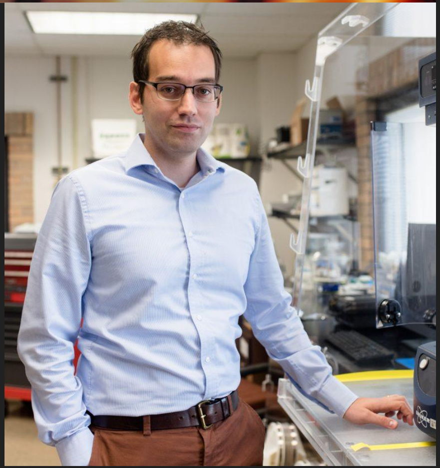
Designing the Load Cell for a Tribometer

David A. Yun

PROJECT INTRODUCTION

- Senior design project (Summer 2020)
- Project statement: *Design a tribometer with a frictional measurement resolution of 1 micronewton for ⅓ of the cost of existing commercial alternatives.*
- Sponsored by Dr. Mangolini for use in a research laboratory
- Development of very low-friction materials ($\mu = 10^{-3}$)



Dr. Mangolini, Mangolini Research Group

THE TEAM

Thomas Erickson

Henry Jiang

Irene Lee

David Yun

LHR LONGHORN RACING THE UNIVERSITY OF TEXAS

SPACEX

BLUE ORIGIN

Schlumberger

WHAT'S A TRIBOMETER?

An instrument that measures friction and wear properties of a sample.

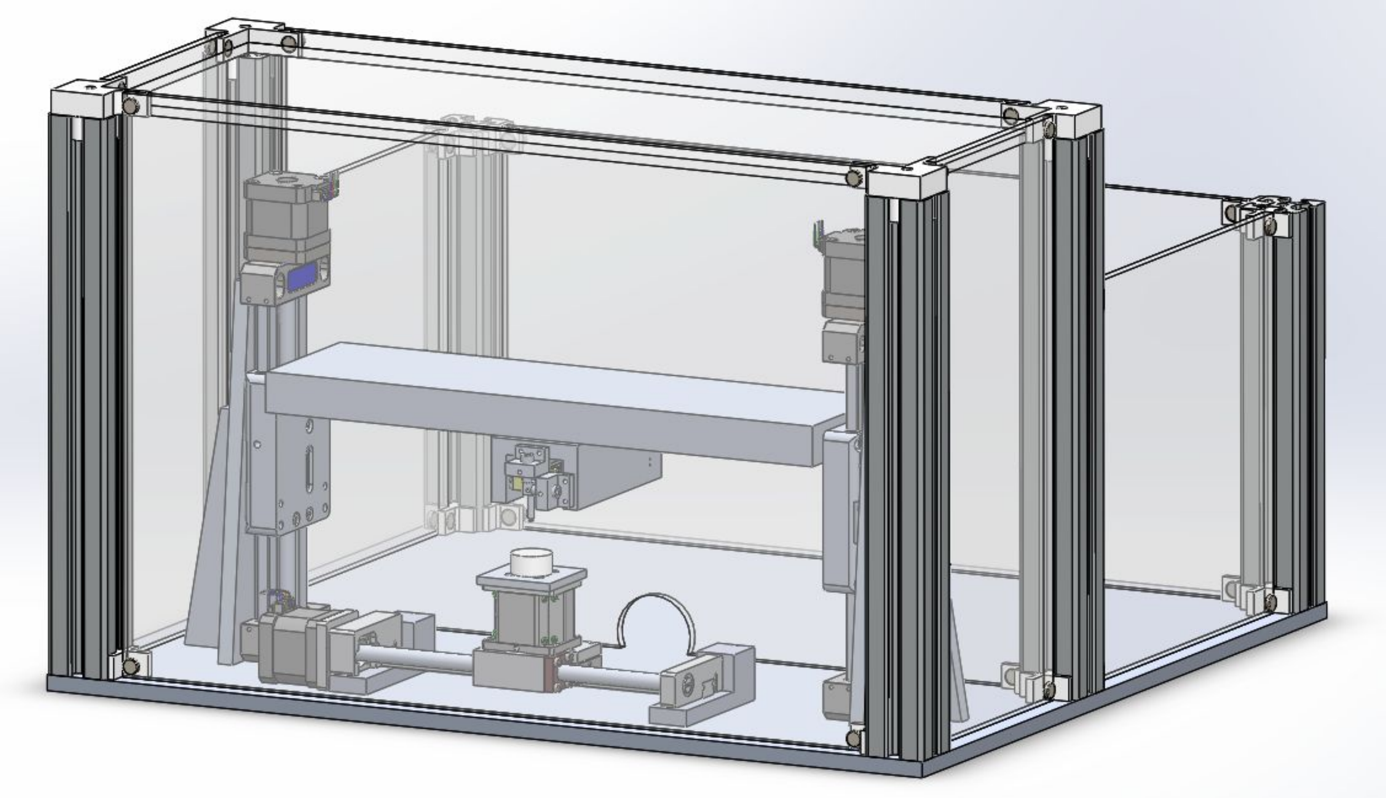
- Measures normal load and friction force

$$f = \mu N$$

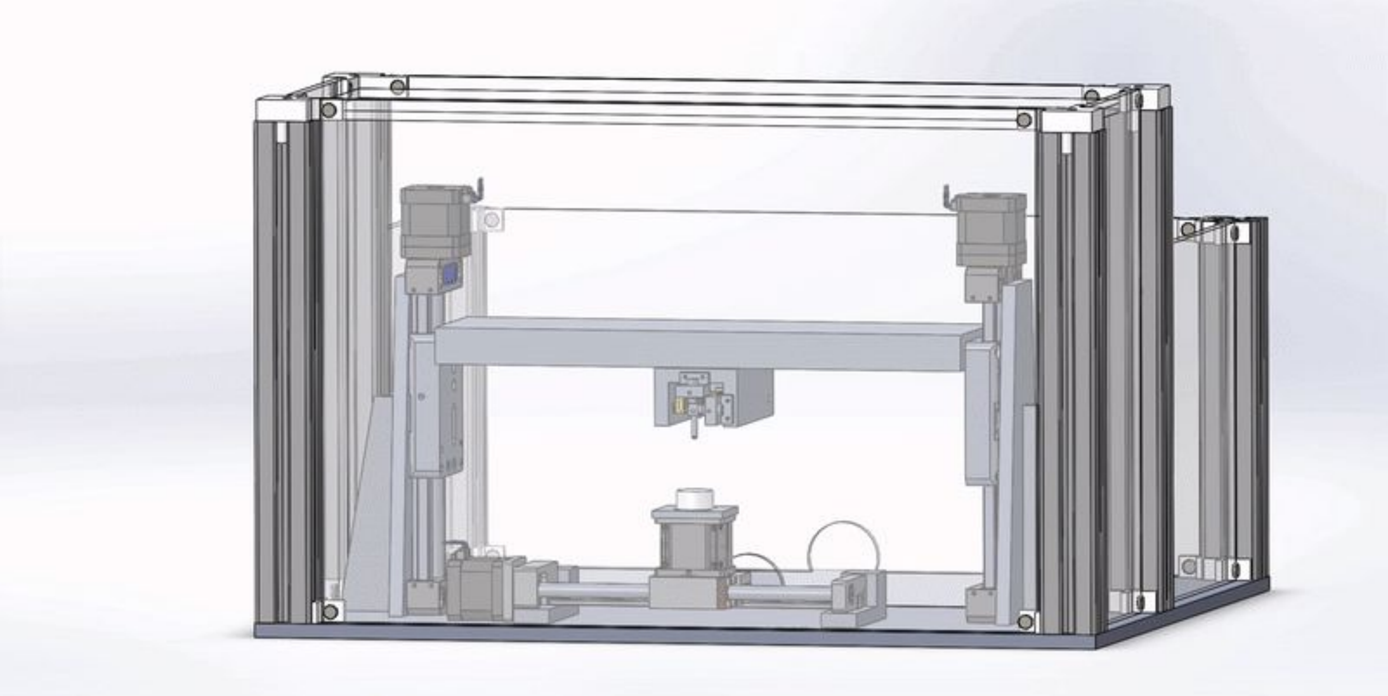
- Commercial alternatives: $120,000
- Budget: $40,000

Pin-On-Disk Tribometer, Anton-Paar

TRIBOMETER DESIGN



TRIBOMETER IN ACTION

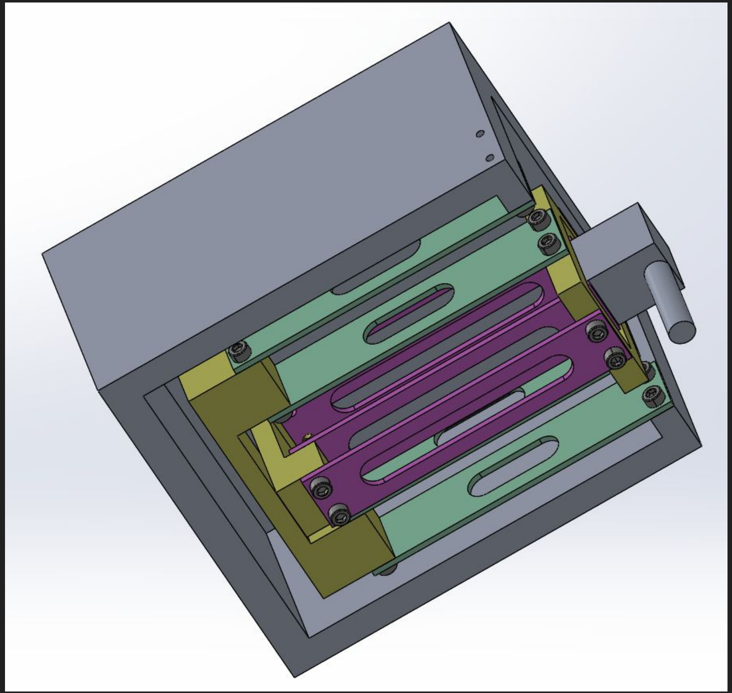


SPECIFICATION SHEET

Demand/Wish	Functional Requirements/ Constraints	Required/Target Values	Units/Scale
D	Velocity Range	0-10	mm/s
D	Max Linear movement distance	5	mm
D	Max normal load	100	mN
D	Max frictional force	25	mN
D	Normal load resolution	1	mN
D	Friction force resolution	1	µN
D	Project cost	40,000	$
D	Device Voltage	120	Volts
D	Max Dimensions	24x24x24	in

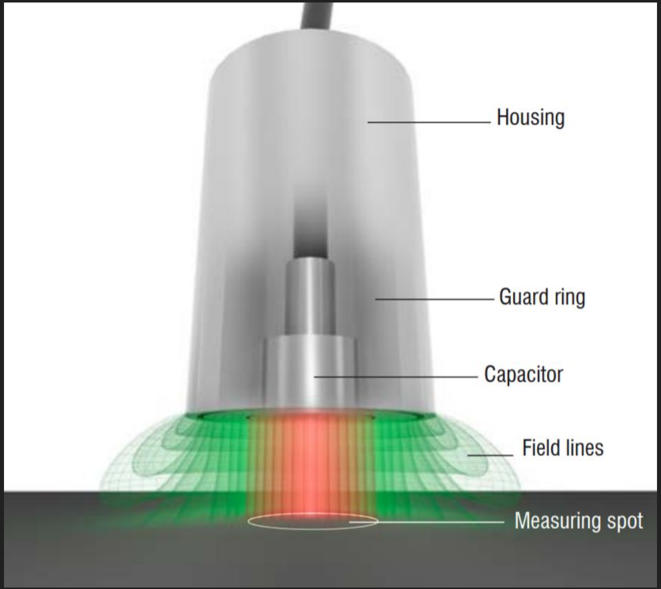
THE LOAD CELL

- Central to the tribometer
- Fully 1060 aluminum alloy
- Sensitive to small forces
- Precise deflections
- Task: Determine beam dimensions



Initial Load Cell Design (Bottom View)

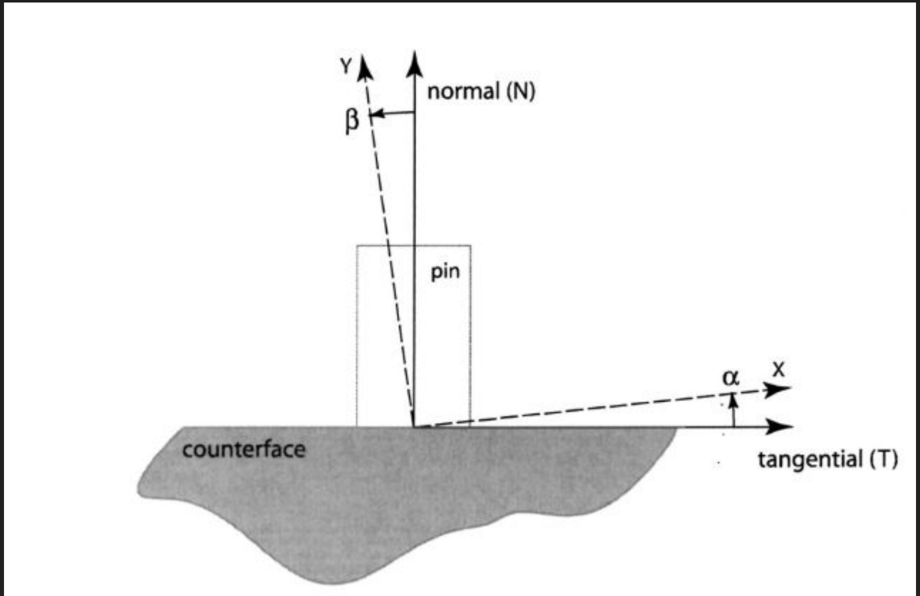
LOAD CELL REQUIREMENTS



Capacitive Displacement Sensor,
Micro-Epsilon Catalog

- Capacitive sensor selected by Henry
- The load cell must <u>deflect vertically between 0.3 mm and 0.4 mm</u> at max normal load of 100 mN
  - Normal load resolution of 1 mN
- The load cell must <u>deflect horizontally between 0.15 mm and 0.2 mm</u> at max friction force of 25 mN
  - Friction force resolution of 1 μN

LOAD CELL CONSTRAINTS

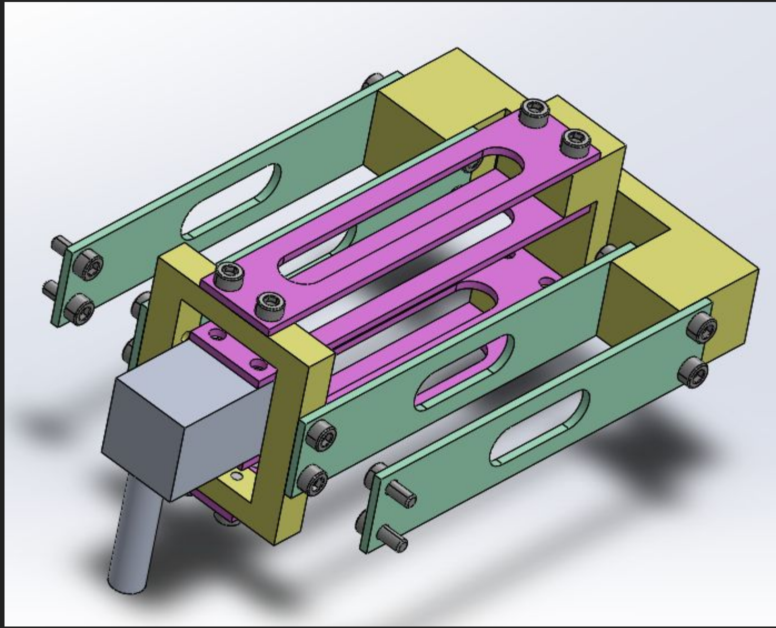


Probe Misalignment Geometry, University of Florida
Department of Mechanical and Aerospace Engineering

- Calculations done by Henry
- Small misalignments can create unacceptable error
- Max of 0.02° of misalignment
- Max unwanted deflections of < 5% of total deflection
- Preferably beams under 120 mm in length

WHY FOUR BEAMS?

