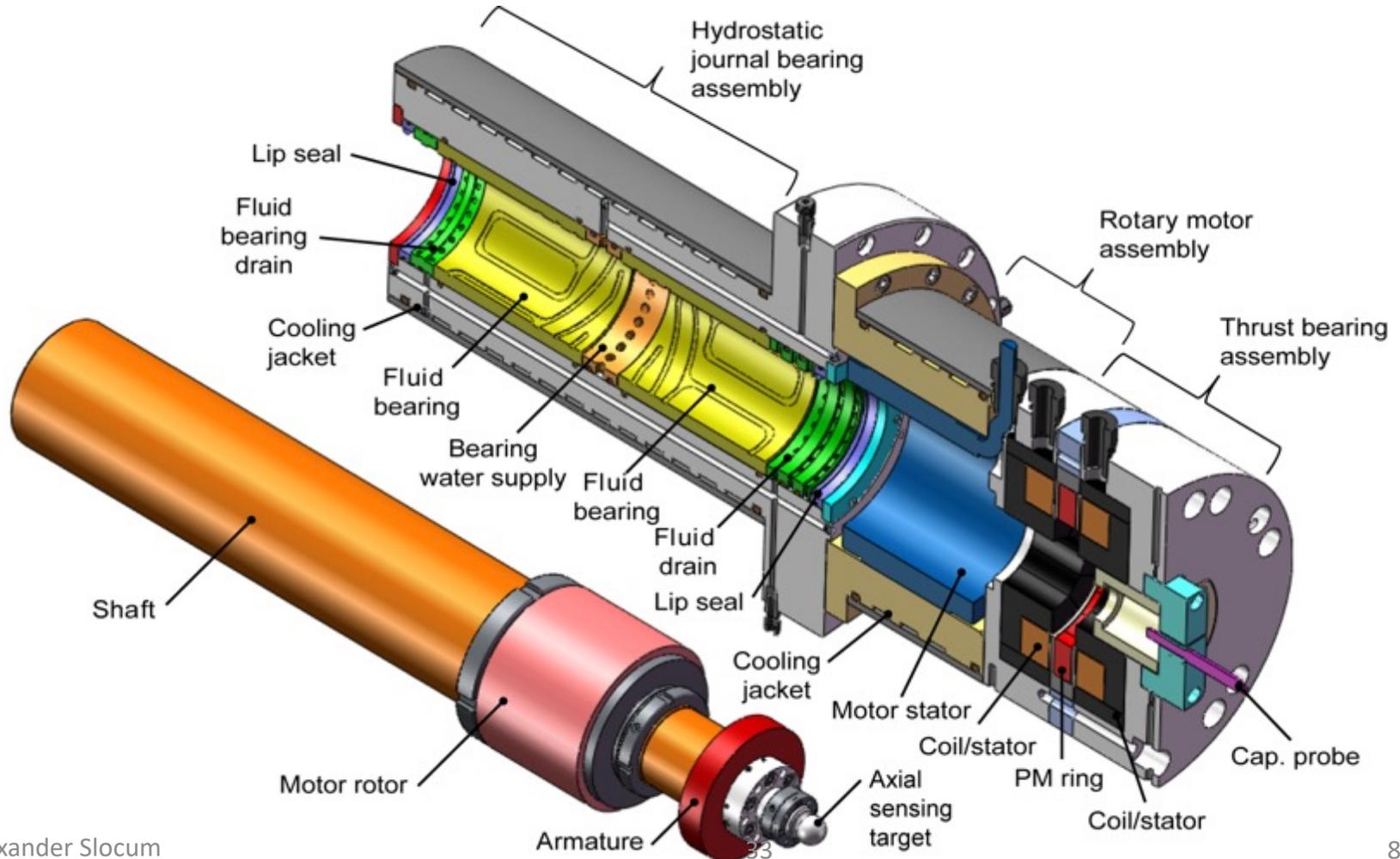- Pressure feedback (internal model control) or closed loop gap measurement feedback to increase stiffness.

