Improving Stiffness on the A-Axis

Daniel Massimino

Fabrication Integrated Design Lab

Outline

1. Background
2. Problem statement
3. FREDPARRC
4. Machine analysis
5. Failure analysis
6. Design analysis and implementation

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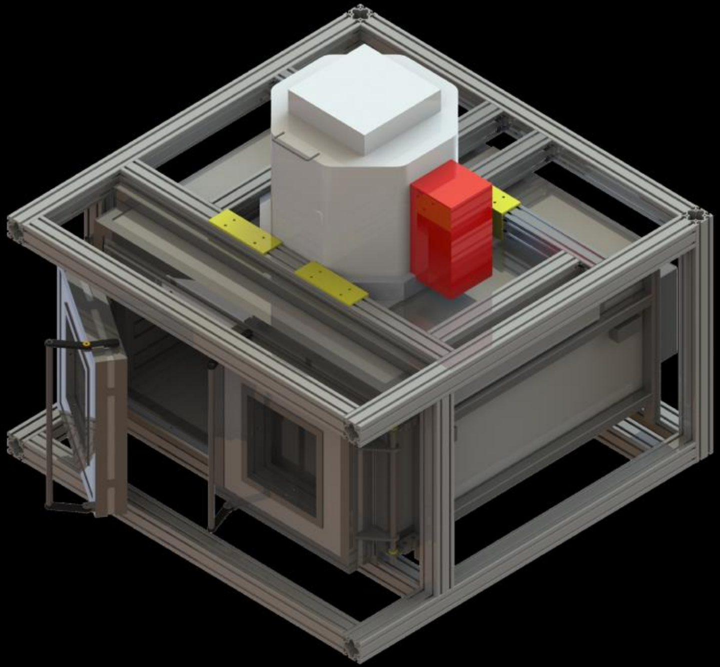
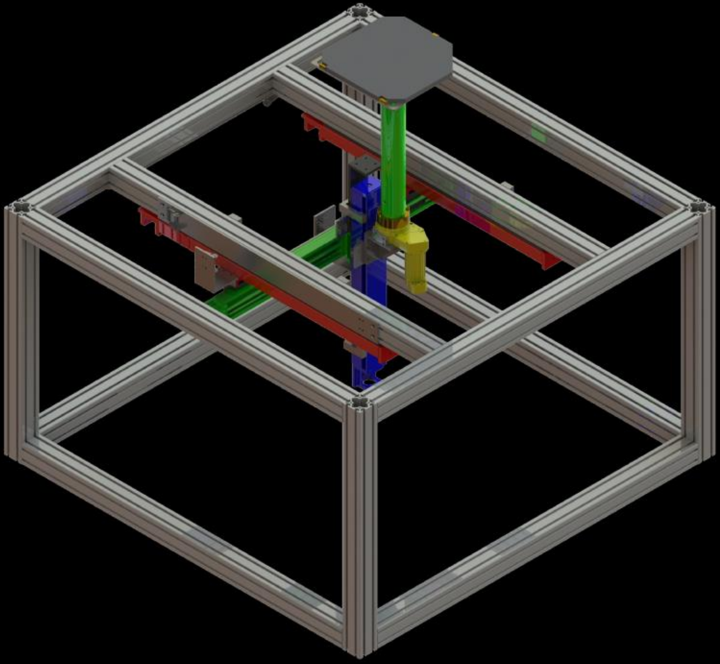
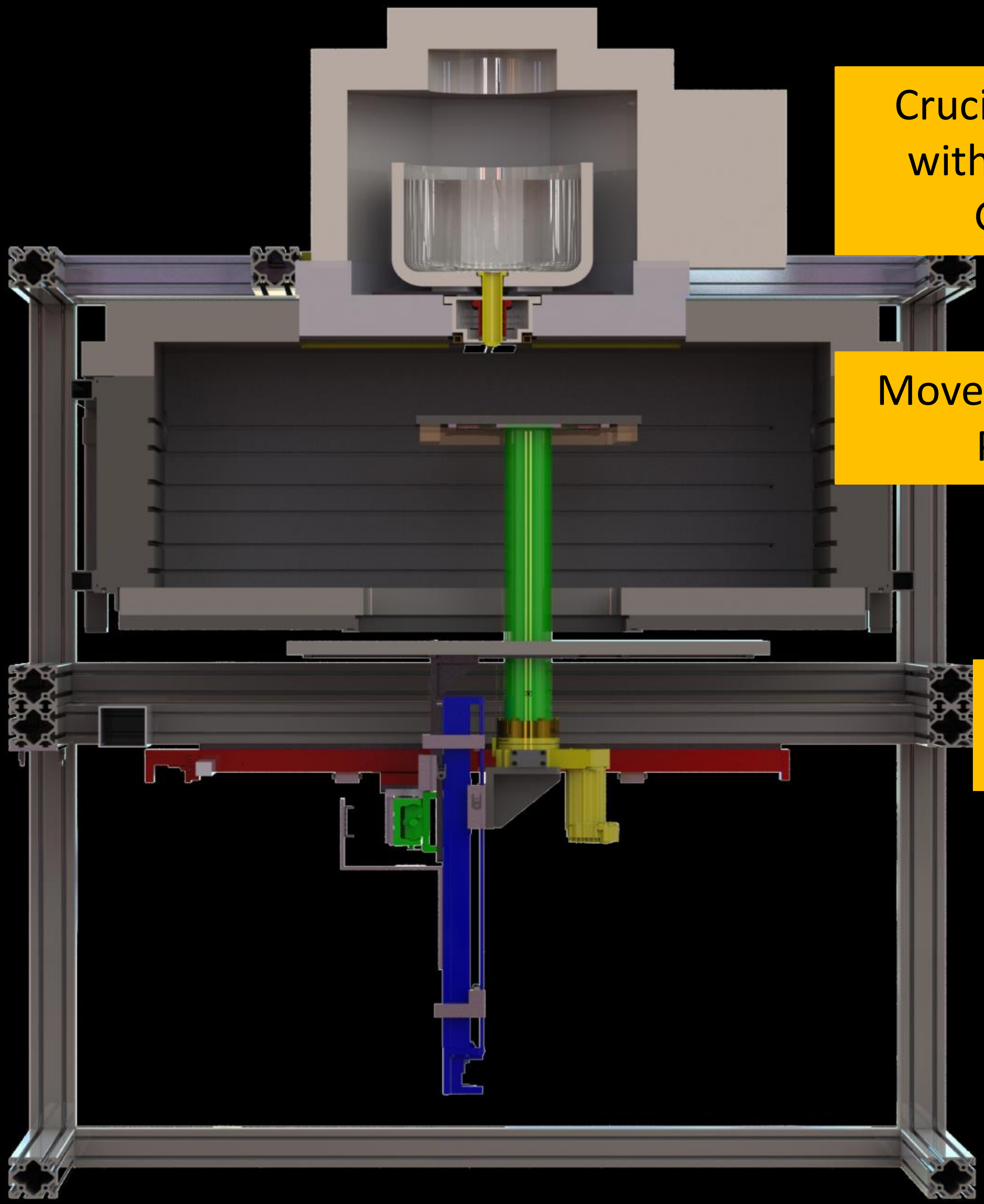
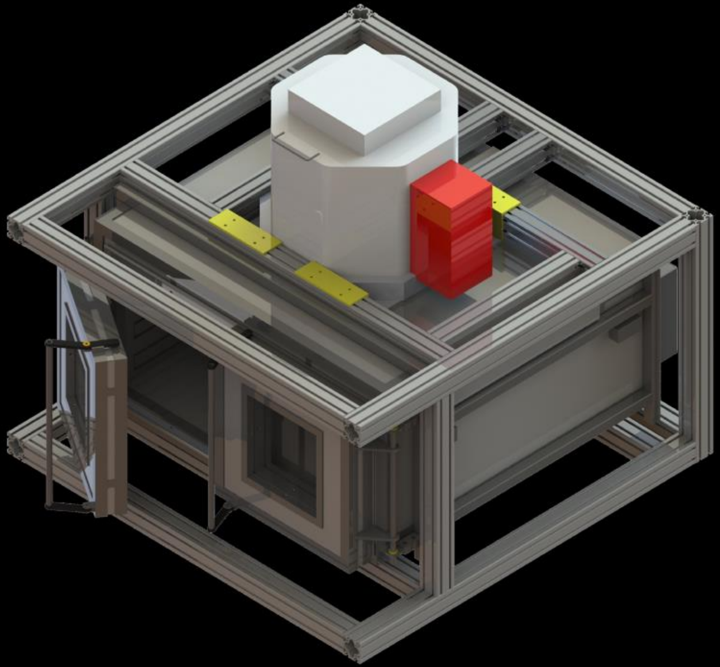
Glass 3D Printer III