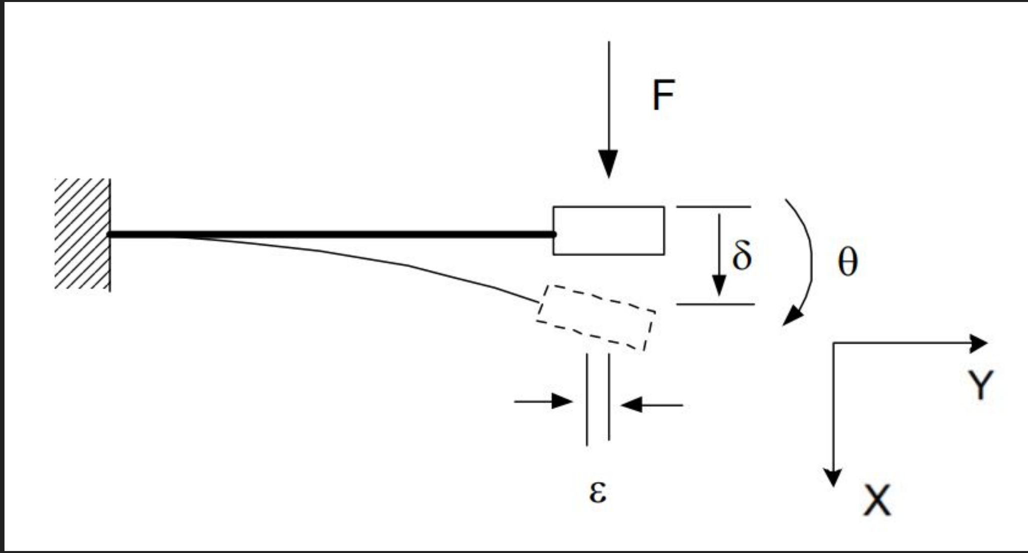
- Four vertical deflection beams (purple)
- Four horizontal deflection beams (green)



An Early Load Cell Design without the Outer Shell

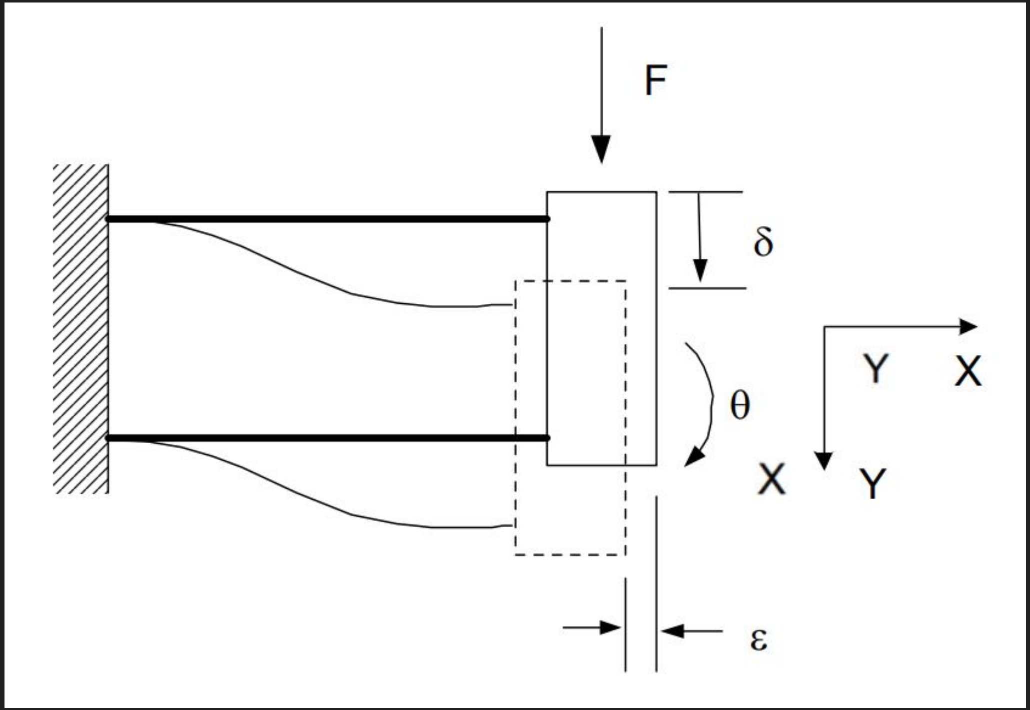
SINGLE BEAM MODEL

- Unwanted θ and δ_y (marked as Ɛ) at the tip
- Inaccurate sensor measurements



Simple Beam (Awtar, 2004)

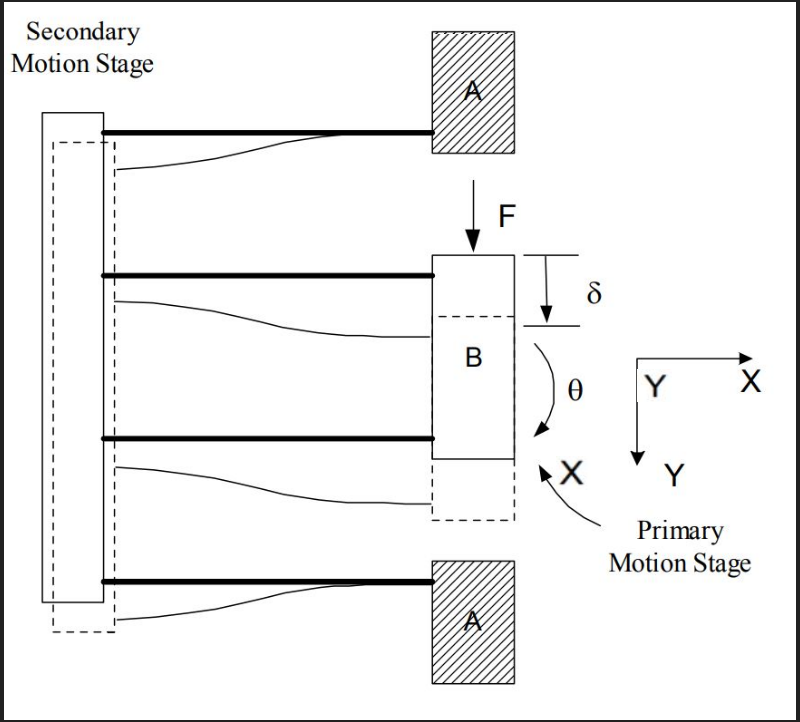
DUAL-BEAM MODEL



Conventional Parallelogram Flexure (Awtar, 2004)

- Eliminates θ
- Still creates δ_y

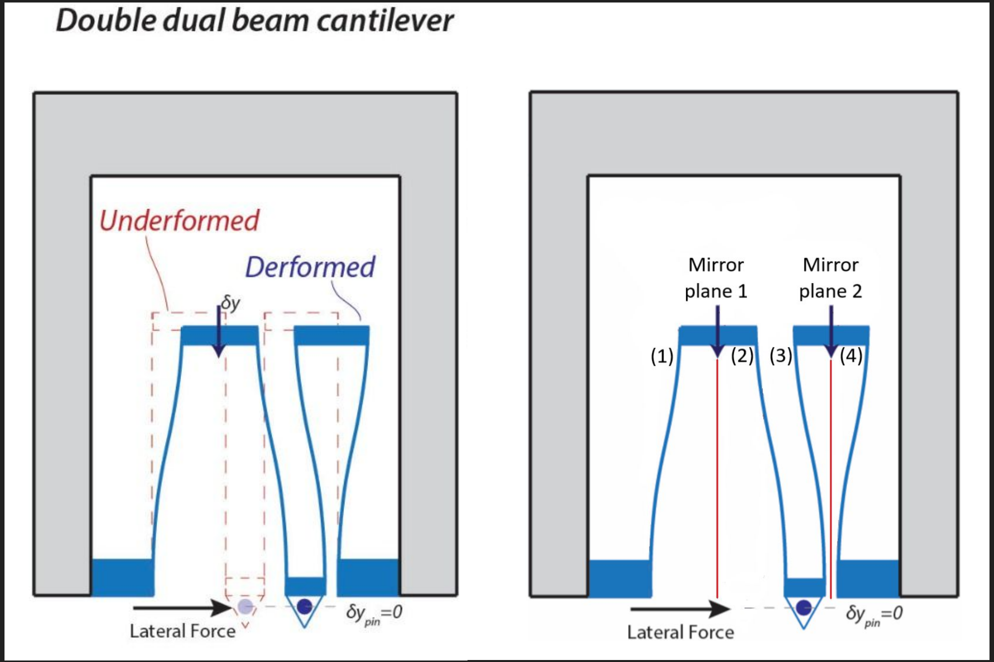
QUAD-BEAM MODEL

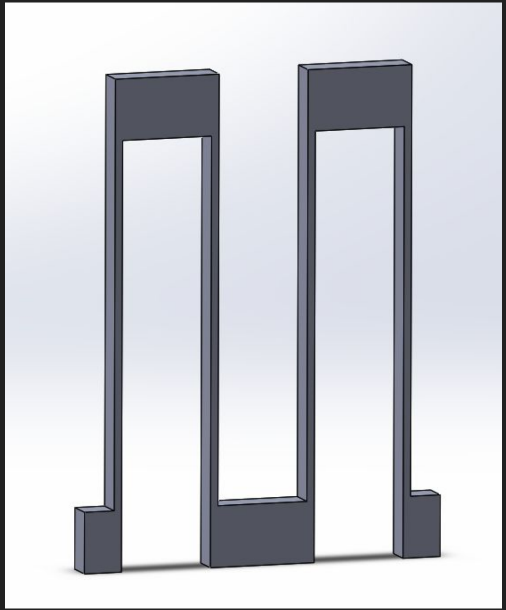


Double Parallelogram Flexure (Awtar, 2004)

- Eliminates θ
- Eliminates δ_y

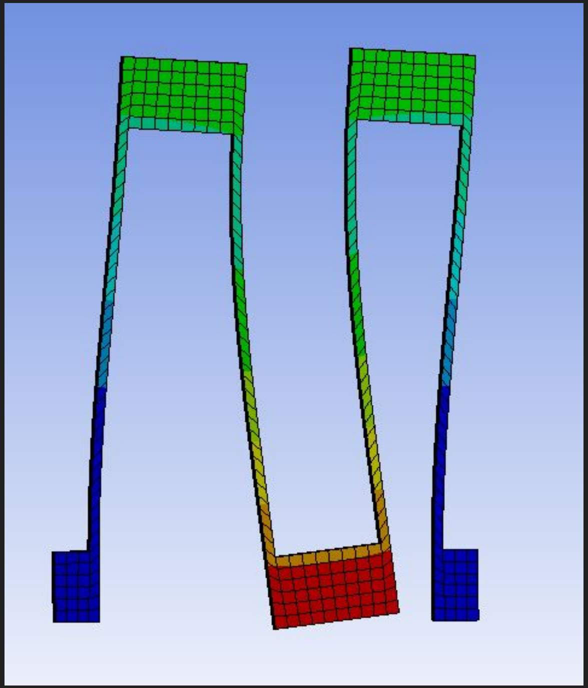
QUAD-BEAM MODEL





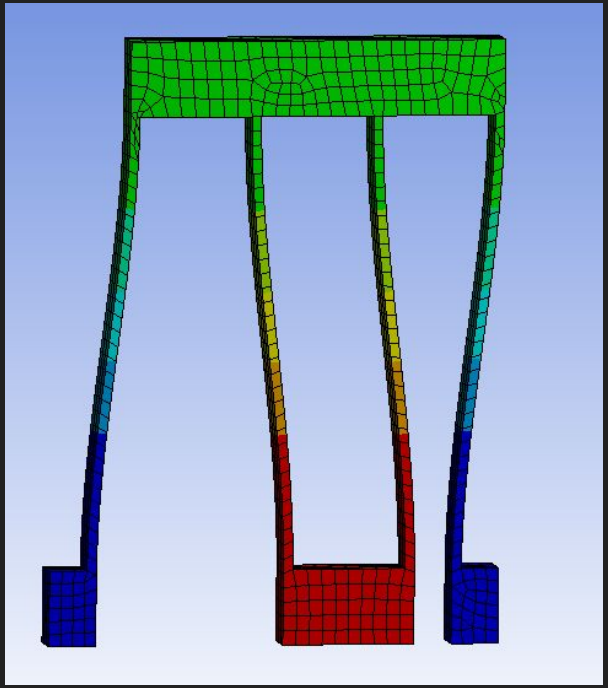
Quad-beam design, Mangolini Research Group