Fig.6 Radial motion deviation of rotary table (120rpm, $Q=10$mL/min)

8/2/23

Hybrid Wheelhead Spindle

- Radial self compensated water hydrostatic bearings
- Axial active magnetic bearing
  - Also controls fine motion axial feed

33

Radial Hydrostatic Bearing Performance

- At 1.8 MPa water pressure, stiffness about 600 N/µm
  - 160 N/µm radial stiffness at the front end of the shaft

Radial Stiffness Characterization, Hydrostatic Bearing in Full Scale RAS

8/2/23
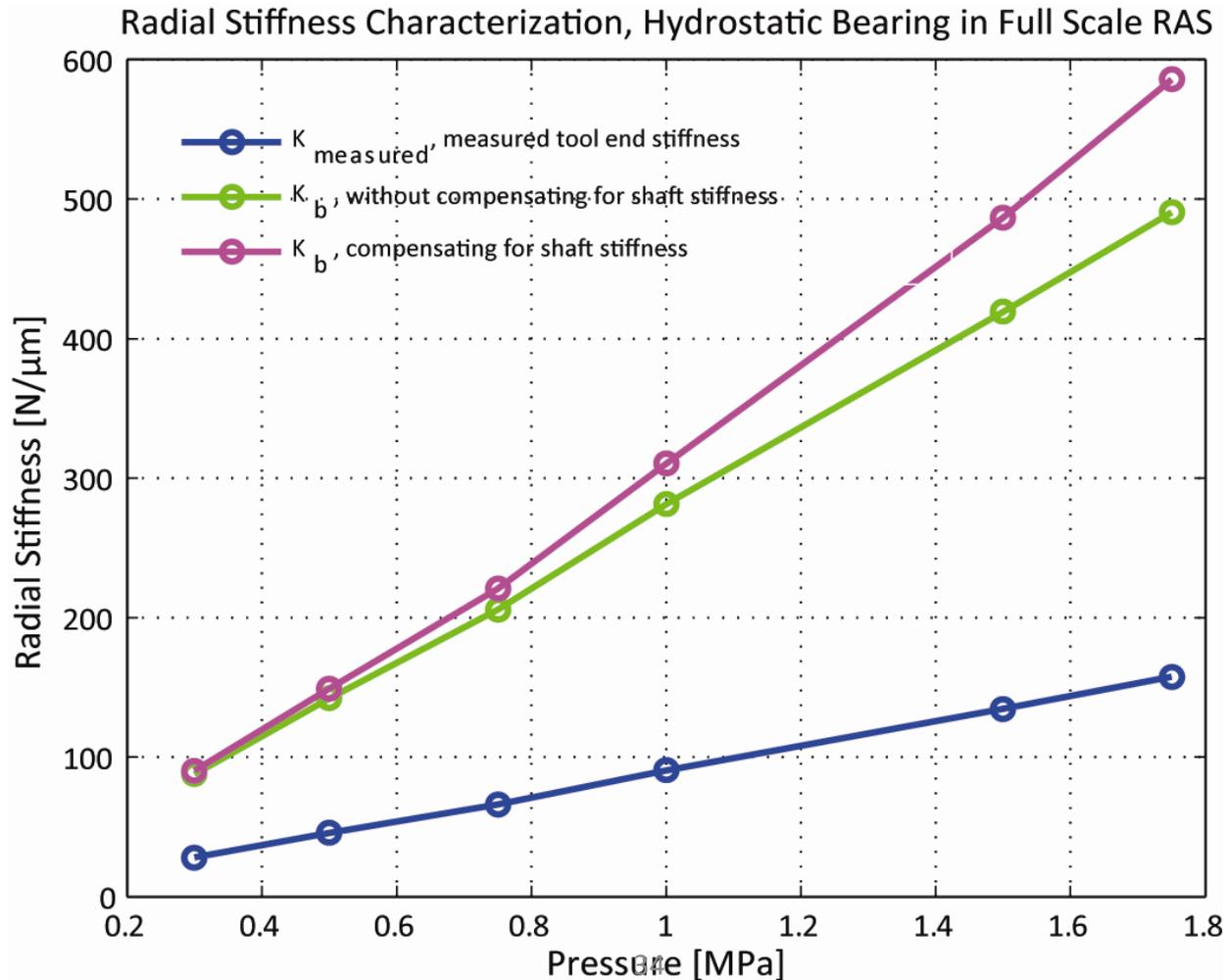
Axial Magnetic Bearing performance