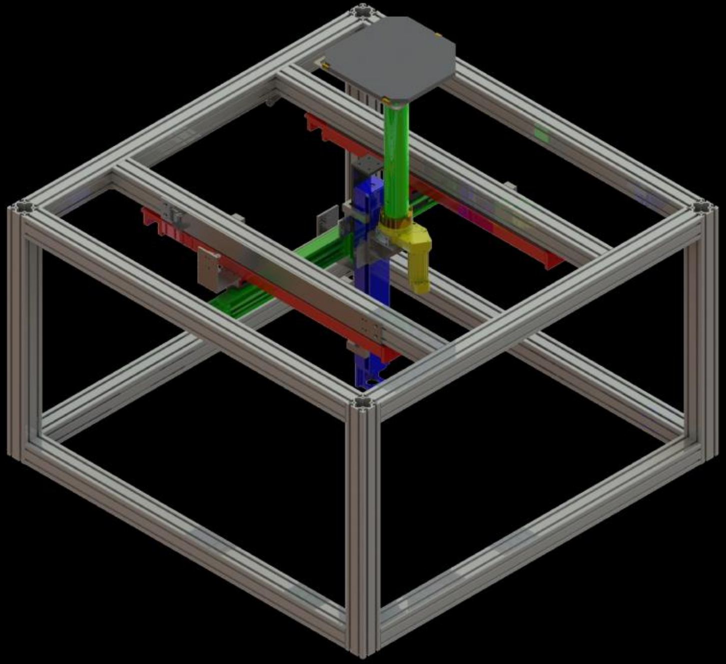


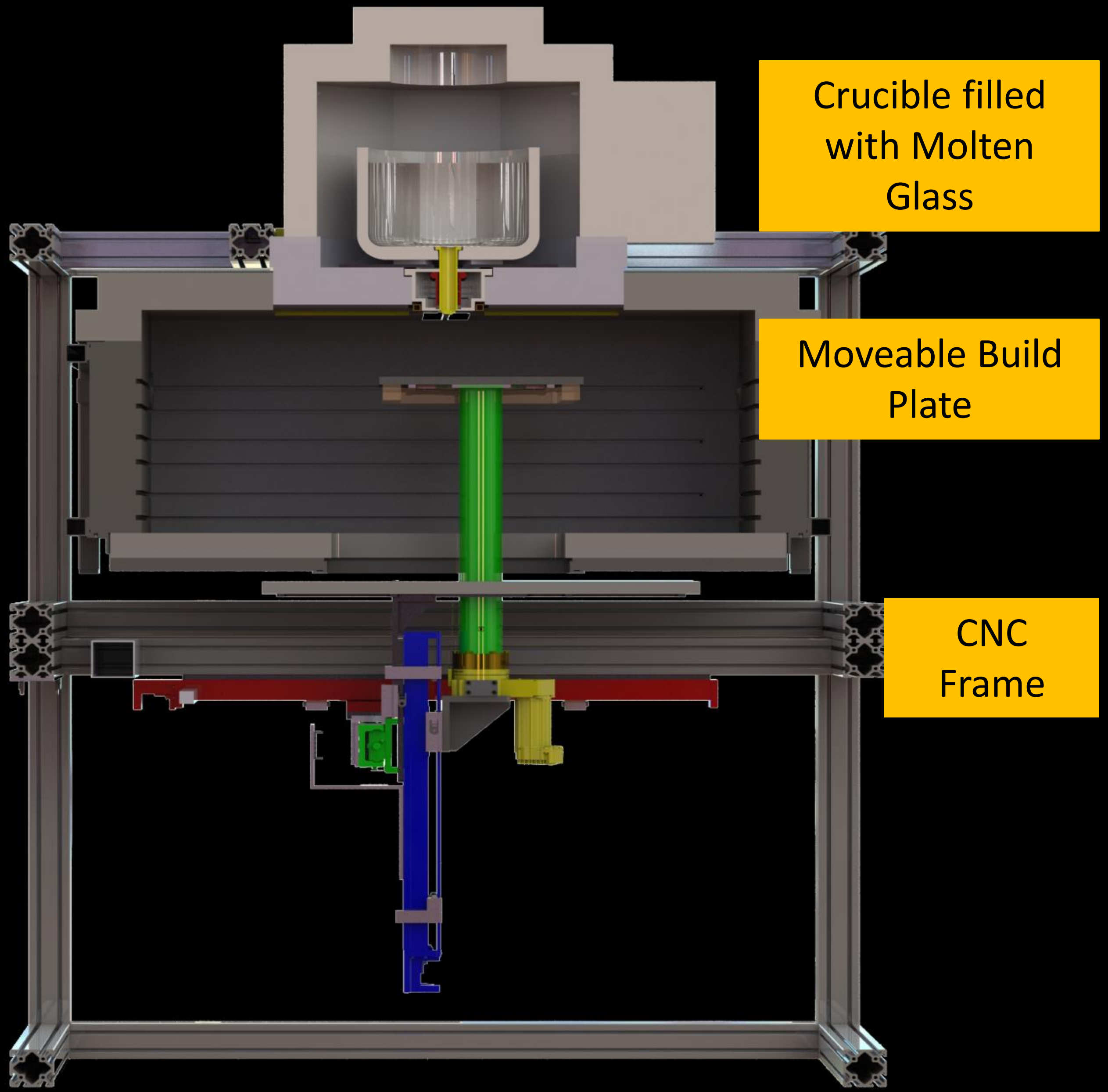

Crucible filled with Molten Glass
Moveable Build Plate
CNC Frame

Kiln



CNC




Crucible filled with Molten Glass
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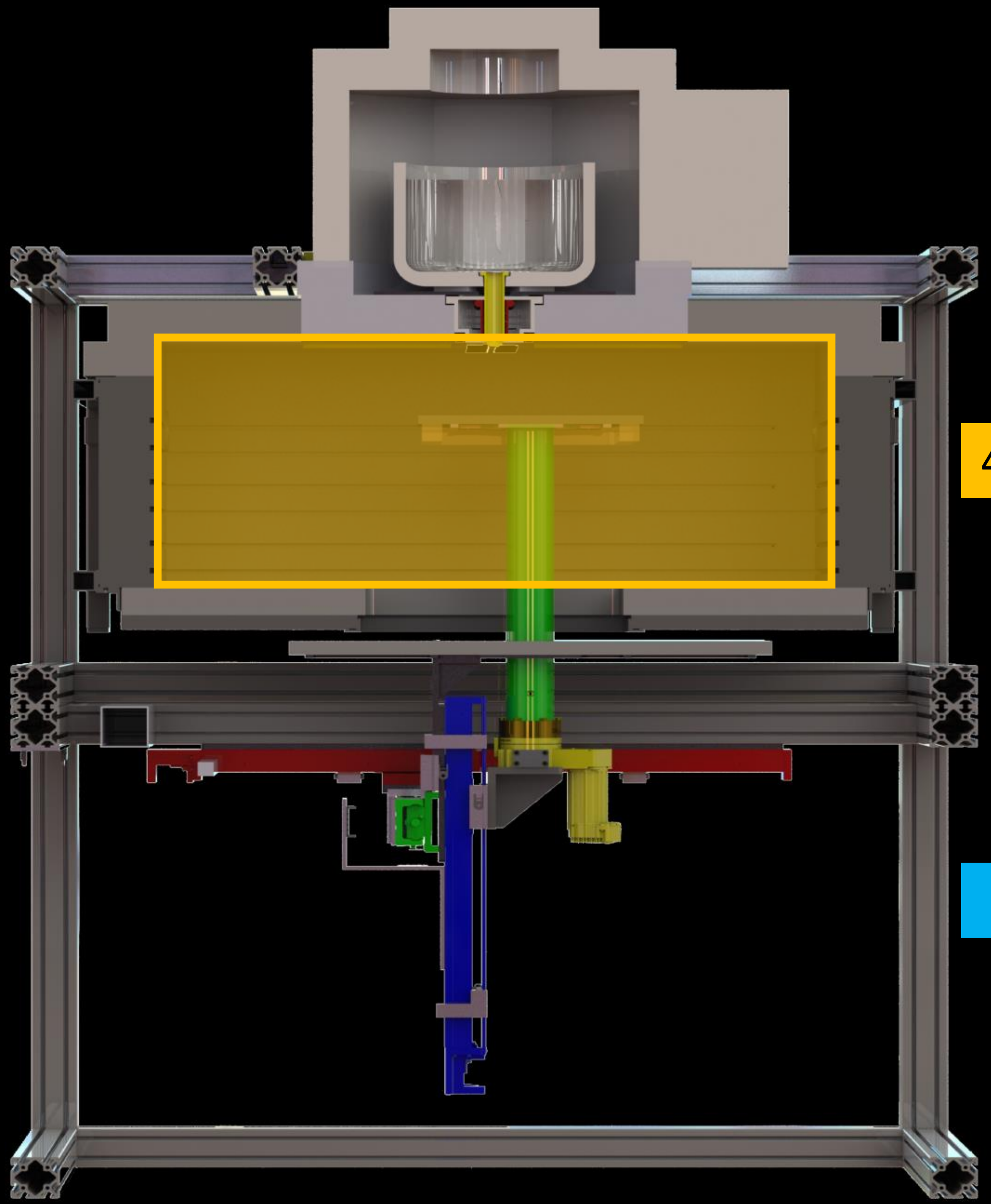
CNC Frame