CONNECTING THE BEAMS



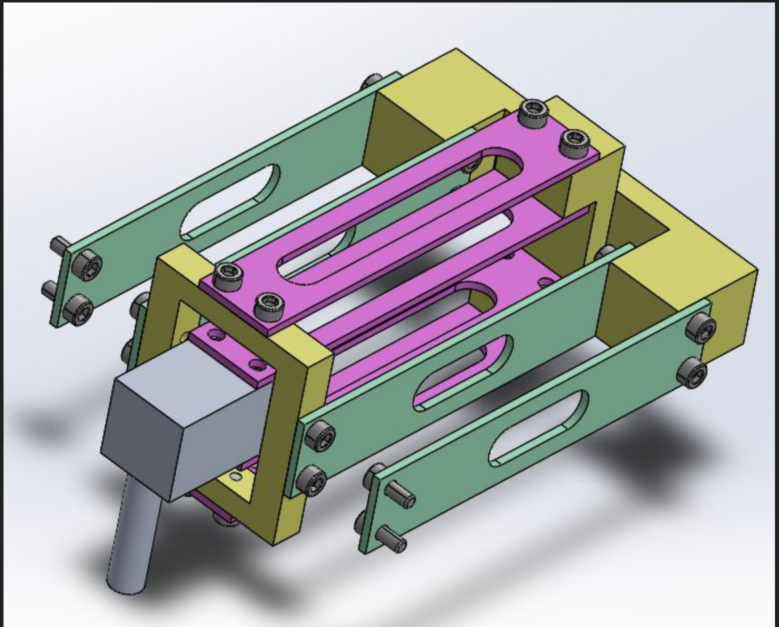
$\Theta = 4.325°$

/165 =



$\Theta = 0.0262°$

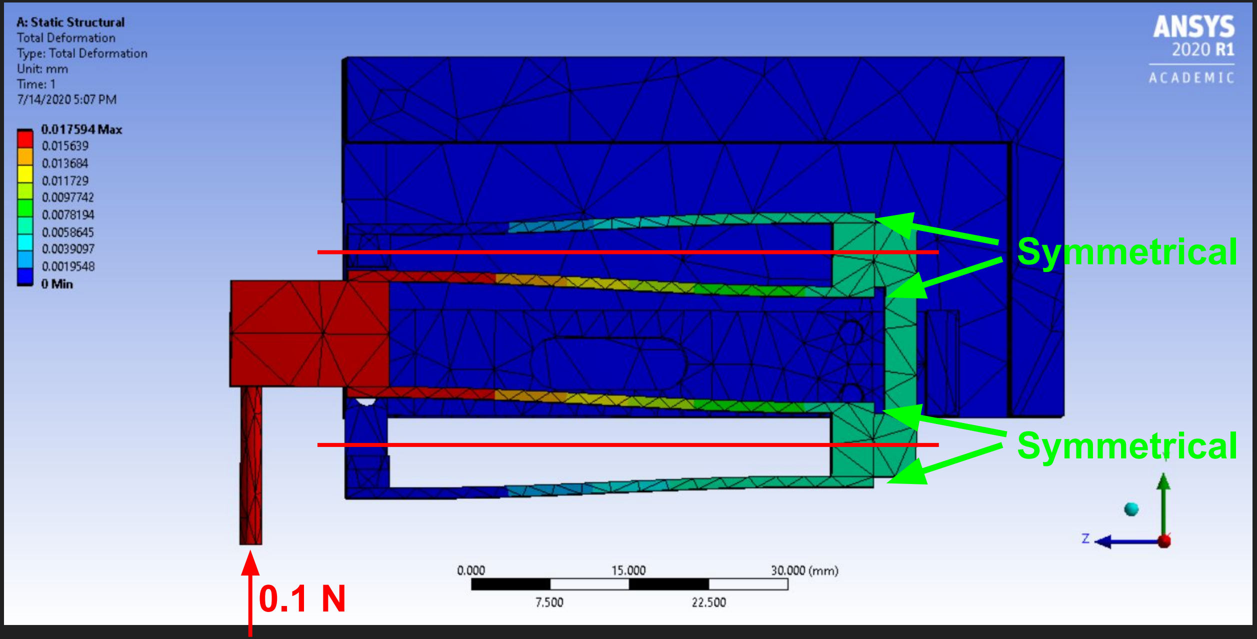
INITIAL LOAD CELL DESIGN



Initial Load Cell Design without the Outer Shell

- Model created by Thomas
- Slots dimensions are placeholders
- Slots increase deflection and are easy to manufacture

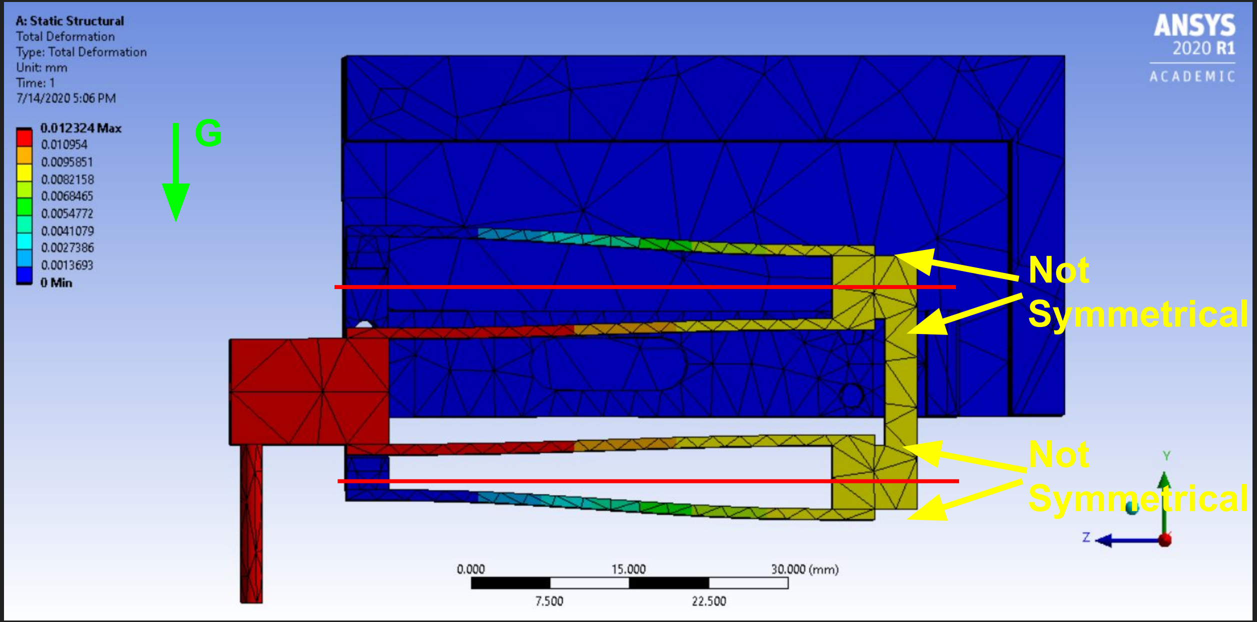
INITIAL LOAD CELL FEA



Cross Section Side View

- Normal load of 100 mN
- No gravity
- Proper symmetry

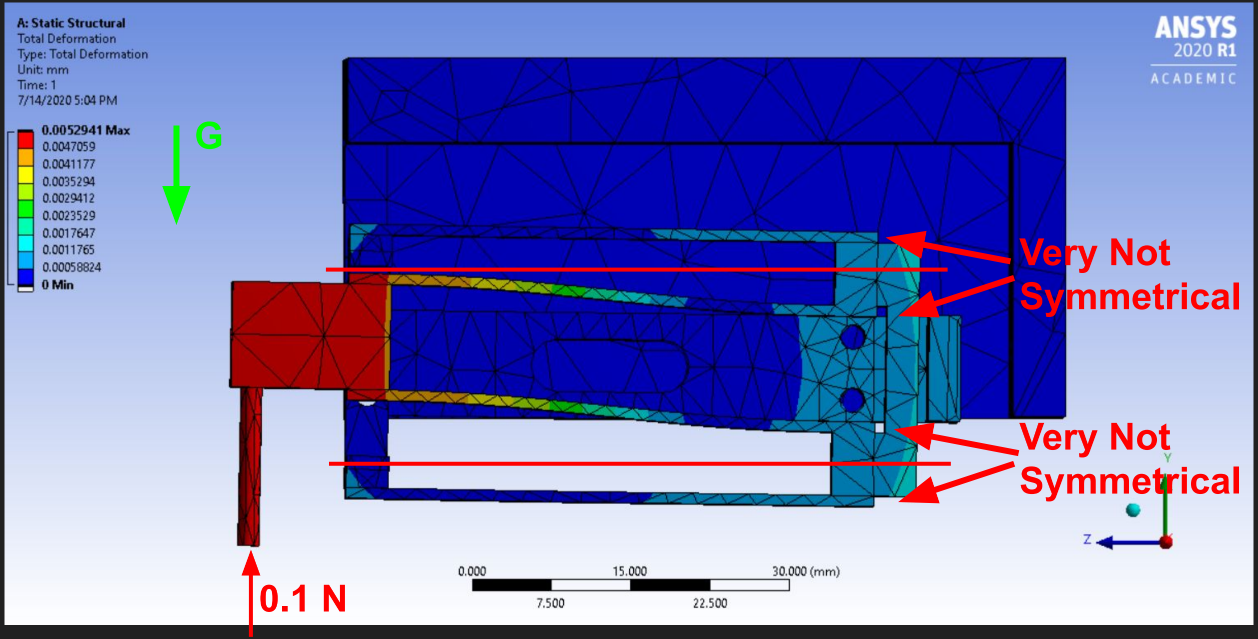
INITIAL LOAD CELL FEA



Cross Section Side View

- No normal load
- Only gravity (-Y axis)
- No symmetry

INITIAL LOAD CELL FEA

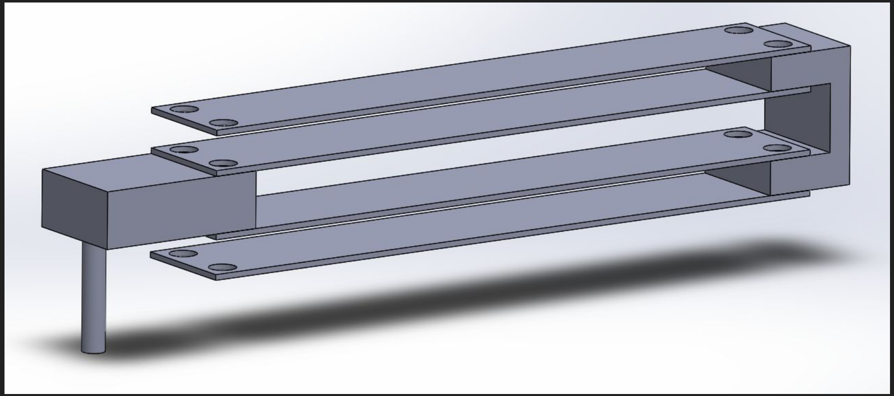


Cross Section Side View

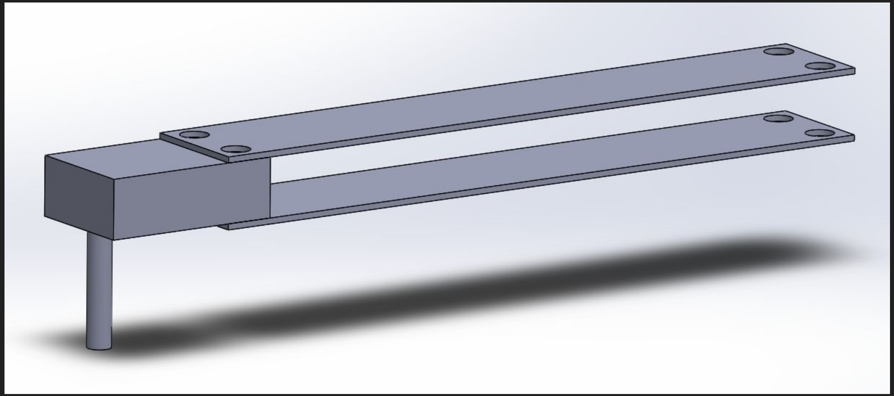
- Normal load of 100 mN
- Gravity (-Y axis)
- No symmetry

QUAD-BEAM VS DUAL-BEAM

Quad-beam model



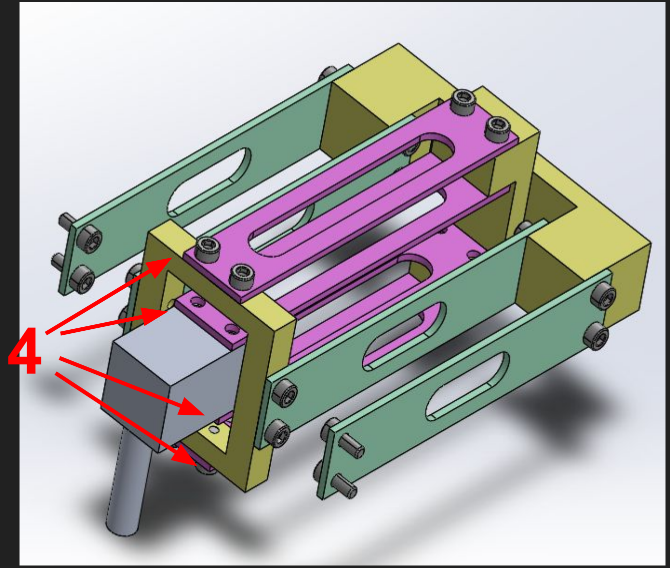
Dual-beam model



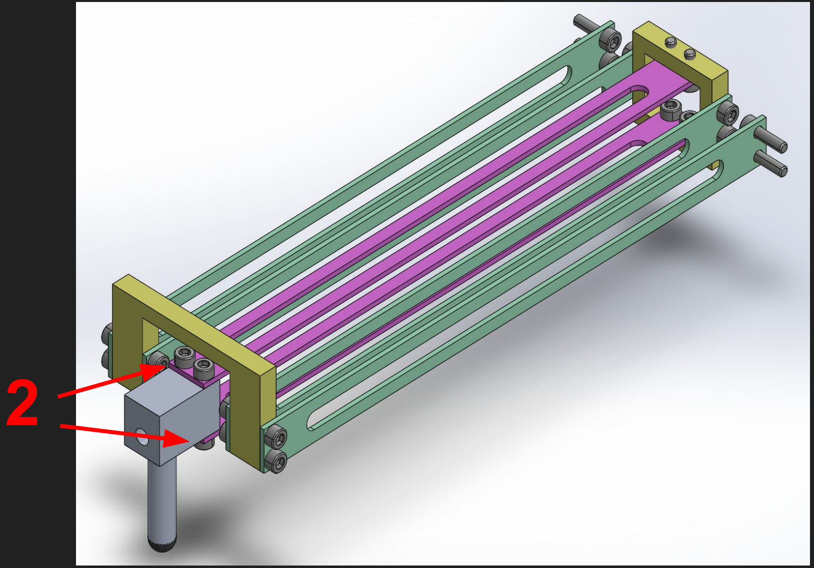
Z-axis Deflection: 1.1562e-4 mm $>$ Z-axis Deflection: 7.9299e-5 mm

RESULTANT CHANGES

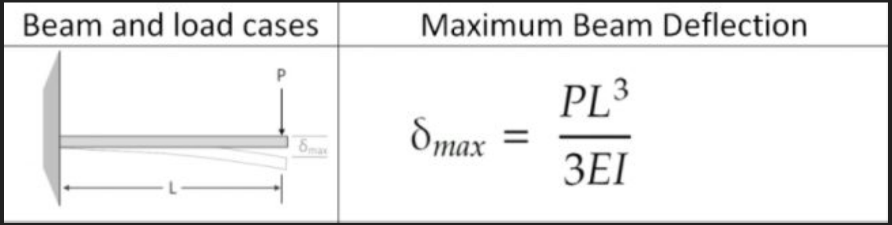
Old



New



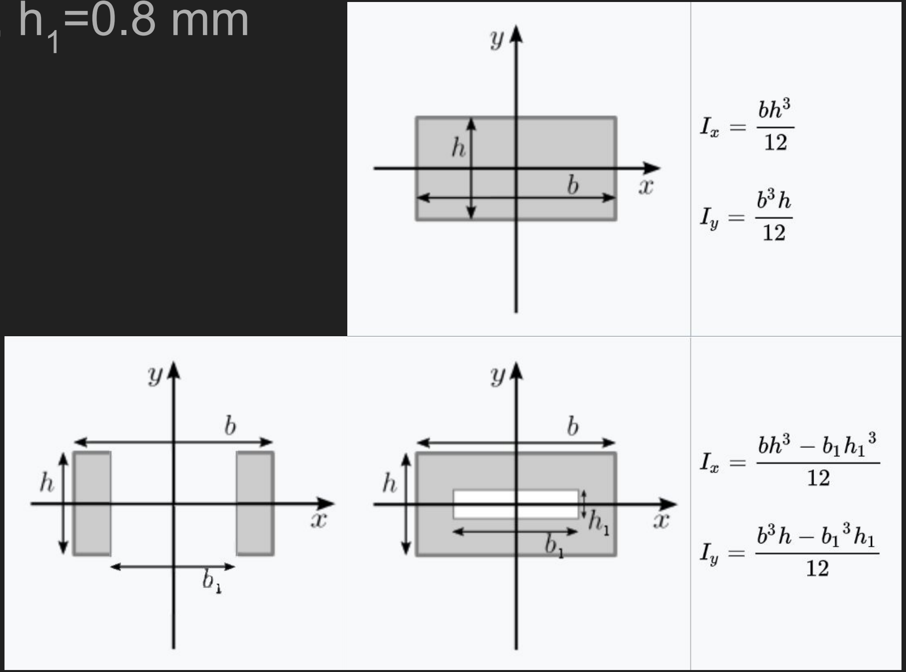
WHY THE SLOTS?