- Minimum dynamic stiffness is 340N/µm at 120 Hz.
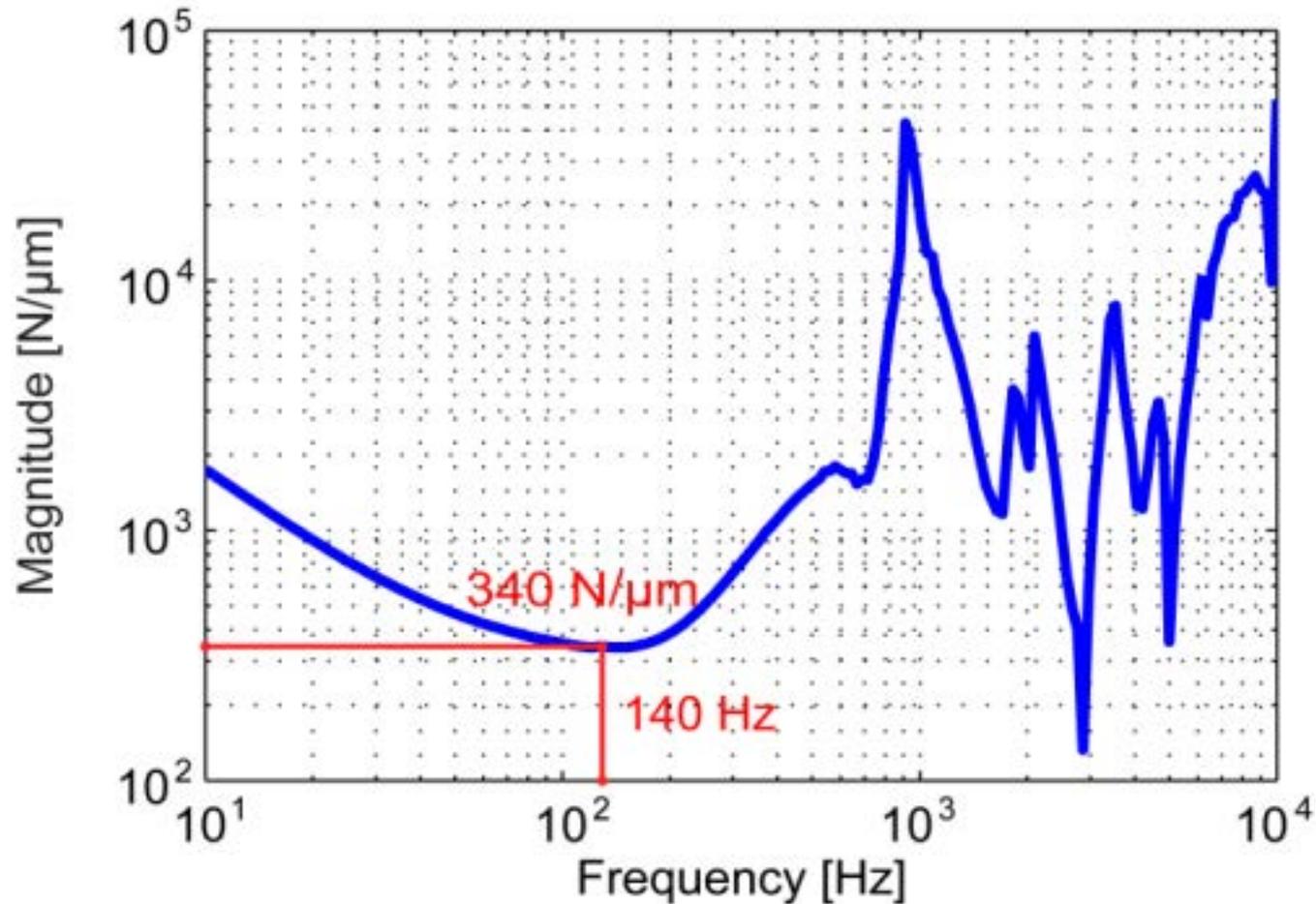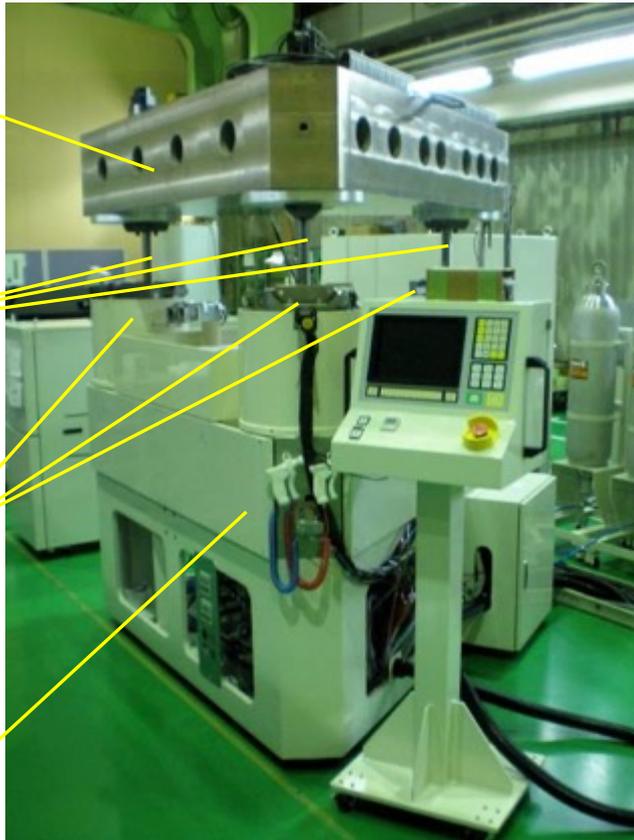
Final Result: Working Machine