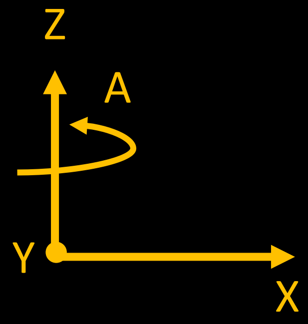
Print Environment

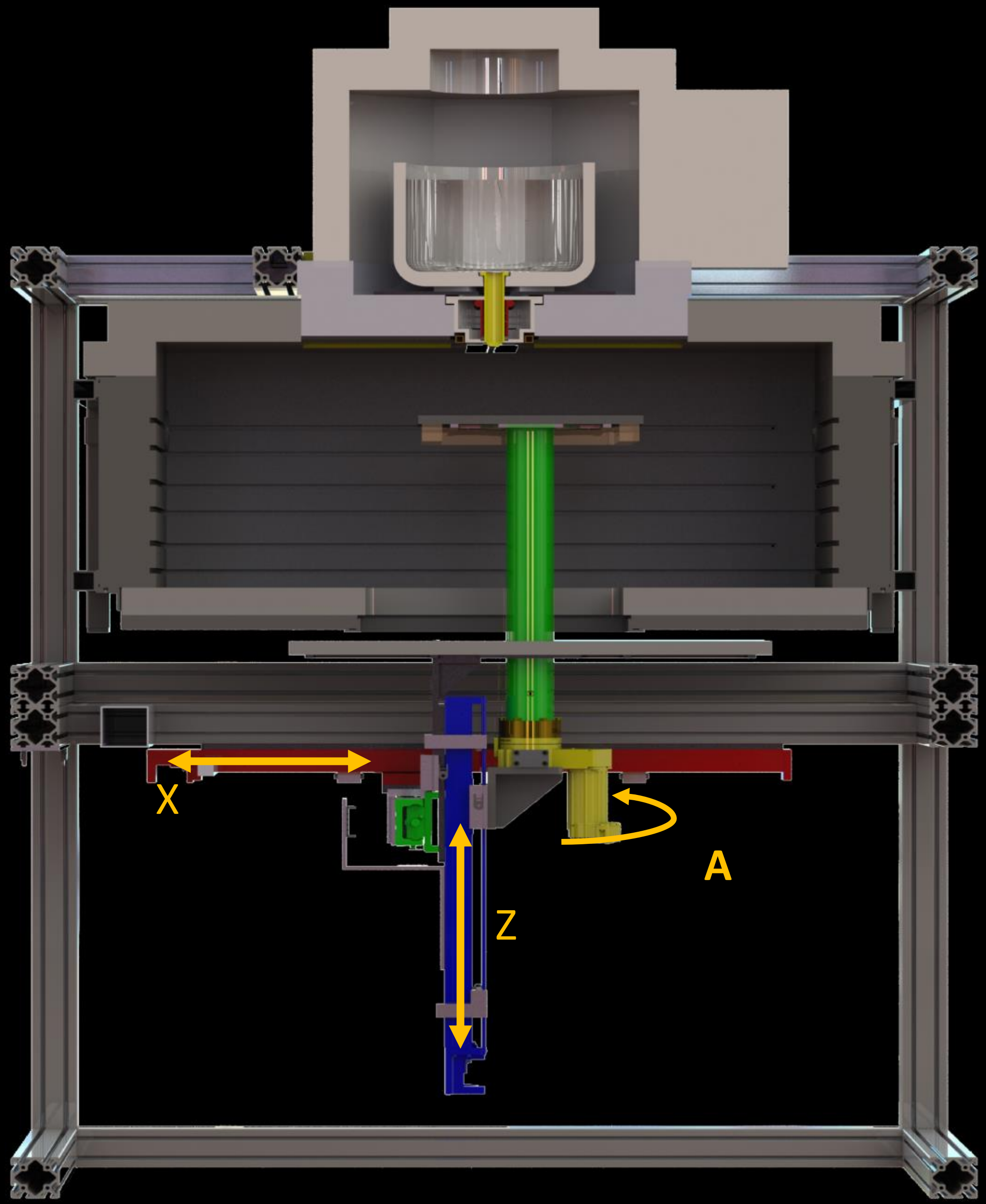


482 ^{o}C

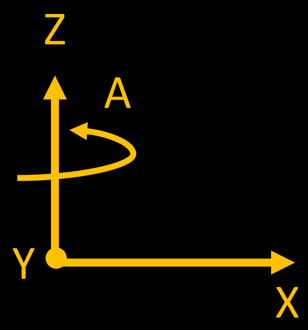
Ambient

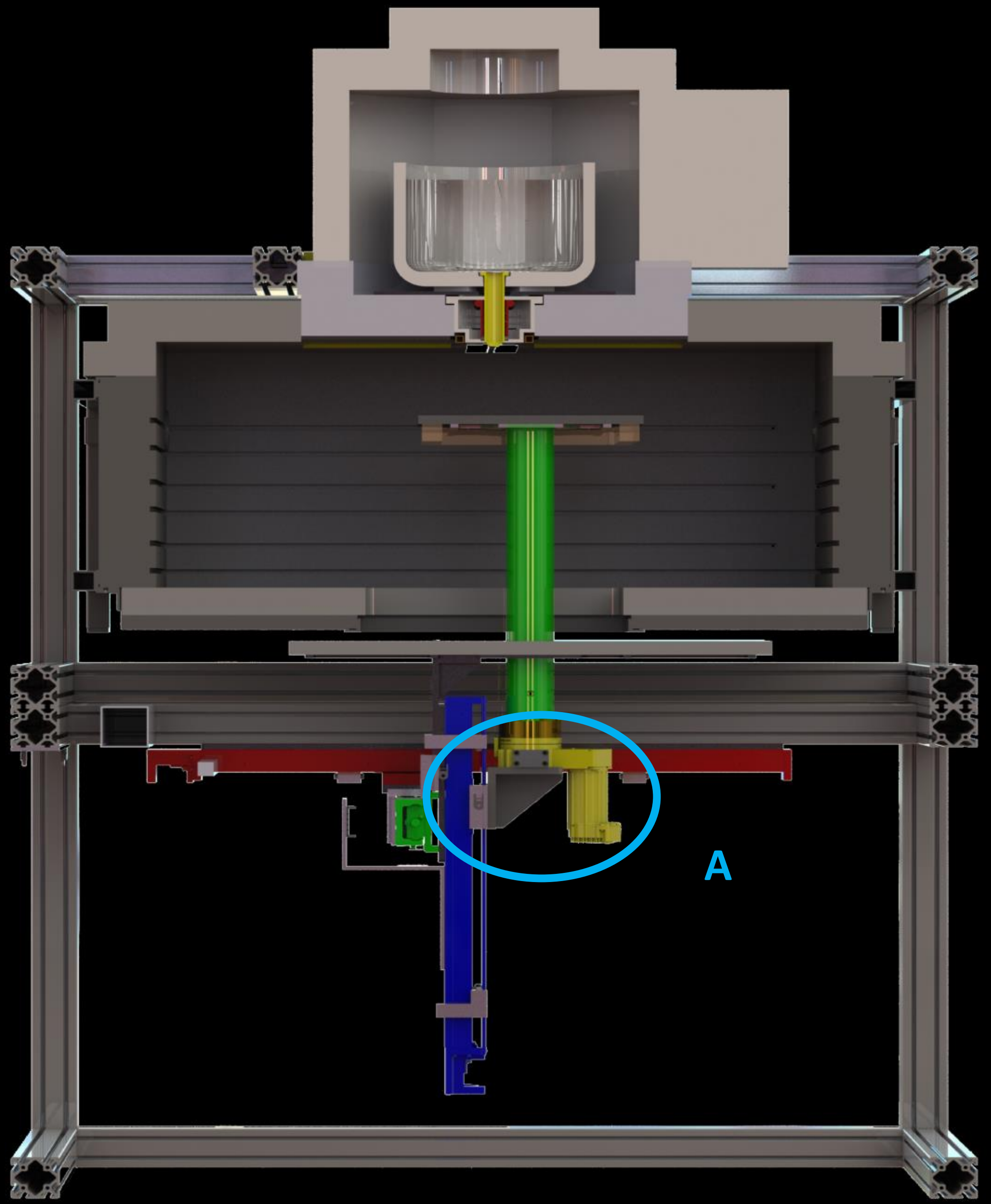
Machine Motion



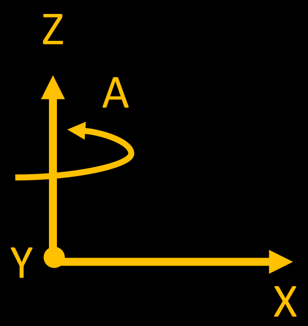


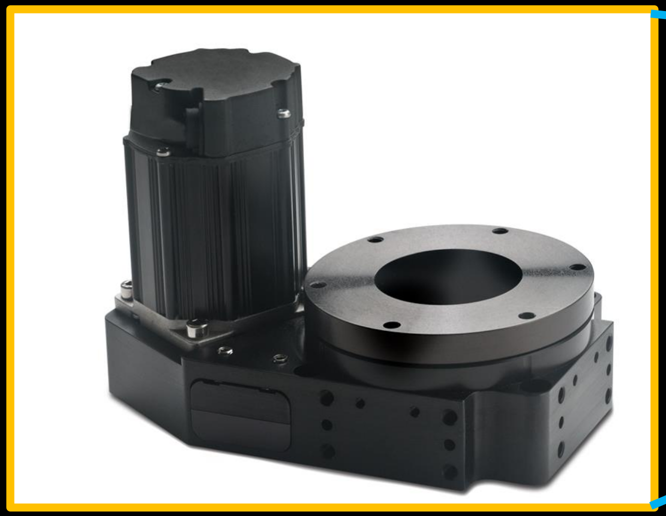
Project Focus: Rotary Stage

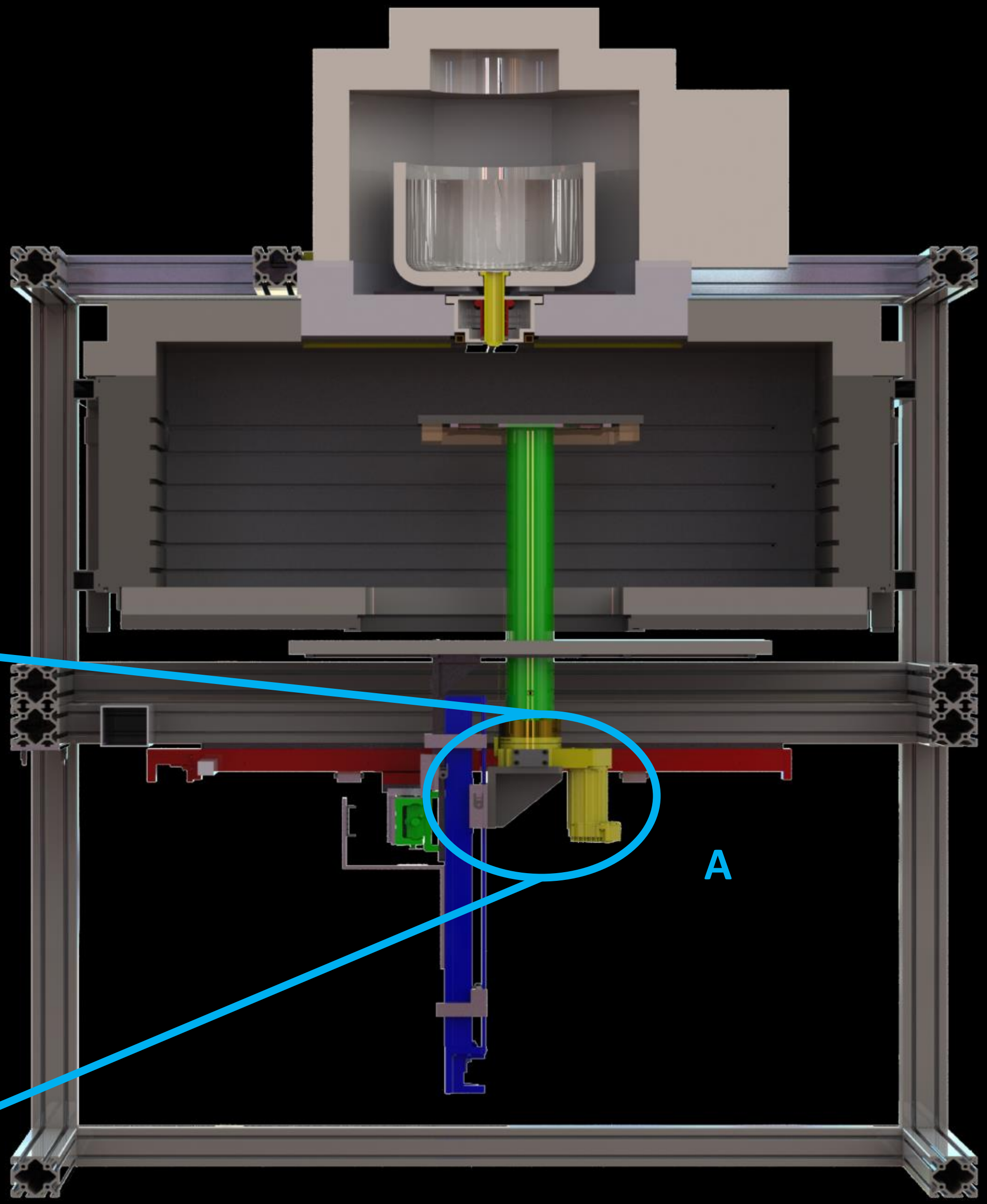




Project Focus 1: Rotary Stage







Bell-Everman SBR-50 Rotary Table

https://www.bell-everman.com/products/rotary-positioning/servobelt-rotary-stage

Problem: Low Stiffness on Rotary Stage

Angular deflection at the stage = 1.7 degrees

Estimated horizontal deflection at the build plate = 17 mm

Print accuracy: 0.5 mm[1]

[1] C. Inamura, "Towards a New Transparency: High Fidelity Additive Manufacturing of Transparent Glass Structures across Scales," 2017.

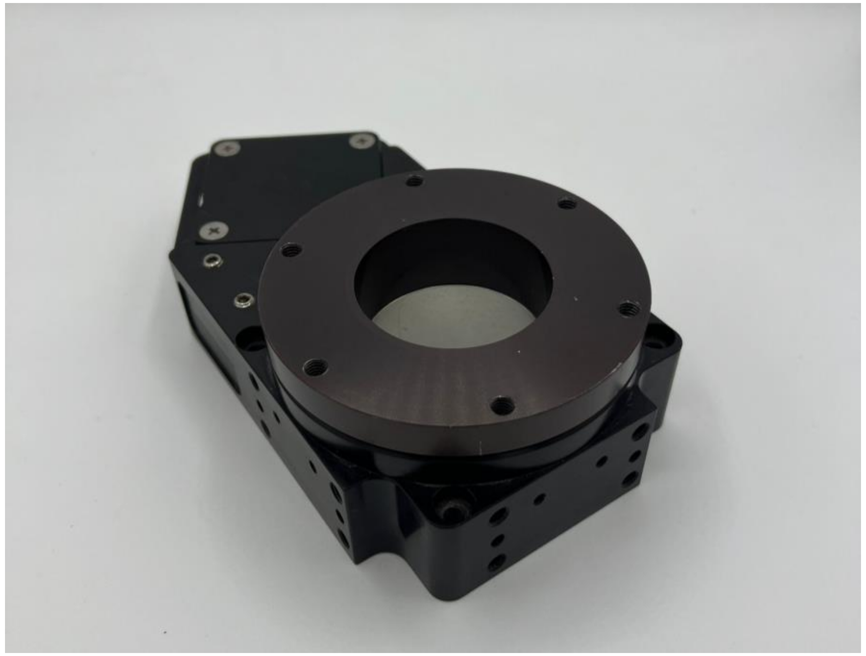
Summary of results

Initial Deflection: 17 mm at the build plate

After redesign: 1 mm (calculated)

Less stiff than modeled

Rotary stage with changes



Fully assembled stage

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FREDPARRC

Requirements:

- Return rotary stage to nominal stiffness
- Limit loads to rotary stage below rated levels
- Improve robustness and reliability of machine

Environment:

- Seamless integrate into the existing machine
- 482 ^{o}C (annealing oven)
- 30 ^{o}C (ambient environment)