Slots change the moment of inertia, I

Assume b=13 mm, h=0.8 mm, b_1=6.5 mm, h_1=0.8 mm

- No slot
  - $I_x = 0.555\ L^4$
  - $I_y = 146.5\ L^4$
- Slot
  - $I_x = 0.277\ L^4$
  - $I_y = 128.2\ L^4$

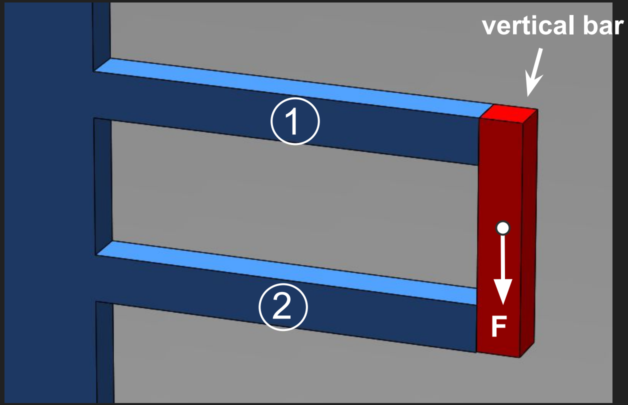


Good way to keep the beams short.

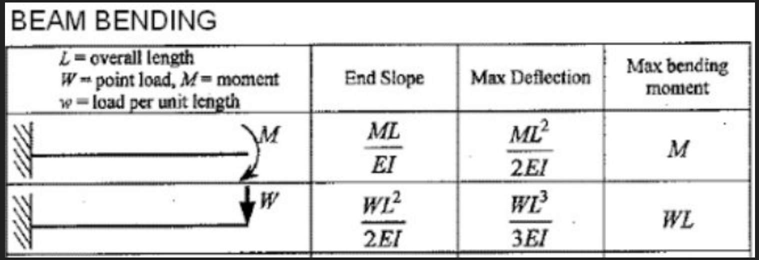
DUAL-BEAM MATHEMATICAL MODEL

Assumptions

1. Both beams are identical
2. Deflection and moment at the vertical bar fixture are the same for both beams
3. Due to symmetry, assume point load on one beam is W= F/2 to compute moment at the free end
4. End slope of both beams is equal to zero assuming the vertical bar stays orthogonal to the other two beams.



Dual cantilever beam schematic



BEAM BENDING

L = overall length W = point load, M = moment w = load per unit length	End Slope	Max Deflection	Max bending moment
M	$\frac{ML}{EI}$	$\frac{ML^2}{2EI}$	M
W	$\frac{WL^2}{2EI}$	$\frac{WL^3}{3EI}$	WL

Beam Bending, Learneasy

DUAL-BEAM MATHEMATICAL MODEL

Apply the principle of superposition to solve for maximum deflection of a dual cantilever beam.

4. End slope of both beams is equal to zero

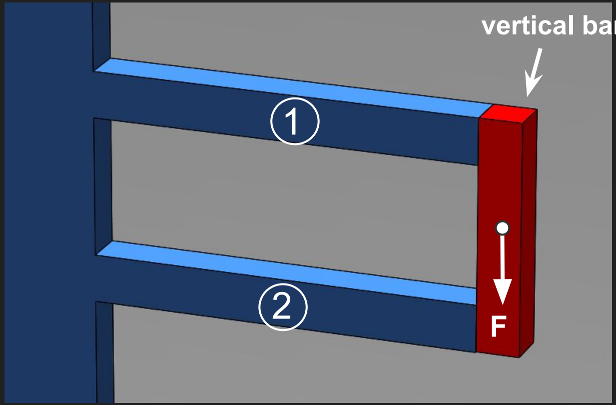
$$\frac{WL^2}{2EI} + \frac{ML}{EI} = 0$$

3. The point load on each beam is W= F/2

$$M = \frac{-FL}{4}$$

Find the deflection at the end of the beam

$$\delta_{total} = \frac{WL^3}{3EI} + \frac{ML^2}{2EI} \qquad \delta_{total} = \frac{FL^3}{24EI}$$



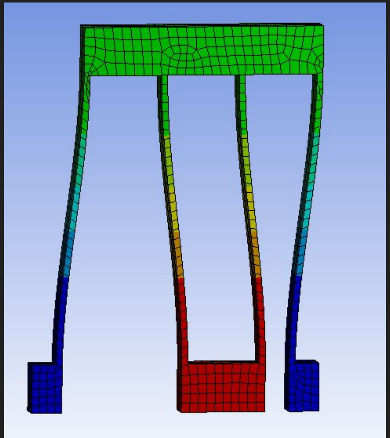
Dual cantilever beam schematic

BEAM BENDING

L = overall length W = point load, M = moment w = load per unit length	End Slope	Max Deflection	Max bending moment
M	$\frac{ML}{EI}$	$\frac{ML^2}{2EI}$	M
W	$\frac{WL^2}{2EI}$	$\frac{WL^3}{3EI}$	WL

Beam Bending, Learneasy

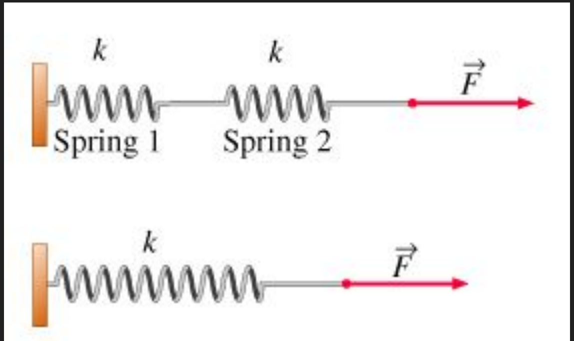
QUAD-BEAM MATHEMATICAL MODEL



Assumptions

1. All beams are identical
2. Each pair of beams acts like a spring with the same spring constant, k

Therefore, the deflection is equal to 2 times the deflection for a single pair of beams:



Dual-beam

$$\delta_{total} = \frac{FL^3}{24EI}$$

Quad-beam

$$\delta_{total} = \frac{FL^3}{12EI}$$

PYTHON SCRIPT

Developed by Irene

Inputs:

- Young’s modulus
- Normal load
- Friction force
- Beam height (thickness)
- Slot width
- Desired deflection

PYTHON SCRIPT

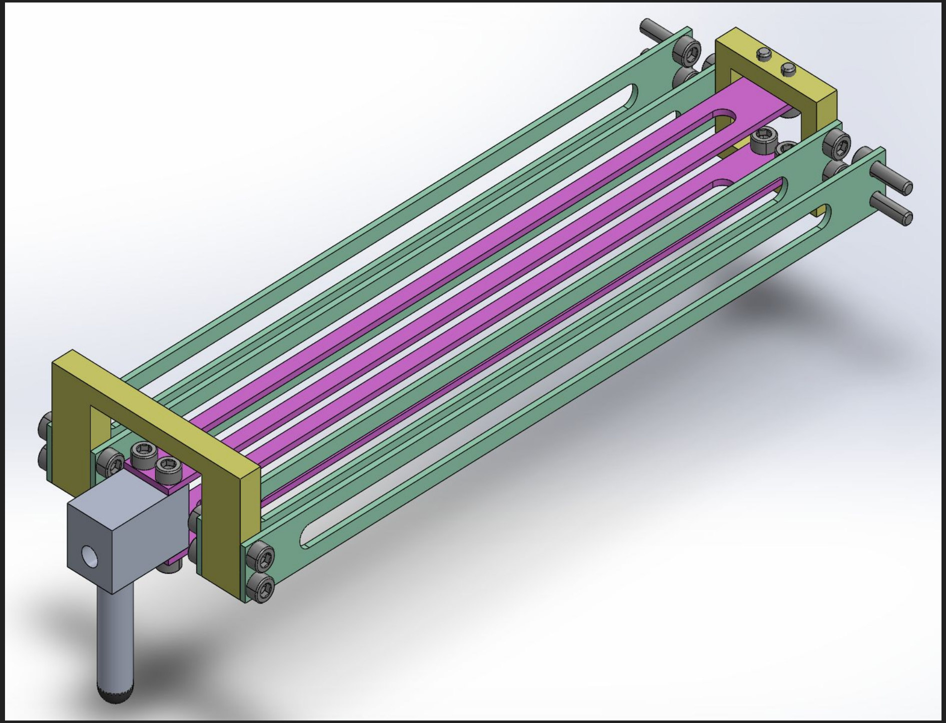
Outputs:

- Combinations of beam length and beam width that create the desired deflection

Selected beam dimensions that:

1. Kept the beam lengths low
2. Made the slots easy to machine

RESULTANT LOAD CELL MODEL



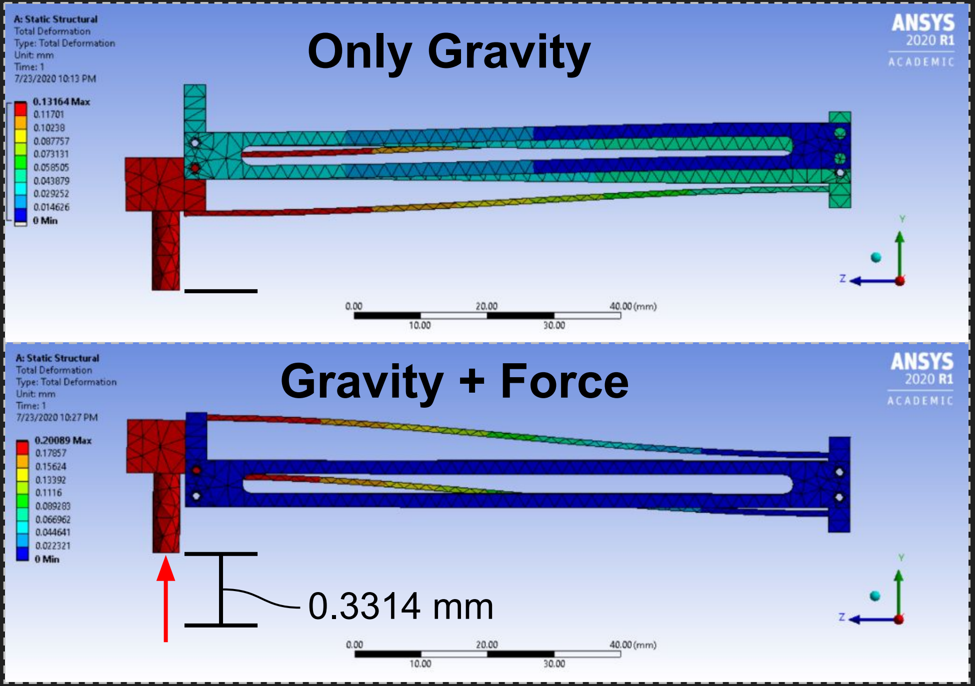
Redesigned by Thomas

Changes:

- Beam width of 8 mm
- Beam length of 100 mm
- Slot width of 4 mm

Task: <u>validate the model with FEA simulations</u>

LOAD CELL FEA



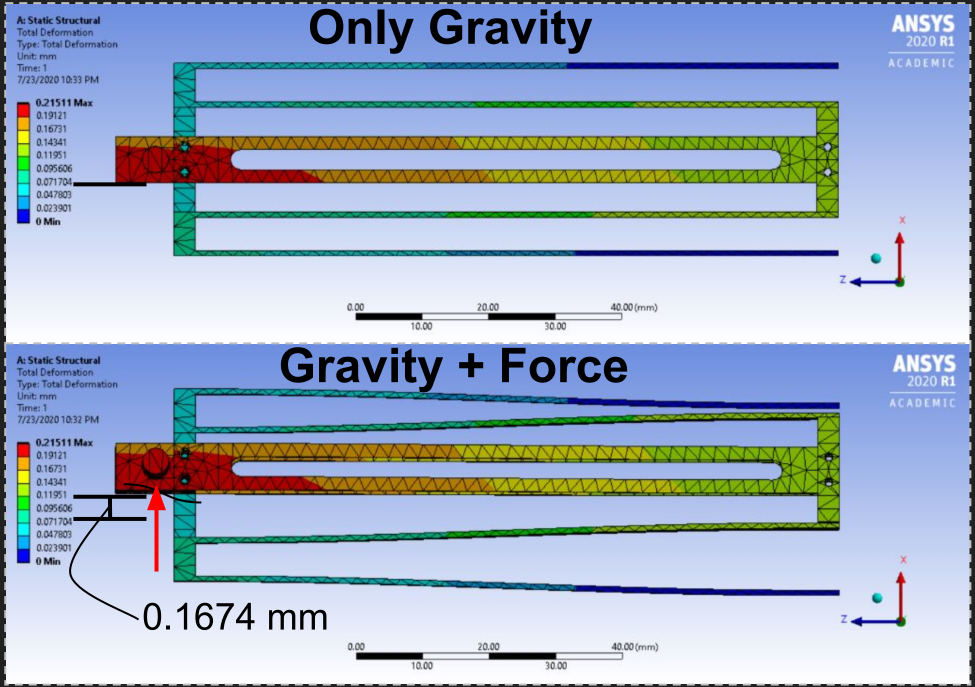
Side View

Y-axis deflection: 0.3314 mm
(Target: 0.3 - 0.4 mm)

Z-axis deflection: 6.369e-3 mm
(Max value: 5%, 1.657e-2 mm)

Max probe angle: 0.0184°
(Max value: 0.02°)

LOAD CELL FEA



Bottom View

X-axis deflection: 0.1674 mm
(Target: 0.15 - 0.2 mm)

Z-axis deflection: 1.1801e-4 mm
(Max value: 5%, 8.37e-3 mm)

Max probe angle: 0.119°
(Max value: 0.02°)

REDUCING TORSION

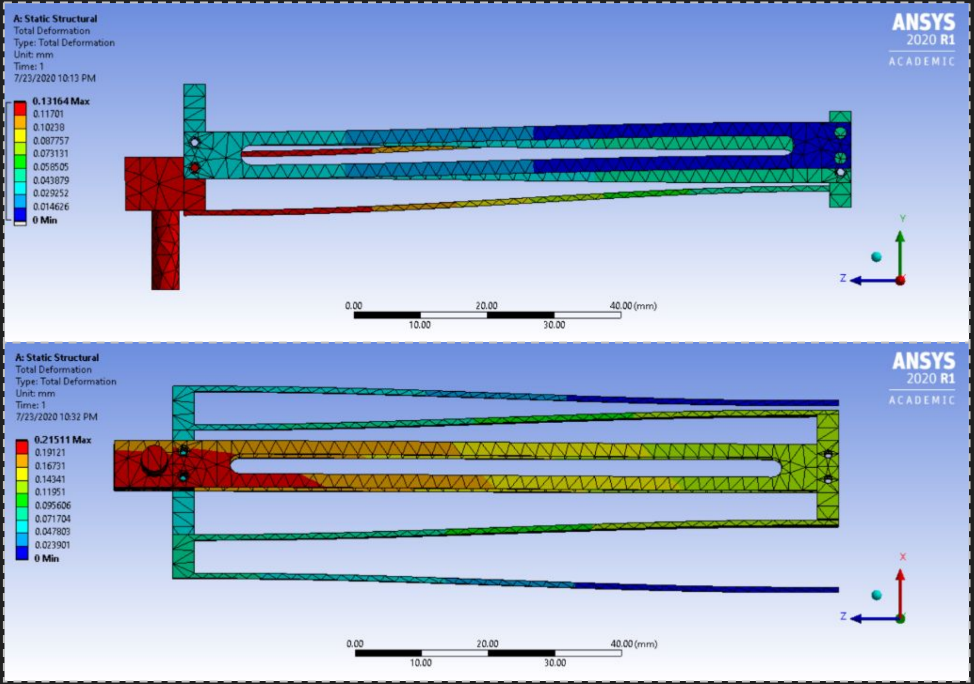
Changes made:

- Reduced probe length
- Separated beams

Results:

Max probe angle: 0.119° → 0.07°

(Max value: 0.02°)



DEFLECTION VS TWIST

Deflection scales cubically with length

Twist scales linearly with length

Dual-beam

$$\delta_{total} = \frac{FL^3}{24EI}$$

Quad-beam

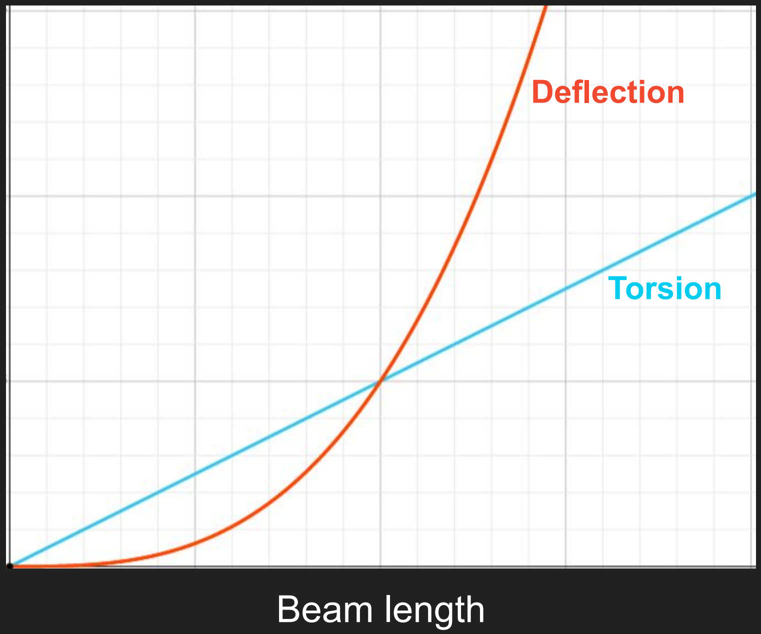
$$\delta_{total} = \frac{FL^3}{12EI}$$

Twist of a beam

$$\theta = \frac{TL}{\beta\, b\, t^3\, G}$$

DEFLECTION VS TWIST

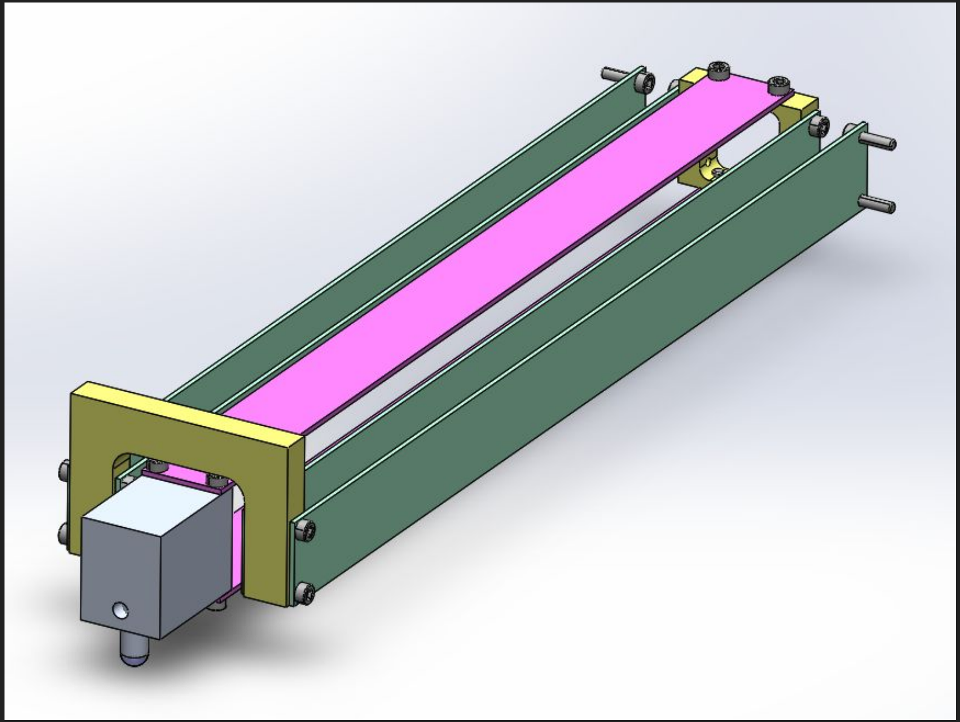
By increasing the moment of inertia and beam length, torsion becomes smaller.



- Increase the moment of inertia
- Scale the beam length to keep the deflection constant
- Angle of twist will be reduced

DEFLECTION VS TWIST

RESULTANT CHANGES



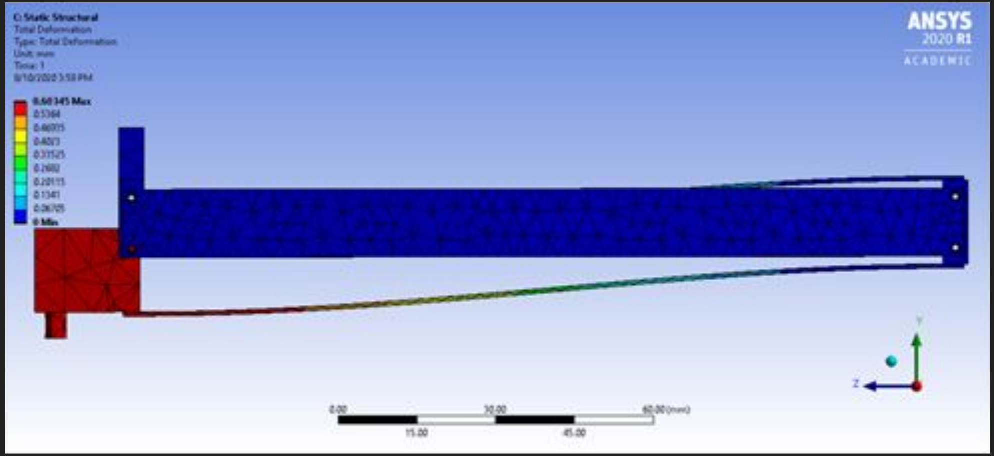
Modeled by Thomas

Changes:

- Removed slots
- Beam width from 8 mm to 13 mm
- Beam length from 100 mm to 160 mm

Task: validate the model with FEA simulations

FINAL LOAD CELL FEA



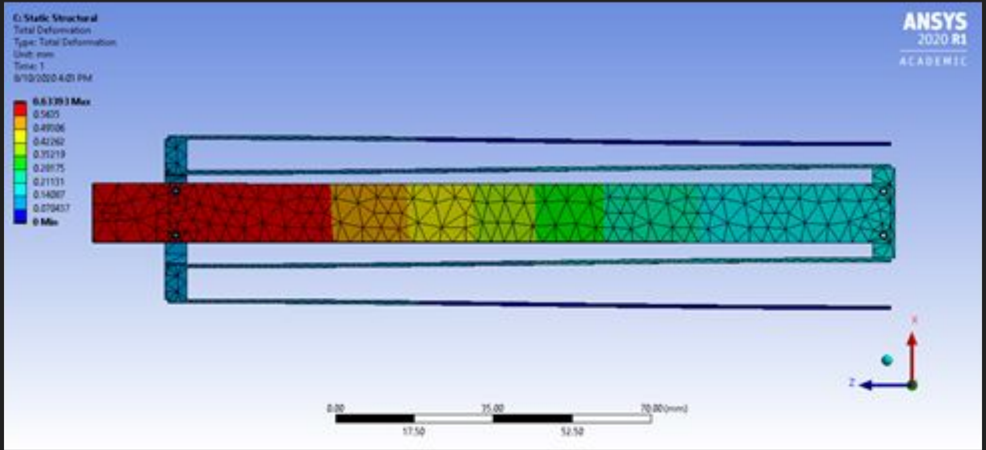
Side View

Y-axis deflection: <u>0.381 mm</u>
(Target: 0.3 - 0.4 mm)

Z-axis deflection: <u>1.237e-4 mm</u>
(Max value: 5%, 1.905e-2 mm)

Max probe angle: <u>0.00142°</u>
(Max value: 0.02°)

FINAL LOAD CELL FEA



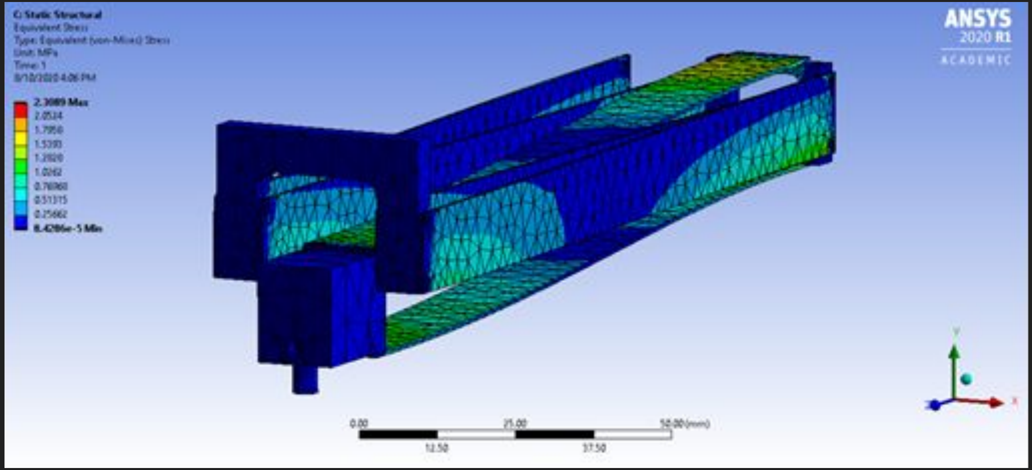
Bottom View

X-axis deflection: <u>0.191 mm</u>
(Target: 0.15 - 0.2mm)

Z-axis deflection: <u>1.107e-3 mm</u>
(Max value: 5%, 9.55e-3 mm)

Max probe angle: <u>0.0123°</u>
(Max value: 0.02°)