- Low stiffness, open handling configuration
- High stiffness, closed structural loop machining configuration
- Kinematic coupling joints provide high damping
- Feedback controlled, adjustable machine elements

Hybrid Hydrostatic-Electro-magnetic wheel spindle
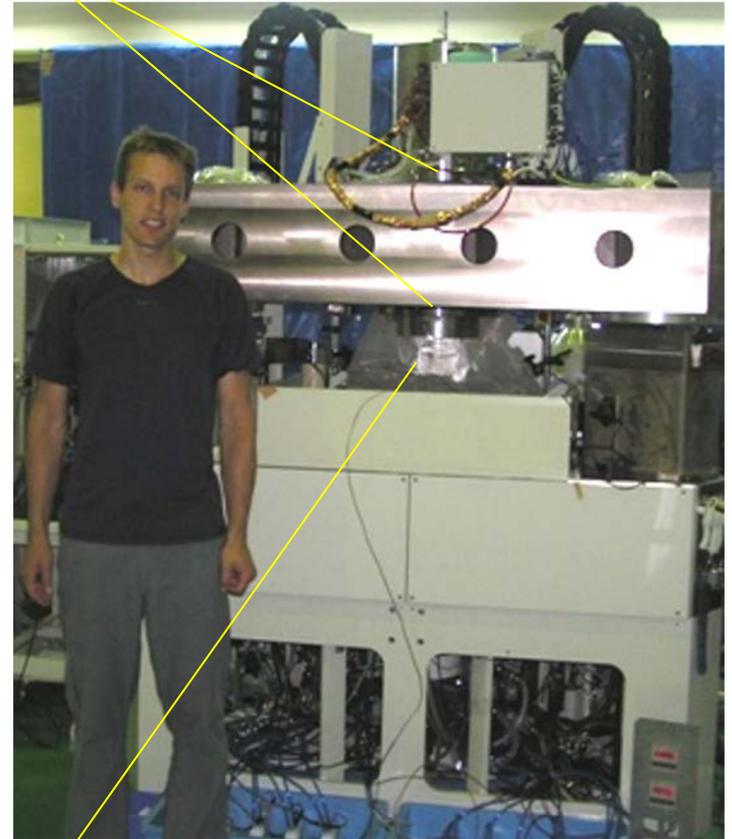
Upper structural triangle

KC Preload ball screws, also open machine up

Adustable Kinematic coupling interface

Lower structural triangle

Doctoral student Gerald Rothenhofer

Hydrostatic work spindle

8/2/23

Machine Conclusions

- 450mm Silicon Wafer Prototype Grinder designed, built and tested
- New topology very successful, and met all requirements
  - Reduced mechanical complexity + compact machine = high loop stiffness
  - 450 mm wafers ground without any subsurface damage
  - *Water hydrostatic bearings very successful*
    - *Better hydrostatic pump design for servo controlled flow is needed*