FRE**DP**ARRC

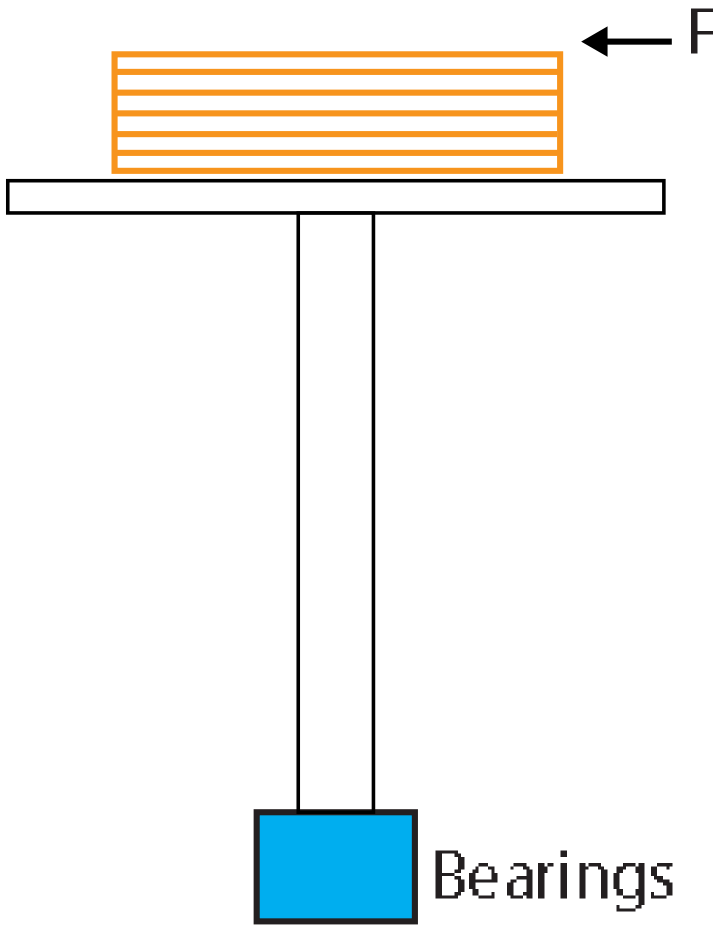
Design Parameters:

- Shaft is 65 cm from build plate to rotary stage
- Load limits for rotary stage:
  - 7.0 kN axially / 4.0 kN radially
  - 120 Nm Torque (200 N lateral force at the build plate)
- Motor torque limits
- Change bearings
- Add constraints

FREDP**A**RRC

Analysis:

- Determine nominal loads during operation
- Determine infrequent loading
- Stress analysis on design solution



FRED**P**A**R**RC

References:

- Previous literature on the machine design
- Patents
- Bell-Everman literature
- Kaydon/SKF catalogs
- ASM Material Catalog

FREDPAR**RC**

Risk	Countermeasure
Misalignment with extra constraints	No extra constraints.
Thermal degradation by convection	Better insulate the annealing kiln.
Thermal degradation by conduction through he shaft from the annealing	Thermally isolate the rotary stage with a low thermally conductive material.

Outline

Functional requirements – machine analysis

Analysis:

1. Extrusion/Drawing Forces
2. Operating Forces
3. Impact Forces
4. Human interaction

Limit = 200 N at the Build Plate

Extrusion at the Crucible

<u>Governed by:</u>

Bernoulli's Equation

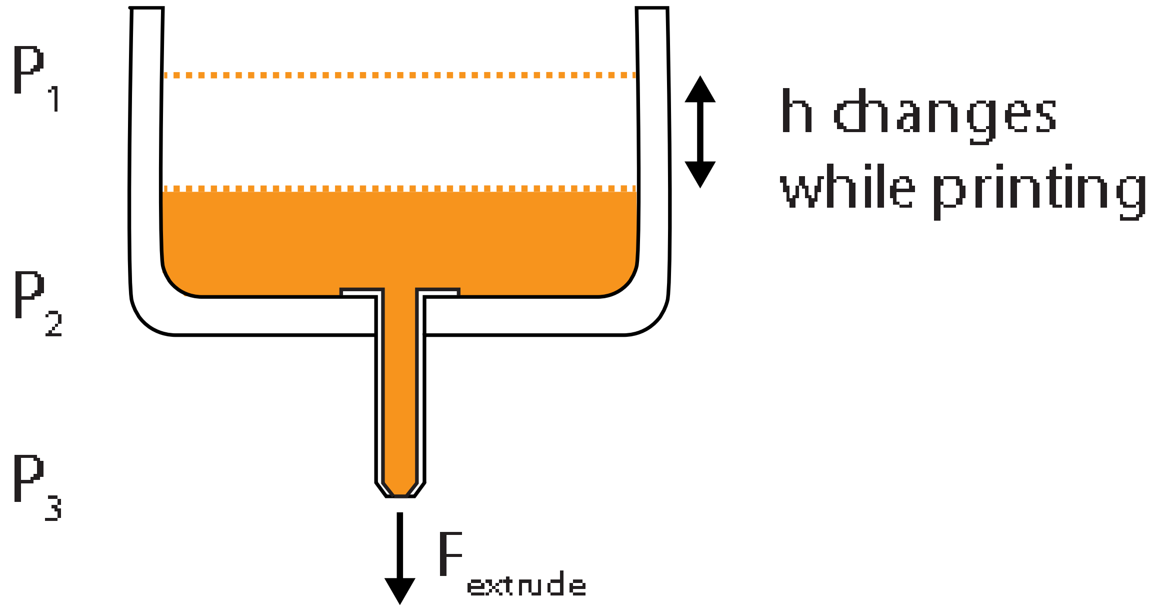
$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

Pouseille's Law

$$P_2 - P_3 = \frac{8\mu L Q}{\pi R^4}$$

$F_{extrude}$ = 5 N

$$F = P_3 * \pi r_{nozzle}^2$$

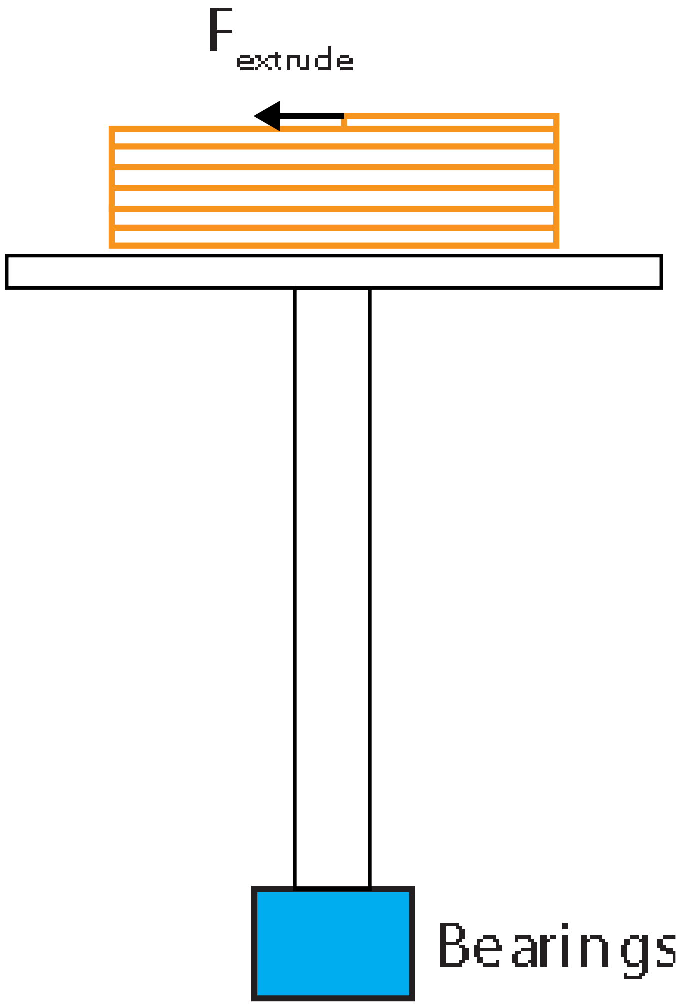


Glass
Bearings
Printer Structure

Operating Forces

$F_{extrude} = 5\ N$

Far below bearing limits



Glass

Bearings

Printer Structure

Impact Force

Governed by:
Energy methods

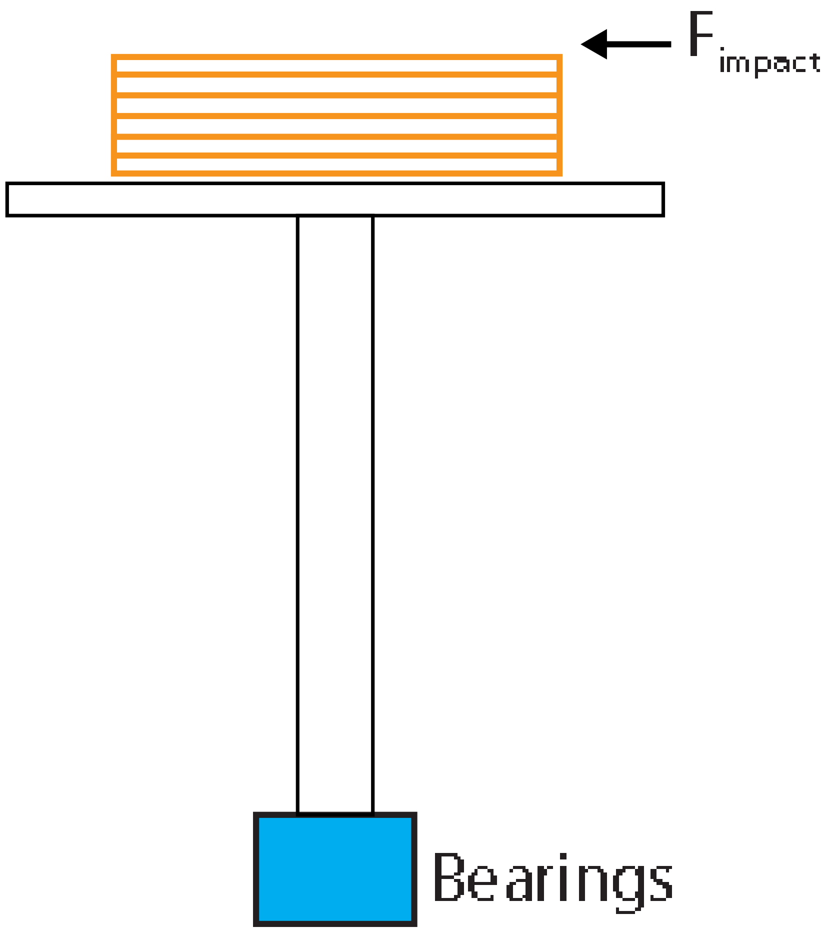
where k = stiffness of the cantilevered beam