FINAL LOAD CELL STRESS ANALYSIS

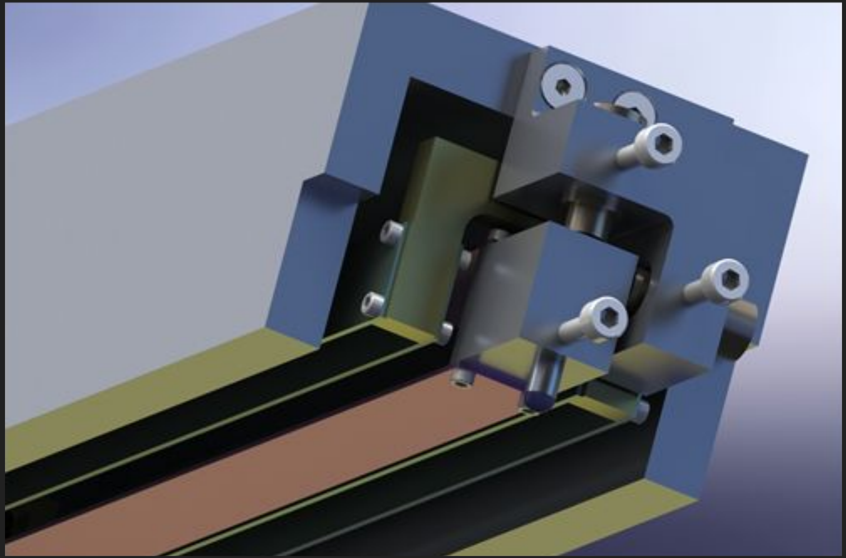


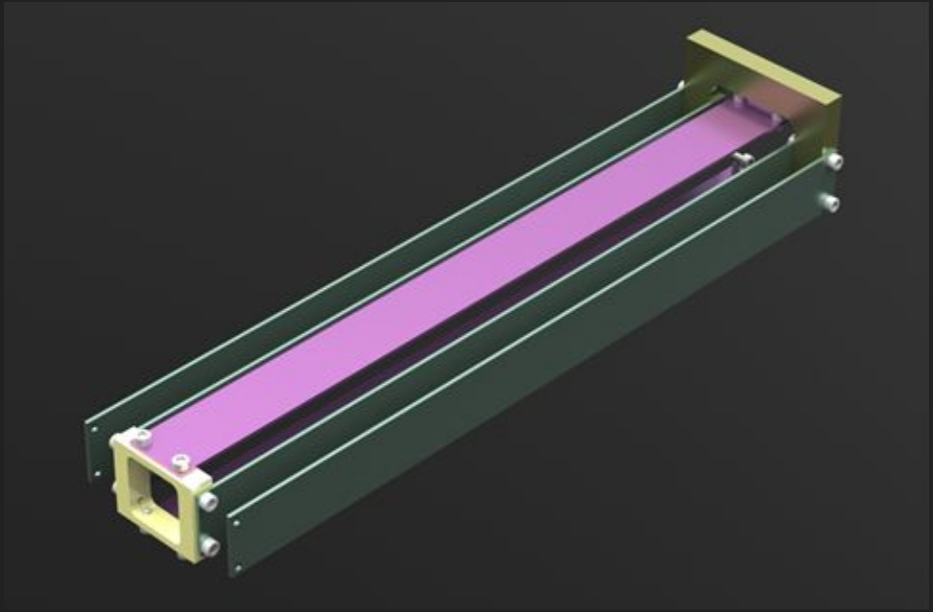
Max stress at max loading: 5.498 MPa

1xxx Aluminum yield strength: 70-175 MPa

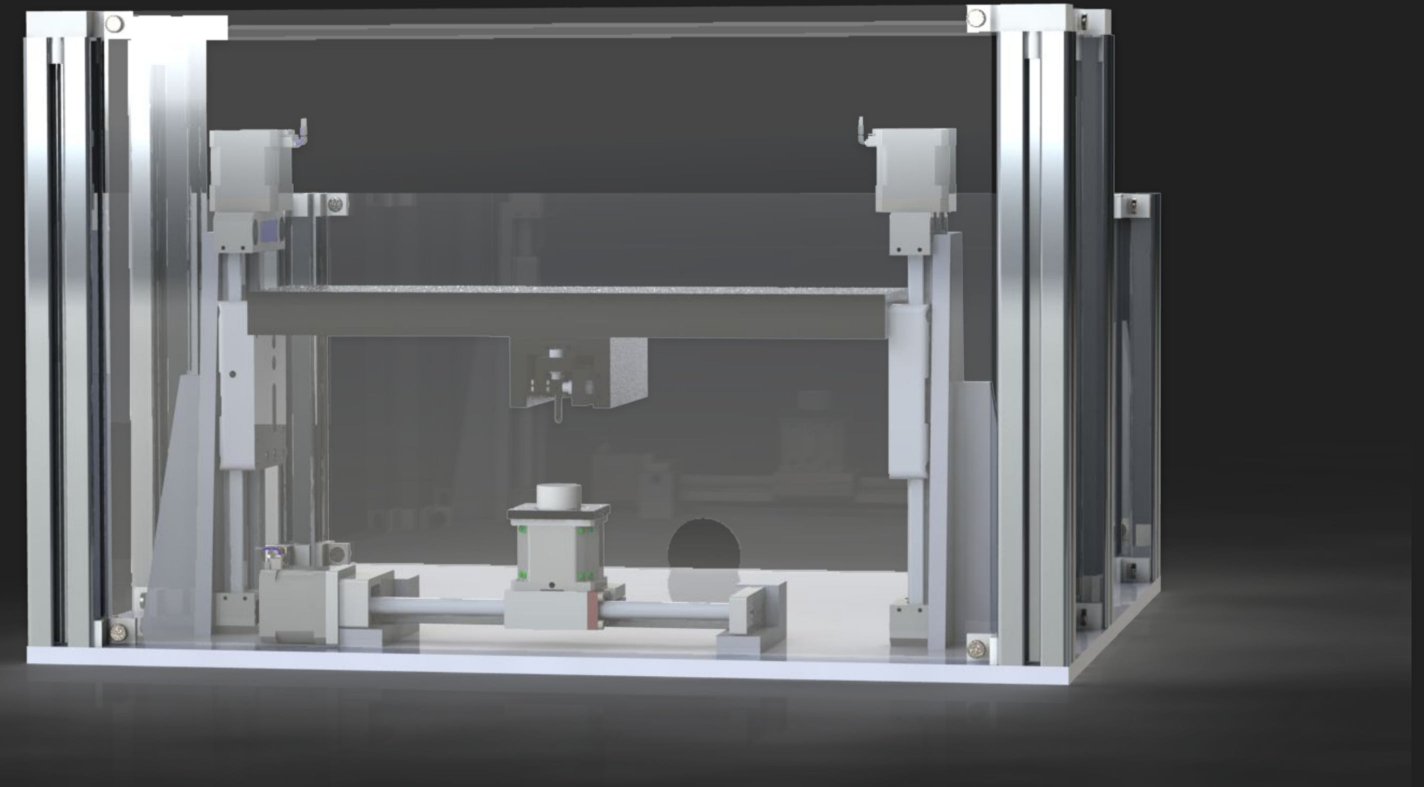
Minimum safety factor: 12.7 ✓

FINAL LOAD CELL MODEL





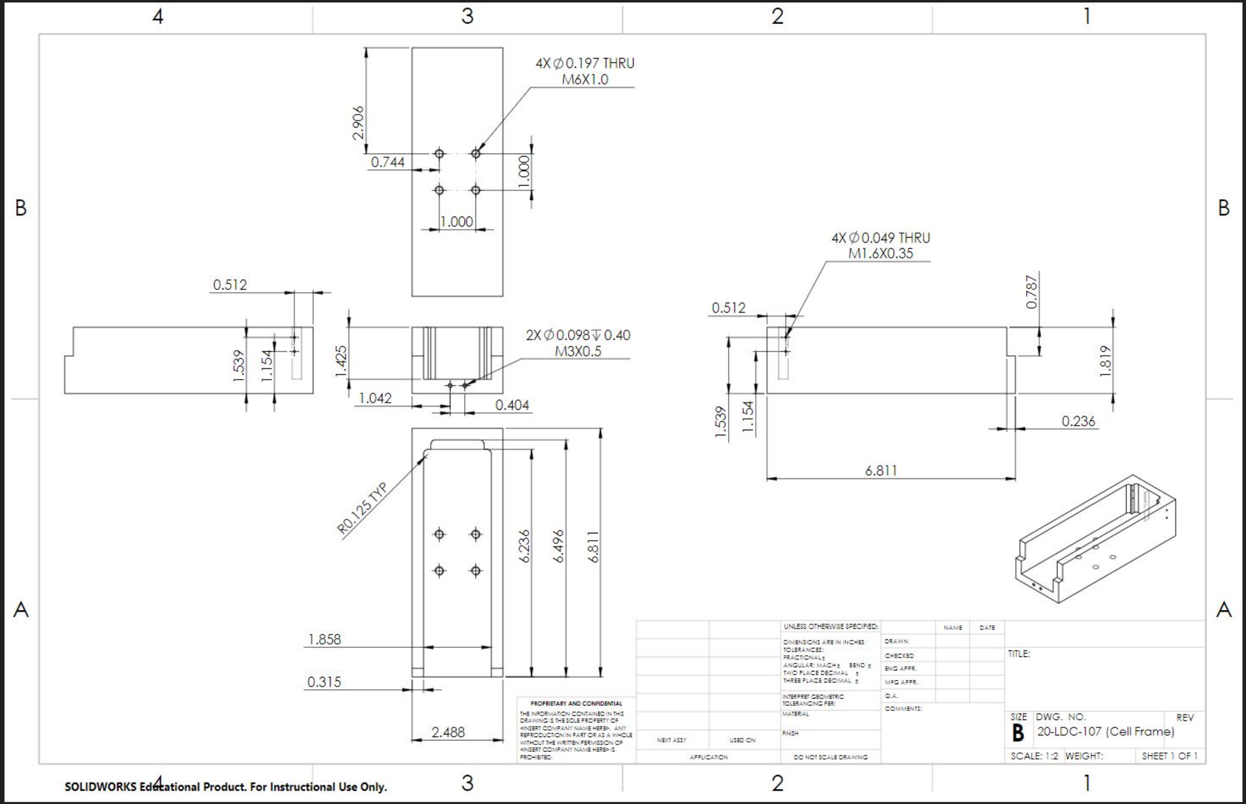
FINAL TRIBOMETER MODEL



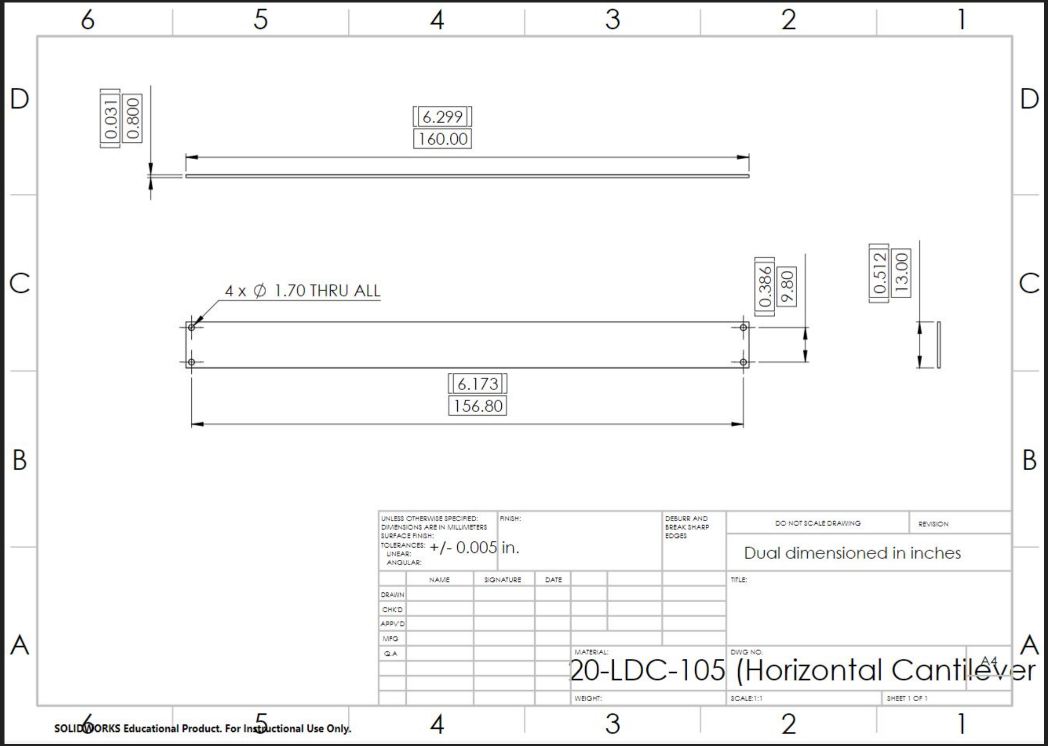
PROJECT DELIVERABLES

- Final engineering paper
- Python script
- CAD models and drawings
- ANSYS simulations
- Supplier quotes/contacts
- Bill of Materials
- Assembly instructions
- Calibration instructions

ENGINEERING DRAWINGS



ENGINEERING DRAWINGS



TRIBOMETER COST ANALYSIS

- Capacitive Sensors - $10,600
- 3 x Lead Screw Linear Actuators - $1,700
- Aluminum & Polycarbonate Stock - $850
- Piezo Actuator w/ Driver - $4,700
- Machining costs - $1,200
- Grand total: $19,050 (Budget: $40,000)
- Savings vs commercial alternatives: about $100,000

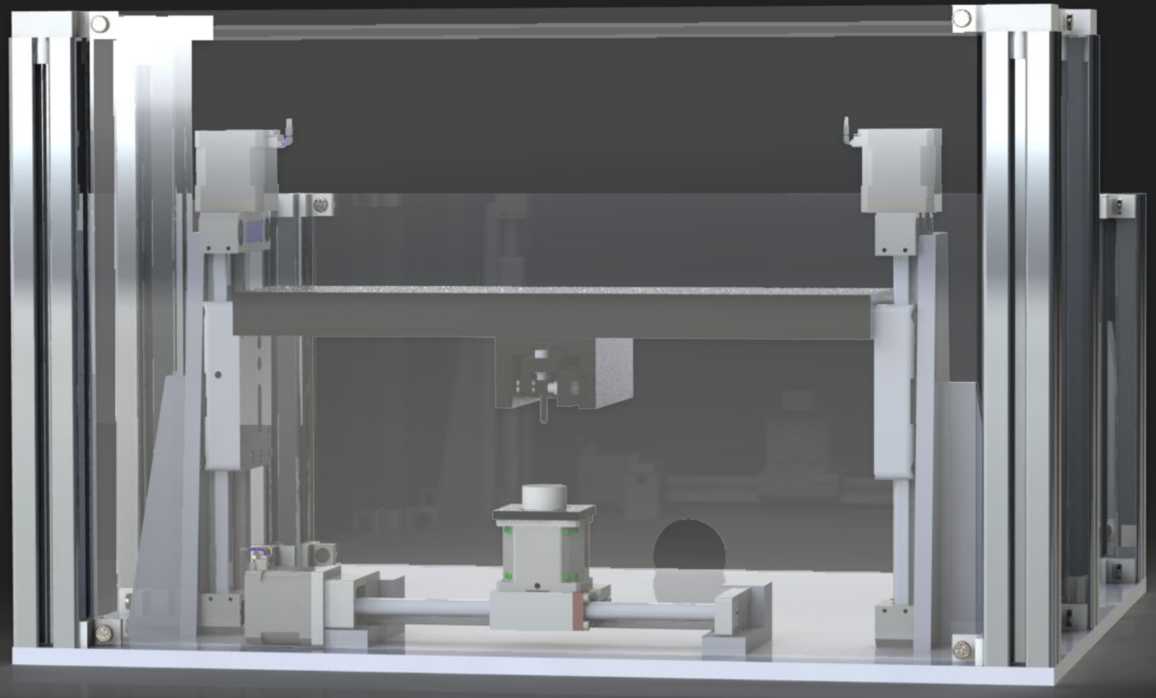
POSSIBLE IMPROVEMENTS

- Create a mathematical model for torsion before creating CAD models
- Shorten the beams even more
- Do a vibration analysis
- Fatigue failure analysis
- Do a tolerance analysis on the load cell beams

TRIBOMETER FUTURE WORK

- Order materials ✓
- Manufacture Tribometer Components
- Assemble Device
- Create LabView Code to Operate
- Calibrate and Test
- Make Adjustments
- Measure Samples

QUESTIONS?



POTENTIAL QUESTIONS

Q: If the capacitive sensor measures down to the micron, what about surface imperfections from machining?
A: We are only interested in the relative displacement, ΔX, not absolute displacement. Any surface imperfections will be measured in the initial and final measurements which means they will be accounted for and cancelled out.

Q: What are some features commercial tribometers have that you will not include?

1. Wear volume and rate
2. Temperature and humidity controls (already in a lab)
3. Pressure controls (no need for vacuum chamber)
4. Optical alignment sensors

Q: How accurate were the mathematical models?
A: The vertical deflection mathematical was off by up to 6.3% while the horizontal deflection model was off by up to 2.7%, shown in A2 and A3, respectively.

Q: Why were the slots on the cantilever beams removed so late in the design process?
A: They are relatively easy to machine and help reduce the total length of the beams. This trade-off was deemed justifiable to keep the length low. However, due to torsion, the beam length had to be increased, removing the purpose of slots.

POTENTIAL QUESTIONS

Q: What's another way to make a mathematical model besides superposition?

A: We can use the double integration method, where we find the moment of the beam in respect to x (along the length of the beam) then integrate twice. Then we use known values to find the integration constants and we end up with equations for the moment and deflections across the beam.

Q: Was a vibration analysis conducted on the system?

A: No, a vibration analysis was not part of the scope of our project. However, the tribometer was to be placed on a damped table.

Q: How did you calculate the machining costs?

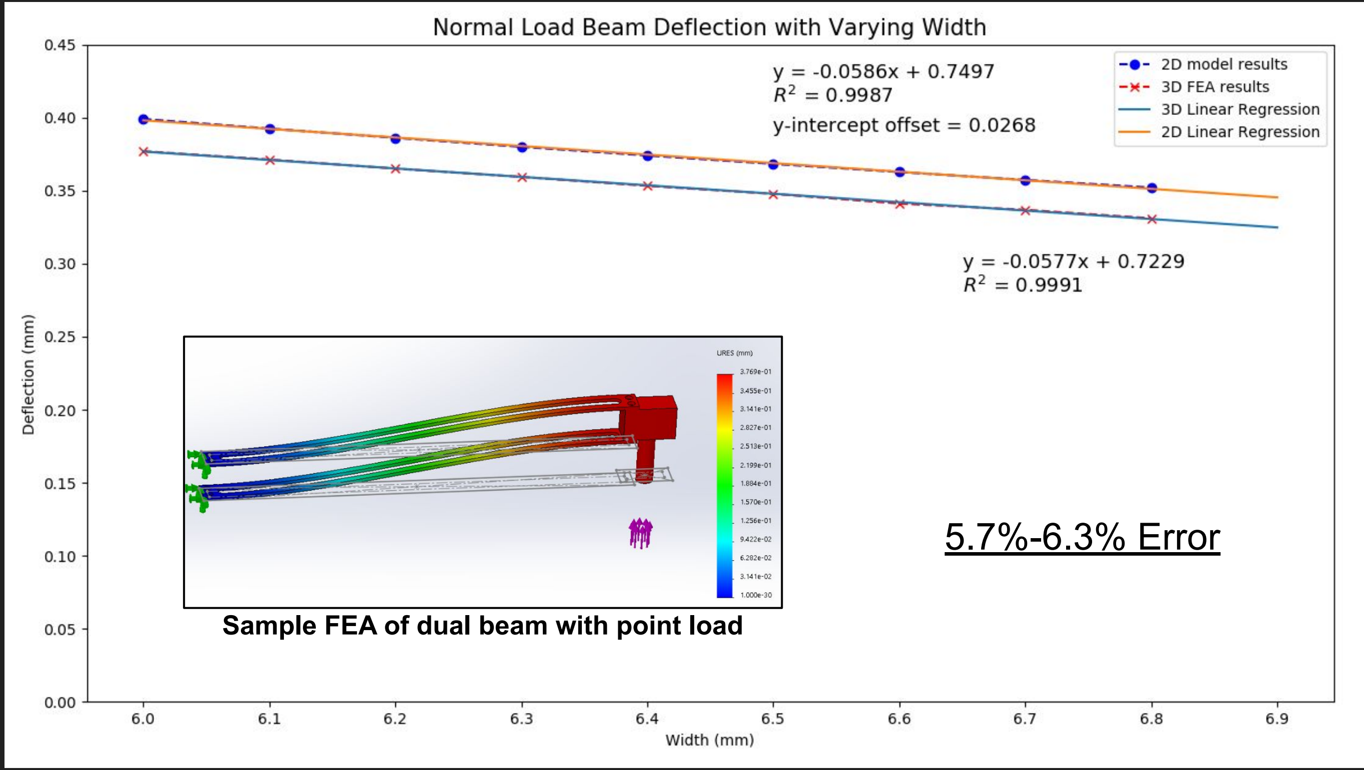
A: We got a quote from UT Austin's Mechanical Engineering Machine Shop for all the components.