8/2/23
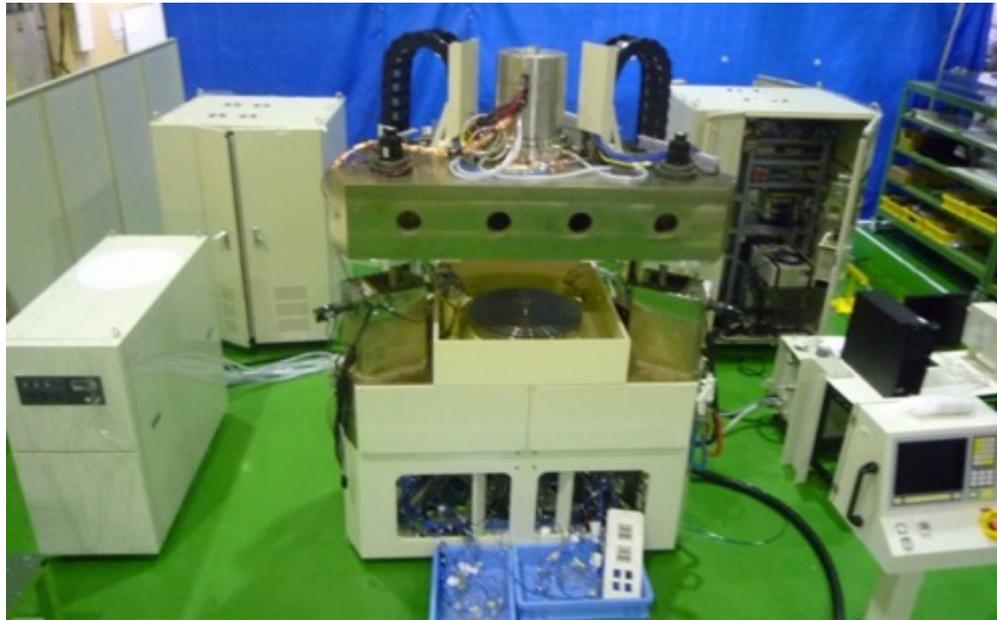
Looking Forward

- Can AI help "automate" or at least Catalyze Precision Design?

  – I believe this can be a new beginning…

    - **T**opological **O**ptimized **P**recision **I**nspired **C**reativity **A**nd **L**earning AI engine

    - **TOPICAL** AI Engine

8/2/23

Conclusions

- Challenges always arise
  - A deterministic process helps create solutions
- Turn *problems* into *solutions*
  - Achieve Peace & Prosperity!

8/2/23
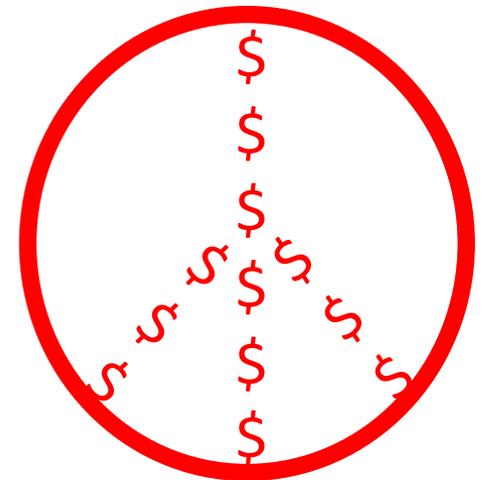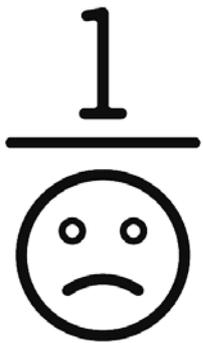
References: 450 mm Silicon Wafer Grinding Machine

- T. Koiwai, A. Honda, G. Okahata, T. Kitajima, A. Yui, S. Okuyama, H. Kobayashi, A. Slocum, "Development of Grinding Machine for 450mm Wafer - 1st report: Specification and Fundamental Performance of The Grinding Machine", JSME 9th Manufacturing & Machine tool Conference, Akita prefecture October 26-27 2012

- A. Honda, A. Yui, T. Koiwai, S. Okuyama, G. Okahata, H. Kobayashi, T. Kitajima, A. Slocum, "Development of Grinding Machine for 450mm Wafer - 2nd Report: Numerical Analysis of Static Stiffness and Load Capacity of Water Hydrostatic Table", JSME 9th Manufacturing & Machine tool Conference, Akita prefecture October 26-27 2012

- A. Yui, A. Honda, S. Okuyama, T. Kitajima, G. Okahata, H. Saito, A. H. Slocum, "Development of a vertical-spindle rotary surface grinding machine for large scale silicon-wafers –Machine specifications and performance of rotary work table–", Proceedings of the 13th euspen International Conference, Berlin, May 2013

8/2/23

Quick Design Tricks

	Invaluable Alex Quick Approximations	Equation
1	Ball Bearing Stiffness Approximation	Bearing Static Load Capacity divided by 1% of ball diameter
2	Roller Bearing Stiffness Approximation	Roller Static Load Capacity divided by 0.3% of roller diameter
4	Air Bearing Stiffness	0.5*Bearing Area*Supply Air Pressure divided by Fly height
3	Motor sizing using shear stress X magnet area	1 atm shear with Water Cooling. 0.5 atm with Forced Air 0.25 atm with Free Convection
5	Say Tuned!	