$$\frac{1}{2}mv^2 = \frac{1}{2}\mathrm{kx}^2$$

$$x = \sqrt{\frac{1}{k}mv^2}$$

$$\mathrm{k} = \frac{3EI}{L^3}$$

$$F_{impact} = kx = \sqrt{\frac{3EI}{L^3}mv^2}$$



Impact Force

Governed by:
Energy methods

where k = stiffness of the cantilevered beam

E = 193 GPa
I = 5E-07 m^4
L = 0.55 m
m = 30 kg
v = 0.01 m/s

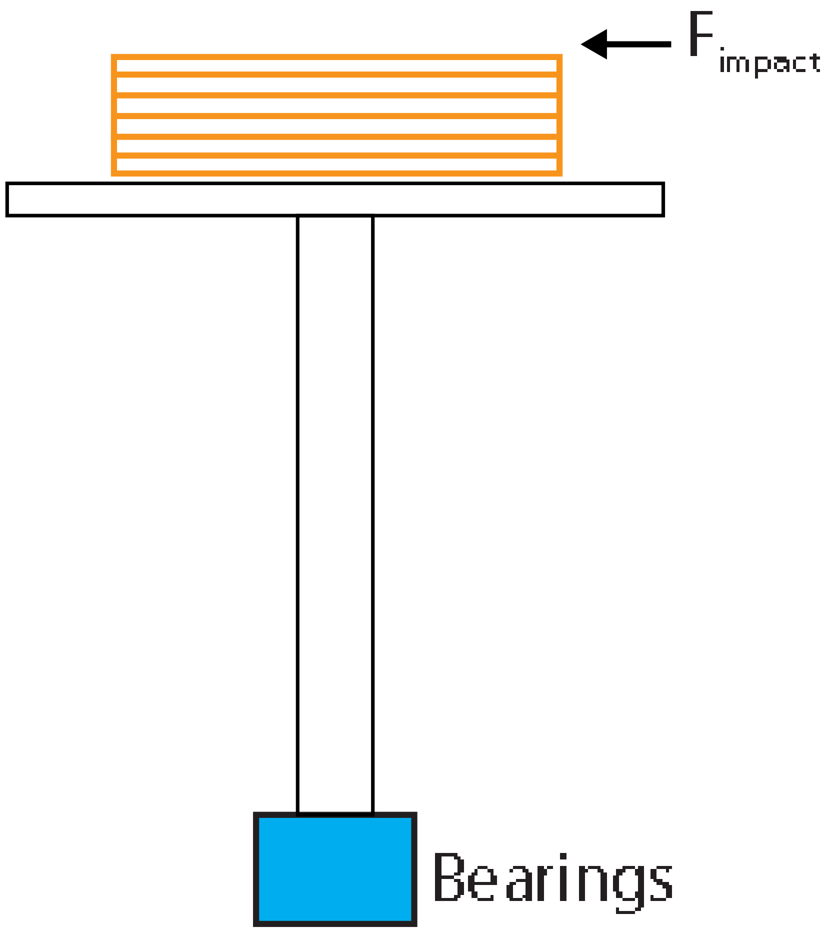
F_{impact} ~ 70 N

$$\frac{1}{2}mv^2 = \frac{1}{2}\mathrm{k}\mathrm{x}^2$$

$$x = \sqrt{\frac{1}{k}mv^2}$$

$$\mathrm{k} = \frac{3EI}{L^3}$$

$$F_{impact} = kx = \sqrt{\frac{3EI}{L^3}mv^2}$$

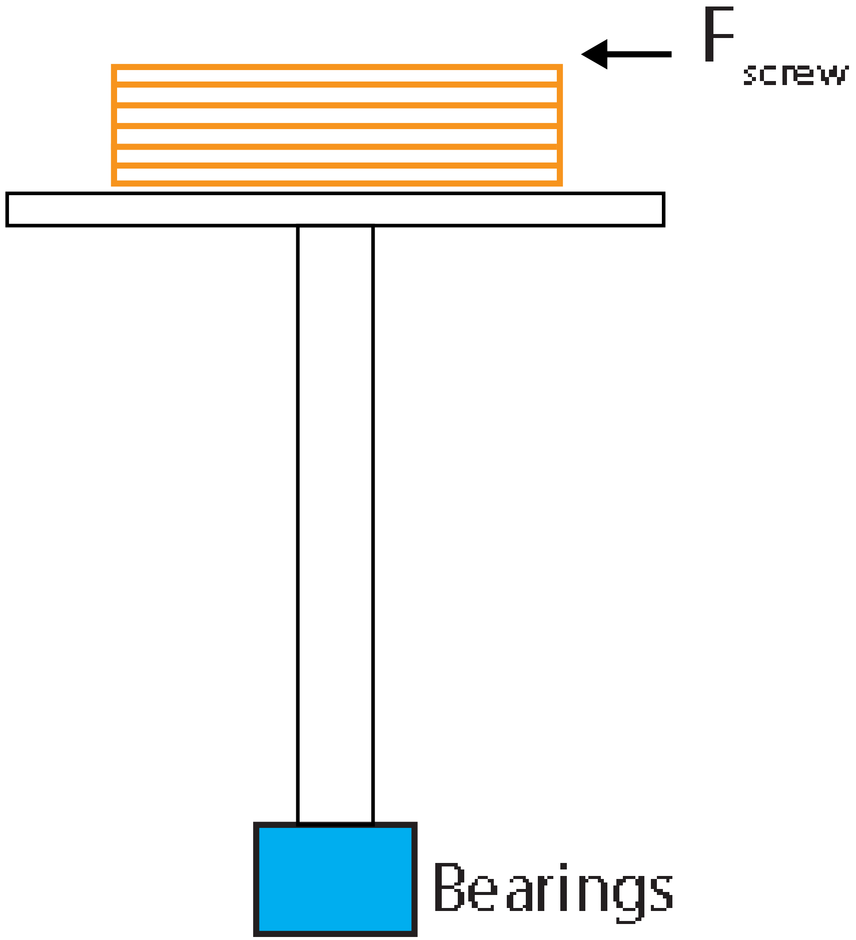


Force after Impact

$$F_{screw} = \frac{2\pi\eta\tau}{l}$$

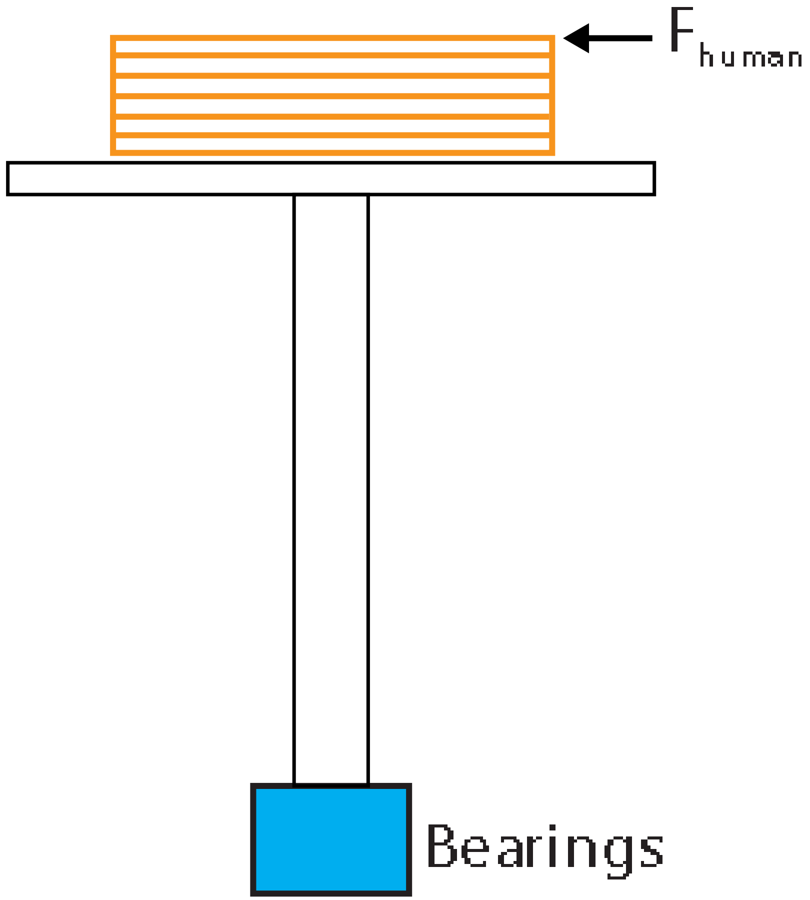
η = 0.9
τ = 5.85 Nm
l = 20 mm

F_{screw} = 496 N = Big Problem!



Human Interaction

F_{human} = 534 N[1]



W. E. Woodson, B. Tillman, and P. Tillman, *Human factors design handbook: information and guidelines for the design of systems, facilities, equipment, and products for human use*, 2nd ed. New York St. Louis San Francisco [etc.]: McGraw-Hill, 1992.

Functional requirements – summarized

Analysis:

1. Extrusion/Drawing Forces
2. Operating Forces
3. Impact Forces = 496 N
4. Human interaction = 534 N

Limit = 200 N at the Build Plate

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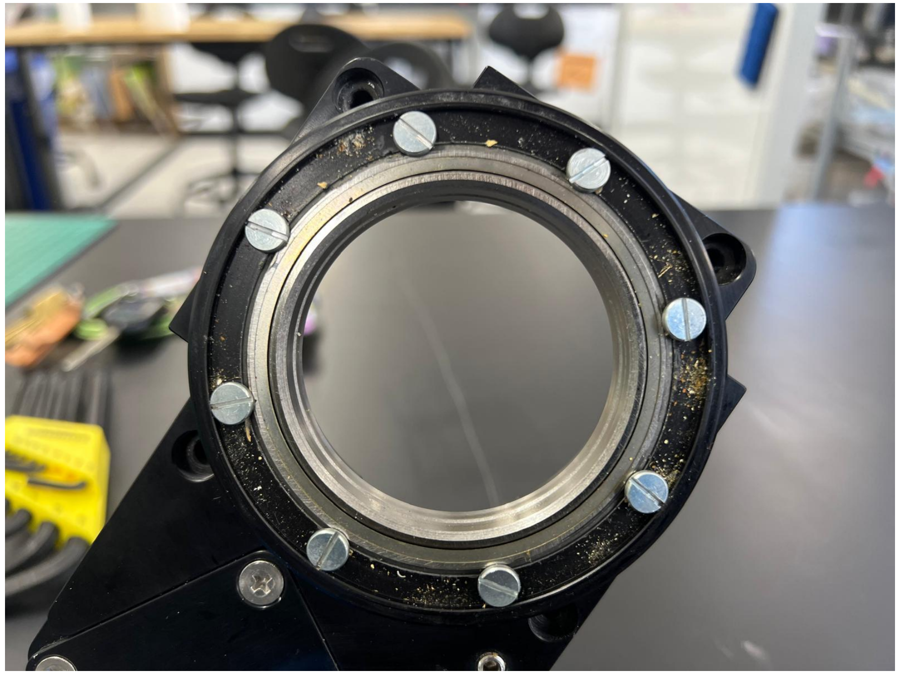
Initial prediction – bearing failure

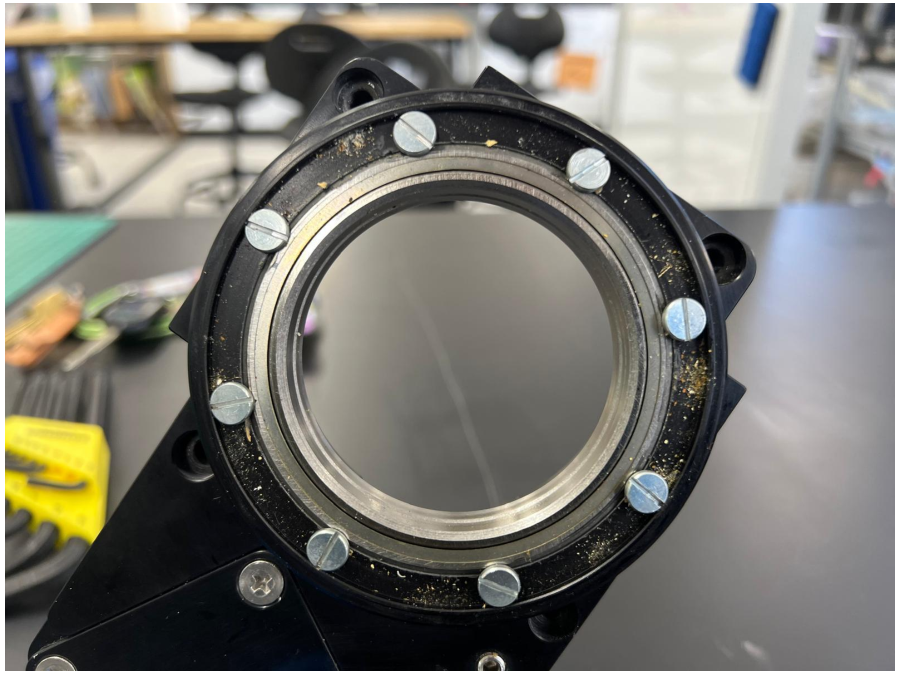
Analysis showed bearings may have been overloaded