APPENDIX

A1: BILL OF MATERIALS

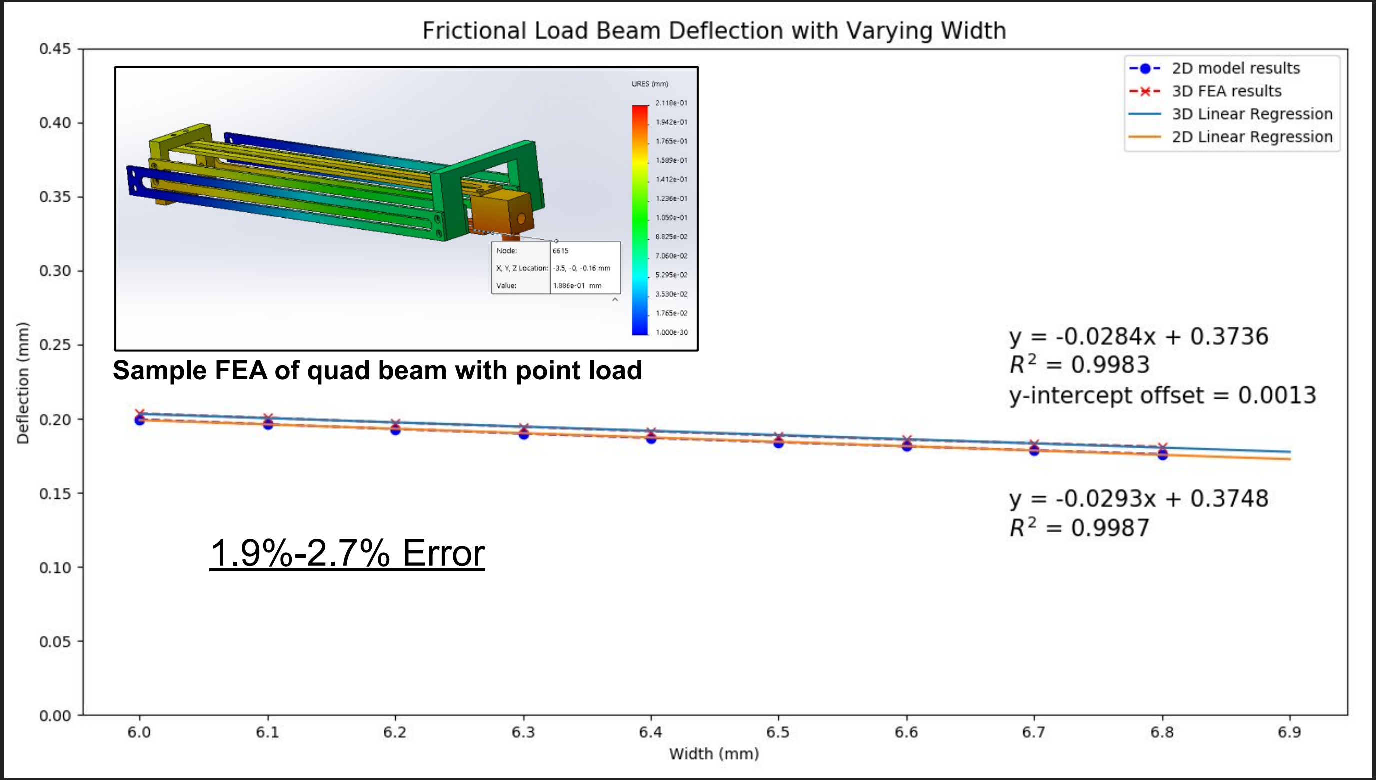
#	Item	Vendor	Unit Price	Quantity	Total
1	4" X 1" X 12" 6061 Aluminum	McMaster-Carr	$ 84.48	1	$ 84.48
2	12" X 48" X 1/8" Polycarbonate Sheet	McMaster-Carr	$ 25.52	7	$ 178.64
3	Linear Actuator (UGA040D-A10-0200-LS3A1-AX11-0)	PBC Linear	$ 562.31	2	$ 1,124.62
4	Piezo Actuator	MICRONIX USA LLC	$ 3,750.00	1	$ 3,750.00
5	Piezo Actuator Controller	MICRONIX USA LLC	$ 900.00	1	$ 900.00
6	Horizontal Compact Series Actuator (CSLSM10AXXR3A1-2LN-0210-0)	PBC Linear	$ 562.27	1	$ 562.27
7	1/2" X 24" X 24" MIC 6 Cast Aluminum Sheet	McMaster-Carr	$ 265.90	1	$ 265.90
8	40mm X 40mm 80/20 T-slot framing - 8ft Length	McMaster-Carr	$ 68.91	1	$ 68.91
9	DT6220 capacitive multi channel controller	Micro-Epsilon	$ 1,250.00	1	$ 1,250.00
10	DL6230 Demodulator with integrated preamplifier	Micro-Epsilon	$ 3,200.00	2	$ 6,400.00
11	CSE05/M8 Capacitive Sensor	Micro-Epsilon	$ 920.00	2	$ 1,840.00
12	CCg2,0B Sensor cable capaNCDT 2,0 m long	Micro-Epsilon	$ 360.00	2	$ 720.00
13	SCAC3/4 output cable analog capaNCDT 3m long	Micro-Epsilon	$ 170.00	2	$ 340.00
14	4" X 12" X 3/8" Tight-Tolerance Multipurpose 6061 Aluminum with Certificate	McMaster-Carr	$ 59.58	2	$ 119.16
15	2" X 12" X 3/8" Tight-Tolerance Multipurpose 6061 Aluminum with Certificate	McMaster-Carr	$ 46.48	1	$ 46.48
16	2-1/2" Thick, 6" x 6" Easy-to-Machine MIC6 Cast Aluminum Shee	McMaster-Carr	$ 91.39	1	$ 91.39
17	3/4" Thick, 6" x 6", Easy-to-Machine MIC6 Cast Aluminum Sheet	McMaster-Carr	$ 30.89	1	$ 30.89
18	Stepper Motor Drivers	Automation Direct	$ 40.00	3	$ 120.00
19	SFB3-8 M3 x 8 mm Countersunk hex heads	Misumi	$ 3.35	2	$ 6.70
20	CBPPS3-10 M3 x 10 mm Socket Head Cap Screws - with Soft Point	Misumi	$ 2.40	2	$ 4.80
21	Machining Cost	UTME Machine Shop	$ 1,215.00	1	$ 1,215.00
				Total	$19,119.24

A2: VERTICAL DEFLECTION MODEL ERROR

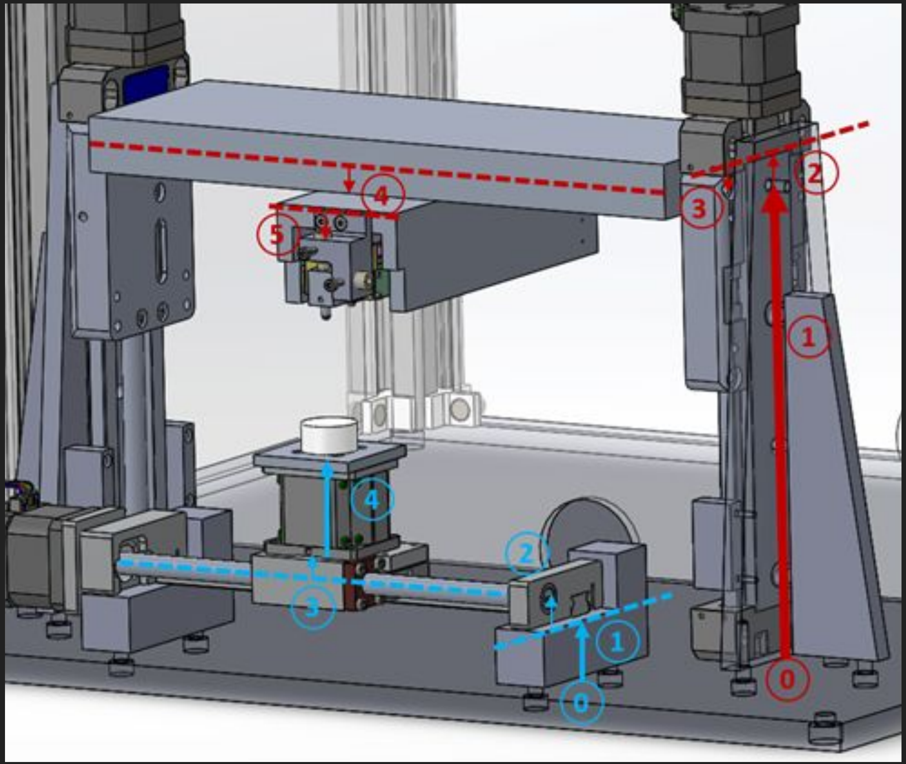


Sample FEA of dual beam with point load

A3: HORIZONTAL DEFLECTION MODEL ERROR



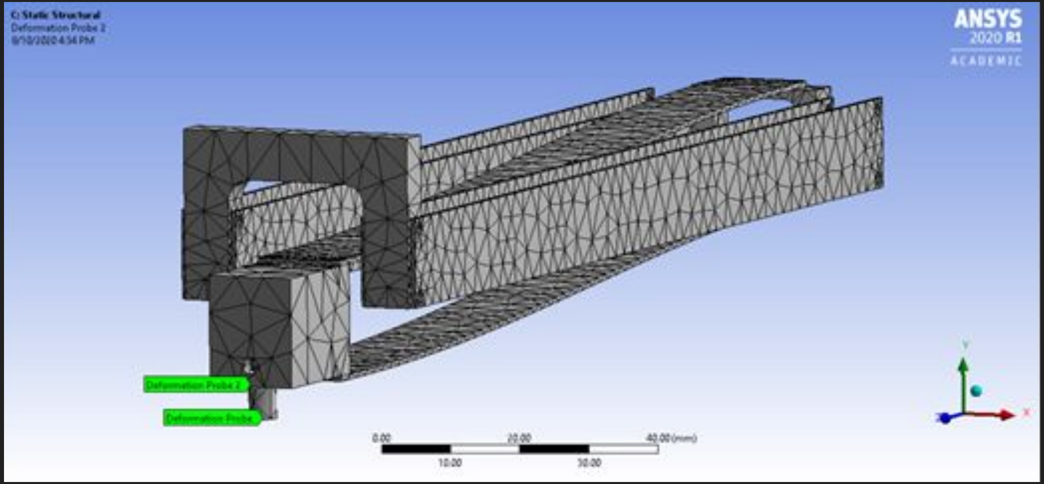
A4: ERROR ANALYSIS

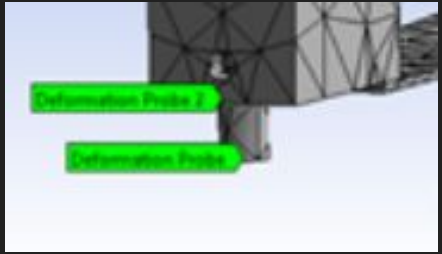


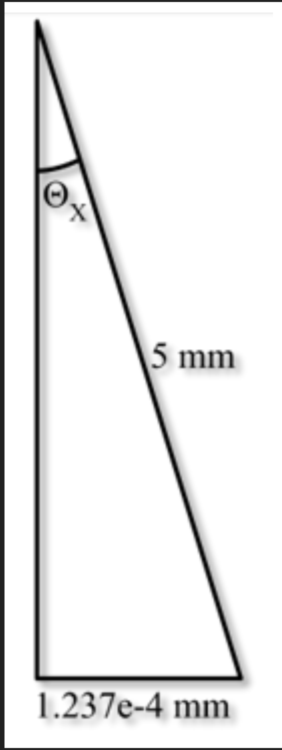
STAGE	DESCRIPTION FROM/TO	+ / -	MAXIMUM MAX / MIN	+ / -	MINIMUM MIN / MAX	TOTAL TOLERANCE	TOTAL TOLERANCE FOR MRSS	TOTAL TOLERANCE SQUARED
0	Mounting Base (Datum) to Linear Rail Support Trapezoid bottom surface	+	0.004	-	0.004	0.0080	0.0080	0.00006
1	Linear Rail Support Trapezoid bottom surface to Linear Rail Support Trapezoid through hole	+	0.005	-	0.005	0.0100	0.0100	0.00010
2	Linear Rail Support Trapezoid through hole to Linear Rail Support Trapezoid top surface	+	0.005	-	0.005	0.0100	0.0100	0.00010
3	Linear Rail Support Trapezoid top surface to Verticle Carriage through hole	+	0.005	-	0.005	0.0100	0.0100	0.00010
4	Verticle Carriage through hole to Cell Frame top surface	+	0.002	-	0.002	0.0040	0.0040	0.00002
5	Cell Frame top surface to Probe Mount top surface	+	0.002	-	0.002	0.0040	0.0040	0.00002
	TOTAL		0.023		-0.023	0.046	0.030	0.020
						WORST CASE	MRSS	RSS

STAGE	DESCRIPTION FROM/TO	+ / -	MAXIMUM MAX / MIN	+ / -	MINIMUM MIN / MAX	TOTAL TOLERANCE	TOTAL TOLERANCE FOR MRSS	TOTAL TOLERANCE SQUARED
0	Mounting Base (Datum) to Compact Actuator Mounting Bracket bottom surface	+	0.004	-	0.004	0.0080	0.0080	0.00006400
1a	Compact Actuator Mounting Bracket bottom surface to Compact Actuator Mounting Bracket top surface	+	0.005	-	0.005	0.0100	0.0100	0.00010000
1b	Compact Actuator Mounting Bracket top surface to Linear Actuator Bracket bottom surface	+	0.005	-	0.005	0.0100	0.0100	0.00010000
2	Linear Actuator Bracket bottom surface to Linear Actuator Bracket bottom through hole	+	0.005	-	0.005	0.0100	0.0100	0.00010000
3	Linear Actuator Bracket bottom through hole to Horizontal Carriage top surface	+	0.0001	-	0.0001	0.0002	0.0002	0.00000004
4	Horizontal Carriage top surface to Piezostage measuring surface	+	0.0001	-	0.0001	0.0002	0.0002	0.00000004
	TOTAL		0.0192		-0.0192	0.0384	0.029	0.019
						WORST CASE	MRSS	RSS