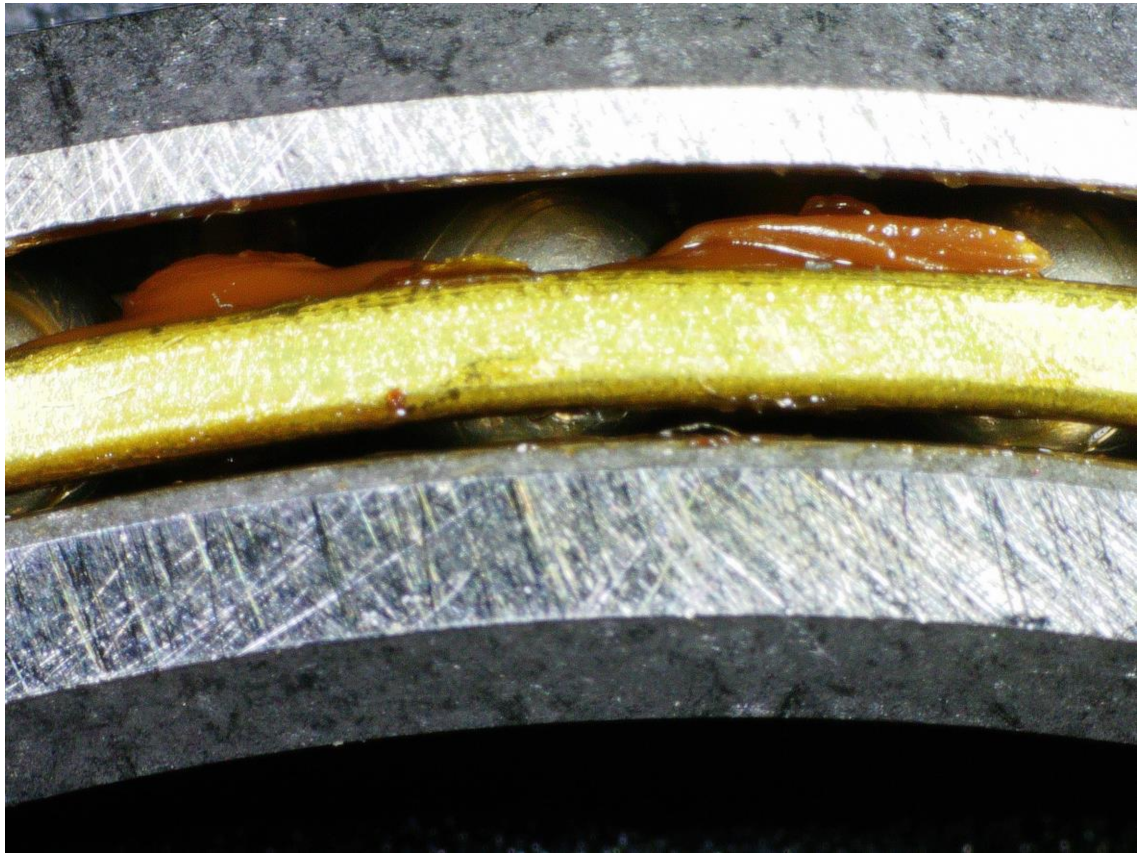
SBR-50 Rotary Stage Bearings

Initial prediction – bearing failure

Analysis showed bearings may have been overloaded



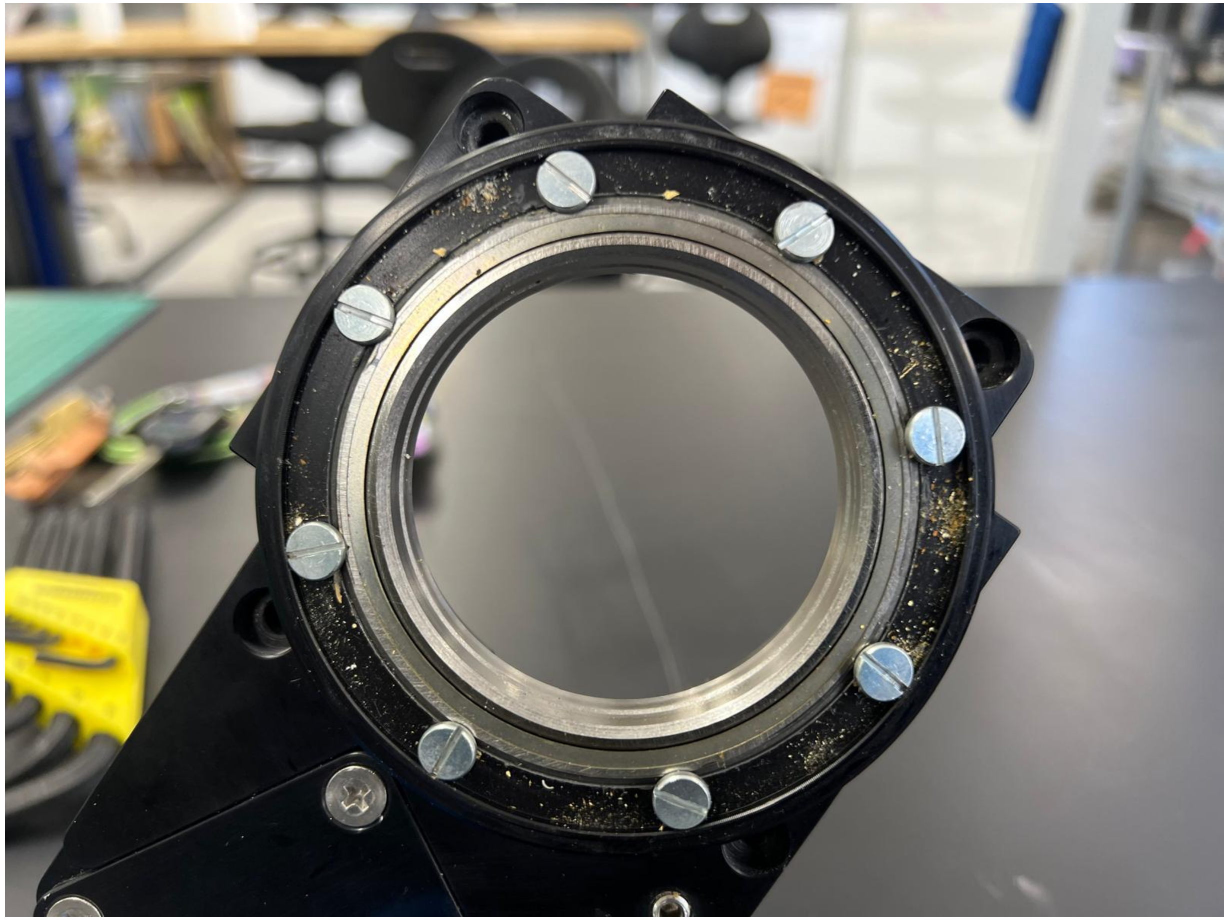
SBR-50 Rotary Stage Bearings



Bearings under magnification

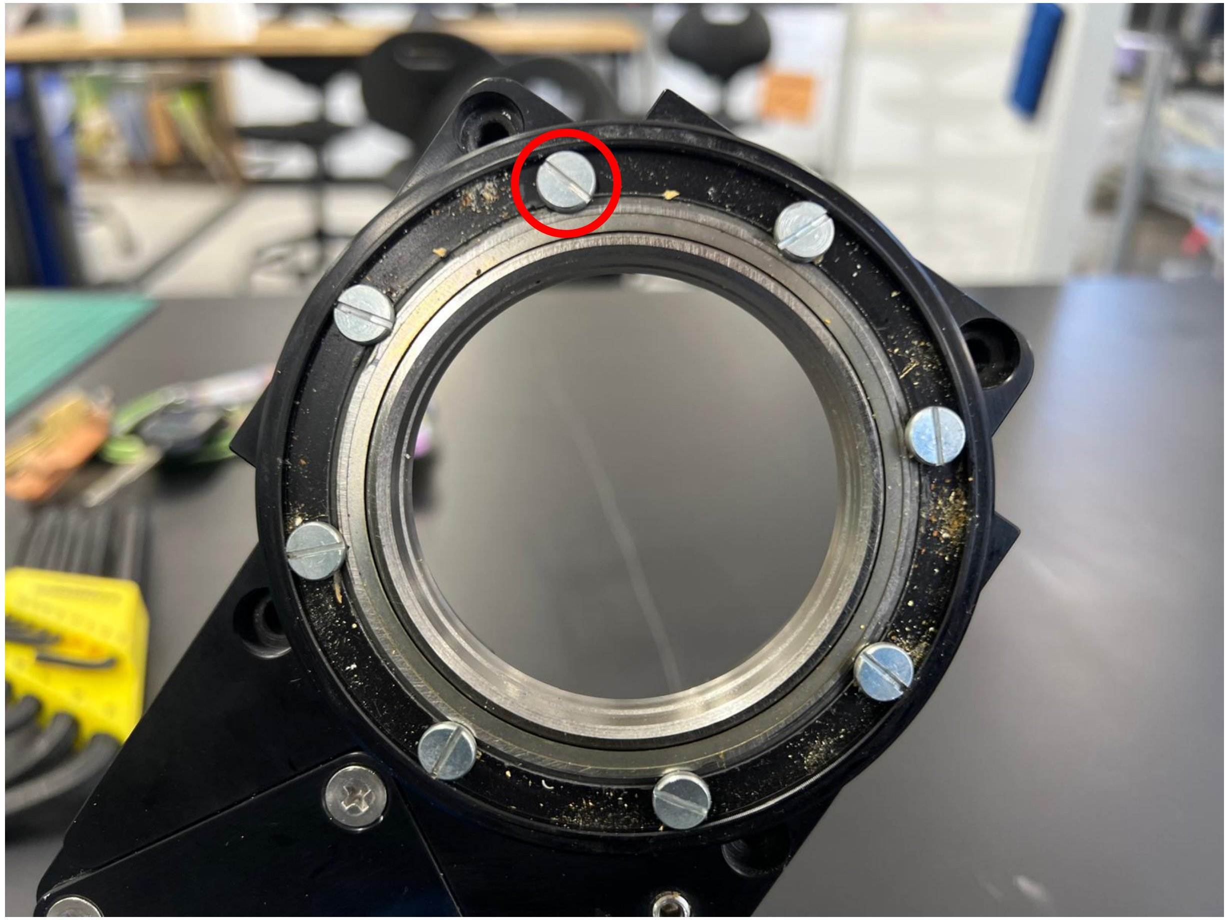
Bearings did not show signs of damage

SBR-50 Rotary Table



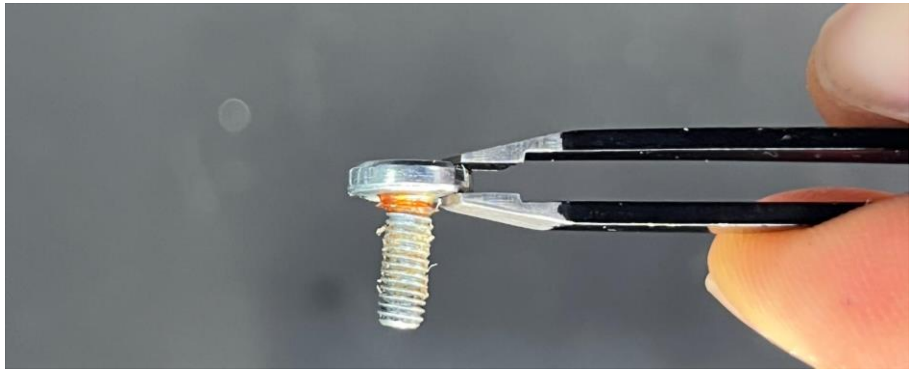
SBR-50 Rotary Table – constraint issue

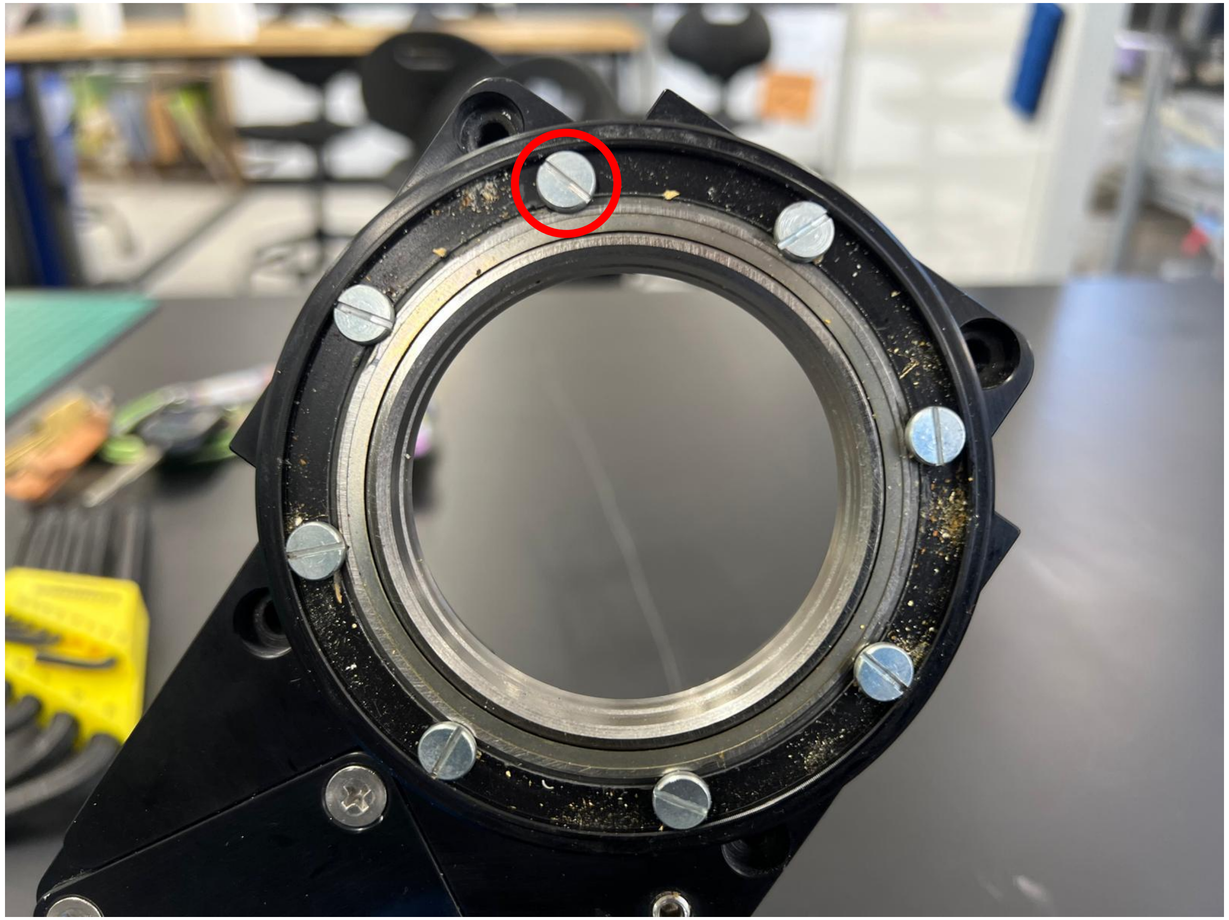
Screws are directly bearing on the outer race



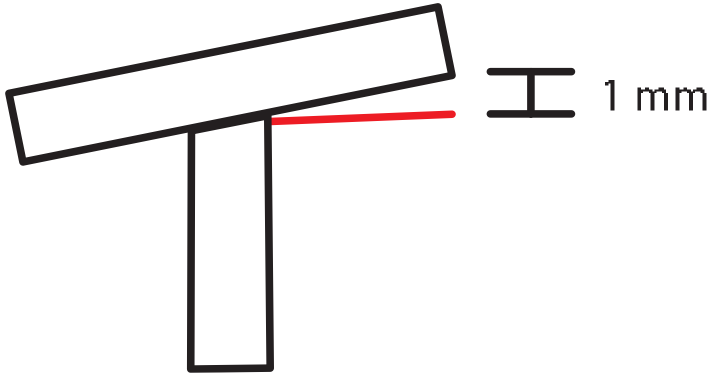
Outer constraint plastically deformed

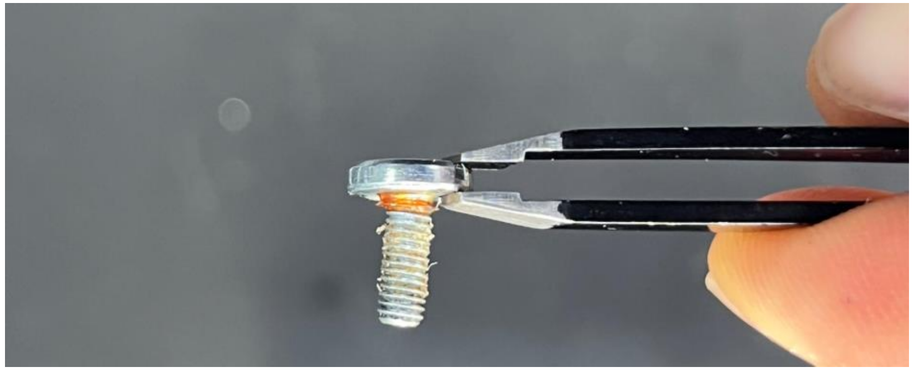
Screws are directly bearing on the outer race



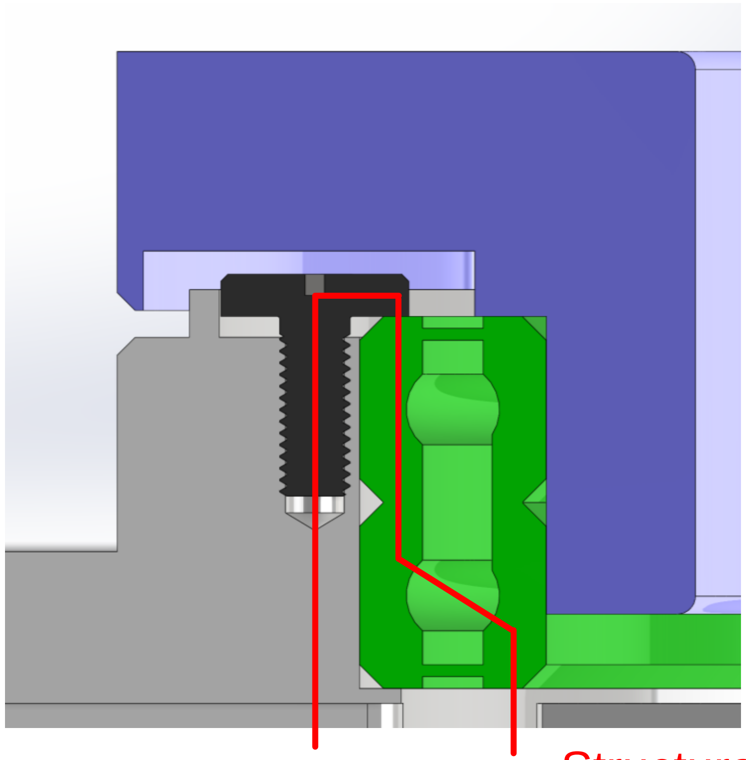


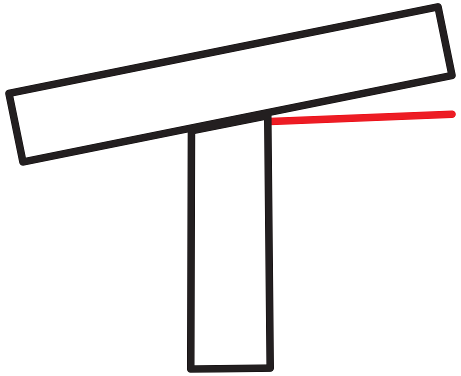
Bent constraint from large moment

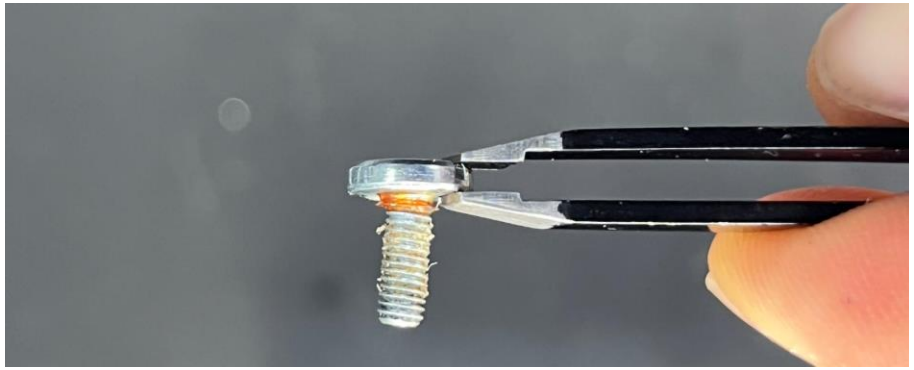




Bent constraint from large moment

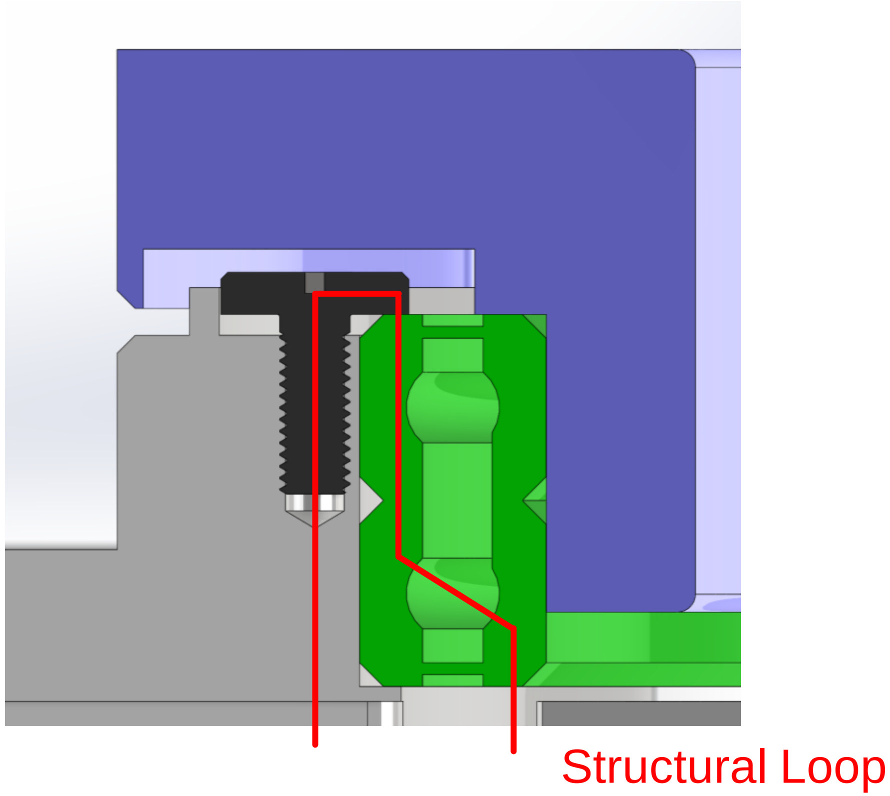


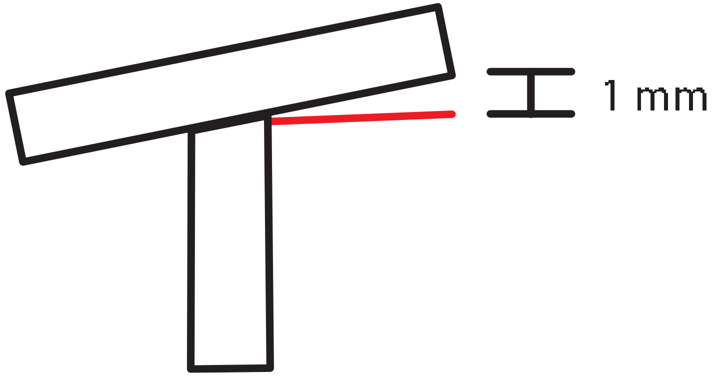


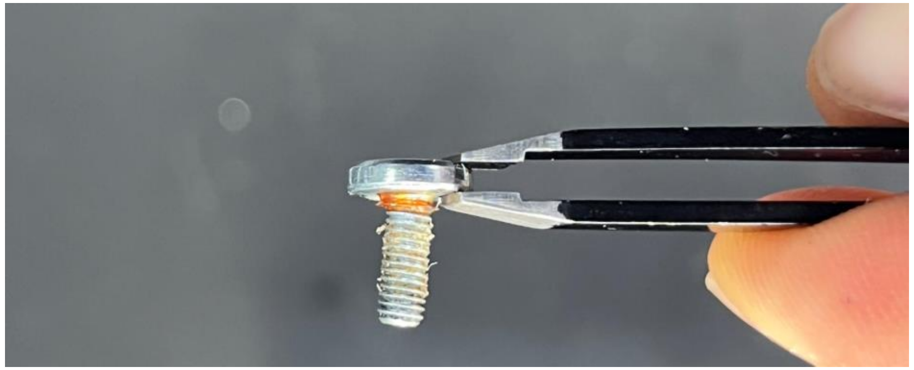


Bent constraint from large moment

Bearings are unconstrained on outer races







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2 Design Strategies

1. Set motor torque limits to avoid impact overload
2. New outer race constraint to improve stiffness

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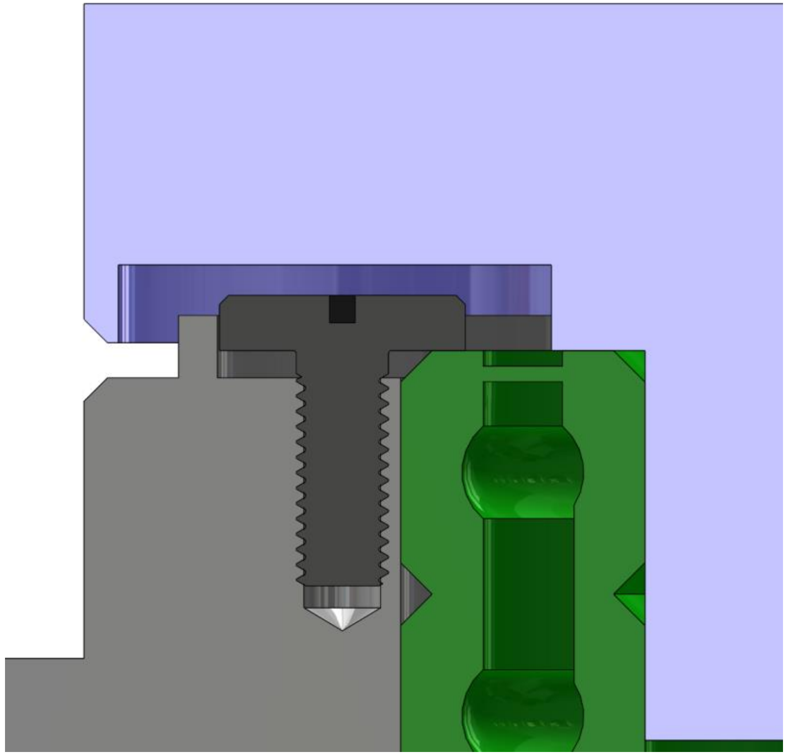
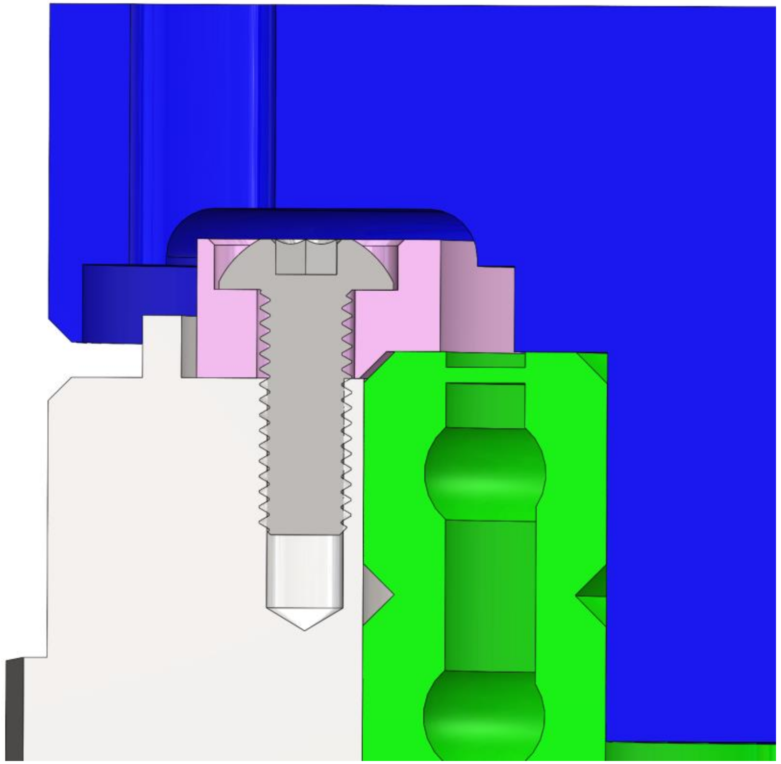