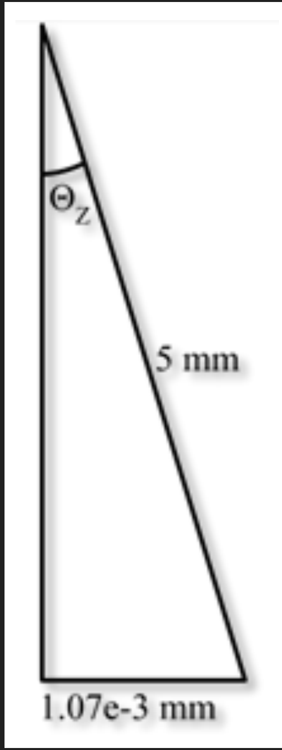
A5: MISALIGNMENT MEASUREMENT





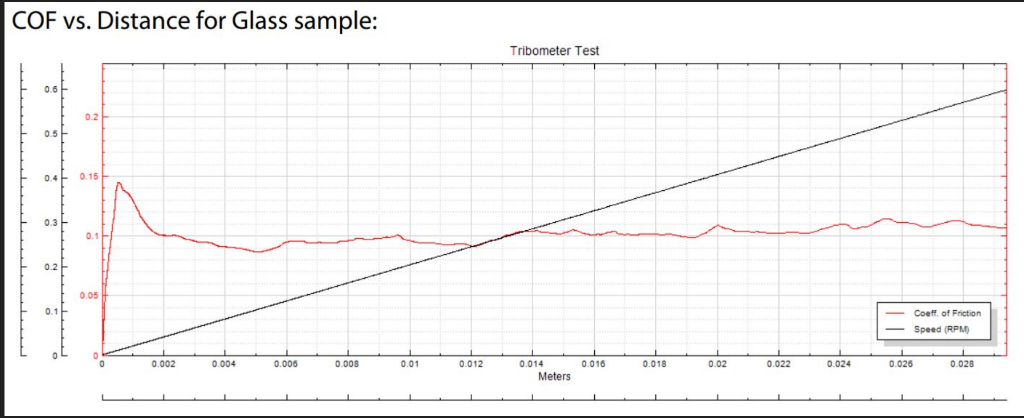


Θ_x Triangle

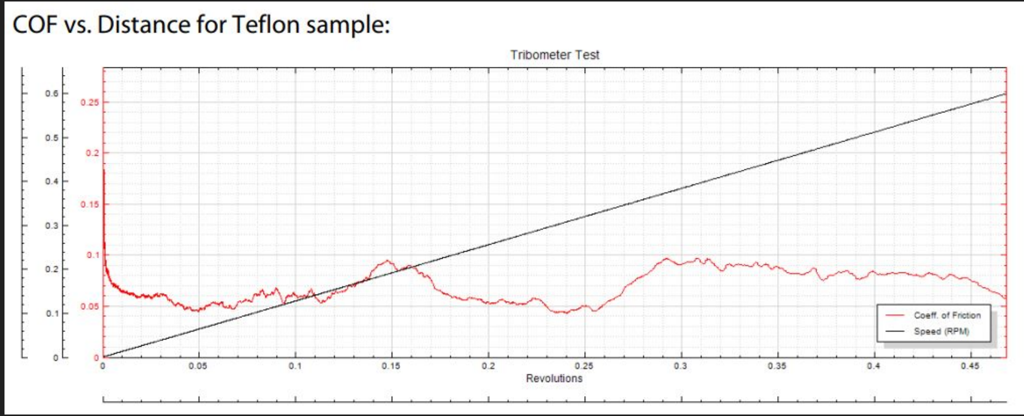


Θ_z Triangle

A6: FRICTION MEASUREMENTS



COF vs. Distance for Glass, NANOVEA, 2014



COF vs. Distance for Teflon, NANOVEA, 2014

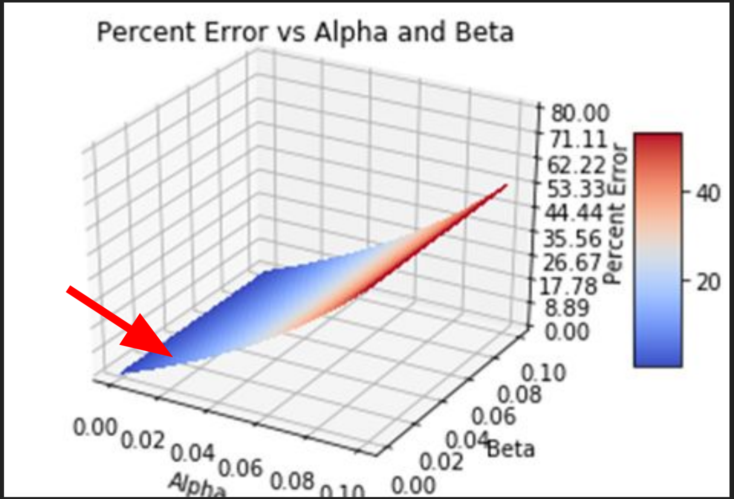
A7: PROBE MISALIGNMENT

$$F_X = F_f \cos\alpha + F_n \sin\alpha = F_n(\sin\alpha + \mu\cos\alpha)$$

$$F_Y = F_n \cos\beta - F_f \sin\beta = F_n(\cos\beta - \mu\sin\beta)$$

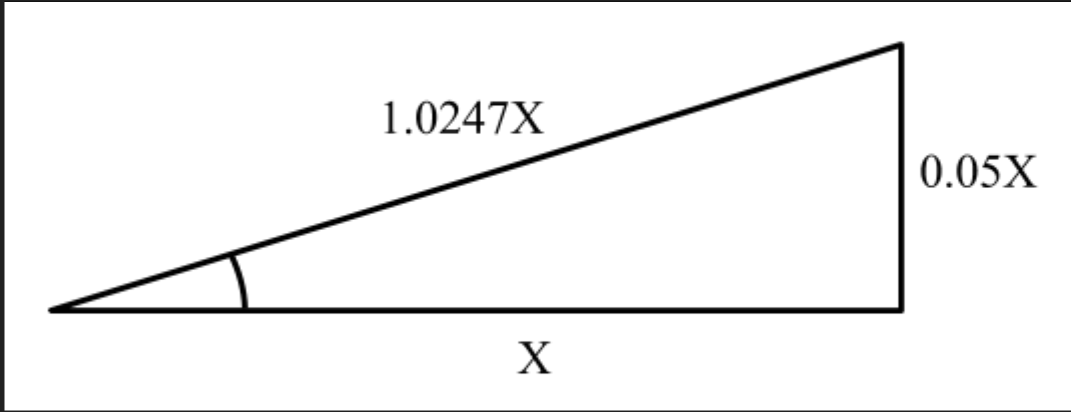
$$\mu = \frac{F_X \cos\beta - F_Y \sin\alpha}{F_Y \cos\alpha + F_X \sin\beta}$$

$$E = \frac{\mu - \mu'}{\mu} = \frac{\mu\cos\beta - \mu^2\sin\beta - \mu\cos\alpha - \sin\alpha}{\mu\cos\beta - \mu^2\sin\beta}$$



Equations from *The Difficulty of Measuring Low Friction: Uncertainty Analysis for Friction Coefficient Measurements,* by Dr. Schmitz.

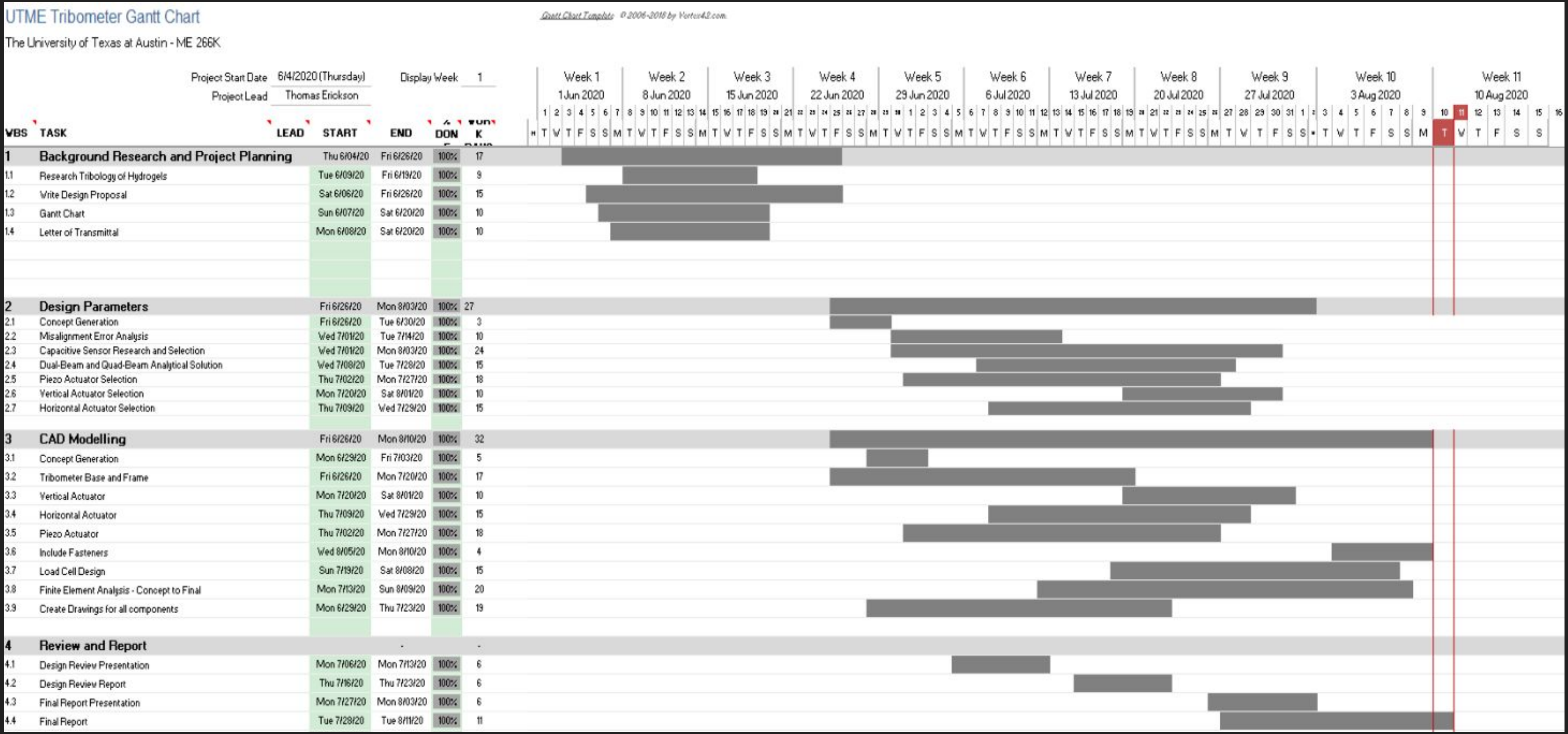
A8: Z-AXIS DEFLECTION ERROR



X = Horizontal tribometer distance

A 5% Z-axis deflection creates a 2.5% error in the horizontal tribometer distance.

A9: GANTT CHART


UTME Tribometer Gantt Chart

The University of Texas at Austin - ME 266K

Project Start Date 6/4/2020 (Thursday) Display Week 1

Project Lead Thomas Erickson

VBS	TASK	LEAD	START	END	% DONE	WORK DAYS
1	**Background Research and Project Planning**		Thu 6/04/20	Fri 6/26/20	100%	17
1.1	Research Tribology of Hydrogels		Tue 6/09/20	Fri 6/19/20	100%	9
1.2	Write Design Proposal		Sat 6/06/20	Fri 6/26/20	100%	15
1.3	Gantt Chart		Sun 6/07/20	Sat 6/20/20	100%	10
1.4	Letter of Transmittal		Mon 6/08/20	Sat 6/20/20	100%	10
2	**Design Parameters**		Fri 6/26/20	Mon 8/03/20	100%	27
2.1	Concept Generation		Fri 6/26/20	Tue 6/30/20	100%	3
2.2	Misalignment Error Analysis		Wed 7/01/20	Tue 7/14/20	100%	10
2.3	Capacitive Sensor Research and Selection		Wed 7/01/20	Mon 8/03/20	100%	24
2.4	Dual-Beam and Quad-Beam Analytical Solution		Wed 7/08/20	Tue 7/28/20	100%	15
2.5	Piezo Actuator Selection		Thu 7/02/20	Mon 7/27/20	100%	18
2.6	Vertical Actuator Selection		Mon 7/20/20	Sat 8/01/20	100%	10
2.7	Horizontal Actuator Selection		Thu 7/09/20	Wed 7/29/20	100%	15
3	**CAD Modelling**		Fri 6/26/20	Mon 8/10/20	100%	32
3.1	Concept Generation		Mon 6/29/20	Fri 7/03/20	100%	5
3.2	Tribometer Base and Frame		Fri 6/26/20	Mon 7/20/20	100%	17
3.3	Vertical Actuator		Mon 7/20/20	Sat 8/01/20	100%	10
3.4	Horizontal Actuator		Thu 7/09/20	Wed 7/29/20	100%	15
3.5	Piezo Actuator		Thu 7/02/20	Mon 7/27/20	100%	18
3.6	Include Fasteners		Wed 8/05/20	Mon 8/10/20	100%	4
3.7	Load Cell Design		Sun 7/19/20	Sat 8/08/20	100%	15
3.8	Finite Element Analysis - Concept to Final		Mon 7/13/20	Sun 8/09/20	100%	20
3.9	Create Drawings for all components		Mon 6/29/20	Thu 7/23/20	100%	19
4	**Review and Report**			-		-
4.1	Design Review Presentation		Mon 7/06/20	Mon 7/13/20	100%	6
4.2	Design Review Report		Thu 7/16/20	Thu 7/23/20	100%	6
4.3	Final Report Presentation		Mon 7/27/20	Mon 8/03/20	100%	6
4.4	Final Report		Tue 7/28/20	Tue 8/11/20	100%	11

A9: FINAL RESOLUTION

Normal load range: 0 - 100 mN
Desired normal load resolution: 1 mN
Vertical deflection range: 0 - 0.381 mm
Capacitive sensor resolution: 0.375 nM
Resulting load resolution: $9.84*10^{-5}$ mN (about 10,000 times smaller)

Friction force range: -25 - 25 mN
Desired friction force resolution: 1 μN
Horizontal deflection range: -0.191 - 0.191 mm
Capacitive sensor resolution: 0.375 nM
Resulting force resolution: 0.05 μN (about 20 times smaller)

BIBLIOGRAPHY

Awtar, Shorya "Synthesis and Analysis of Parallel Kinematic XY Flexure Mechanisms" PhD diss., Massachusetts Institute of Technology, 2004.

Schmitz, T. L., Action, J. E., Ziegert, A. J., & Sawyer, W. G. (2005). The Difficulty of Measuring Low Friction: Uncertainty Analysis for Friction Coefficient Measurements.Journal of Tribology,127(3), 673-678. doi:10.1115/1.1843853