1. Set motor torque limits to avoid impact overload
2. New outer race constraint to improve stiffness

Design strategy – new outer race constraint (pink)



Old Design



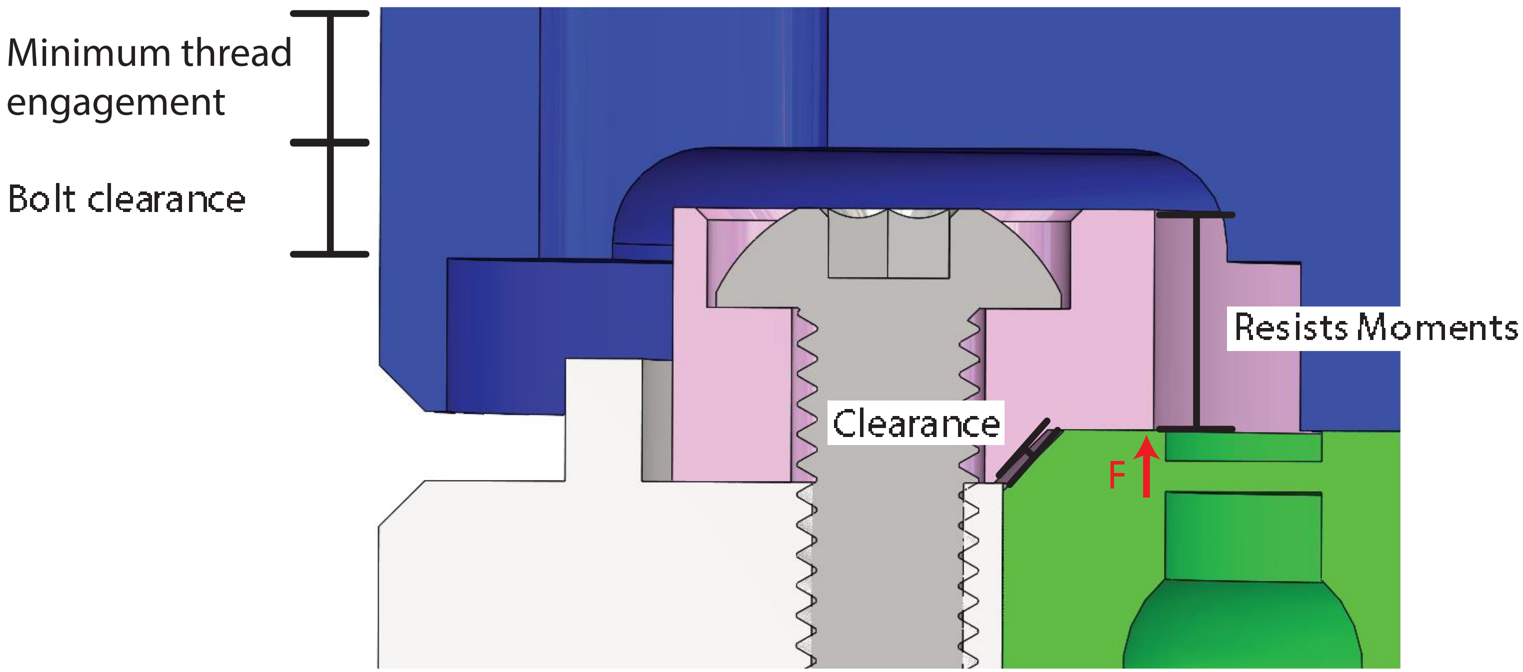
New Design

Design constraints and sizing

Analysis:

1. Clearance
    a) Tolerance analysis

2. Resists moments
    a) Cantilever beam
    b) FEA



Design constraints and sizing

Analysis:

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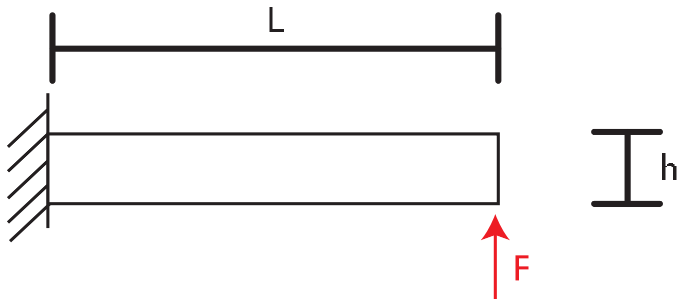


$$M = F * L$$

$$I = \frac{bh^3}{12}$$

$$\sigma_{max} = \frac{My}{I}$$

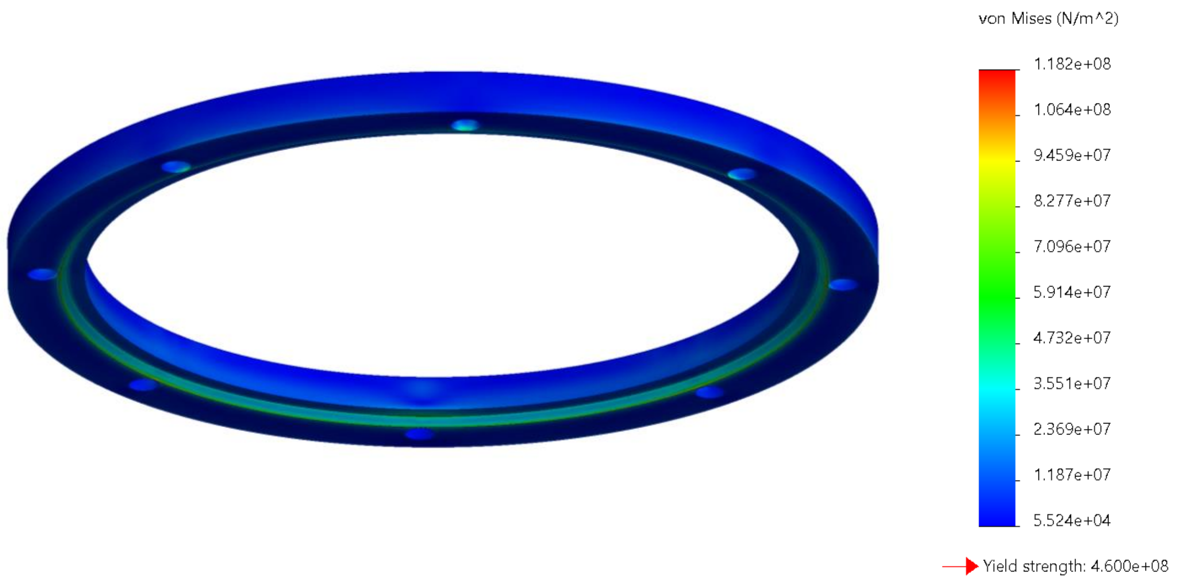
$$\sigma_{max} < \sigma_{yield}$$

Design constraints and sizing

Analysis:

1. Clearance
    a) Tolerance analysis

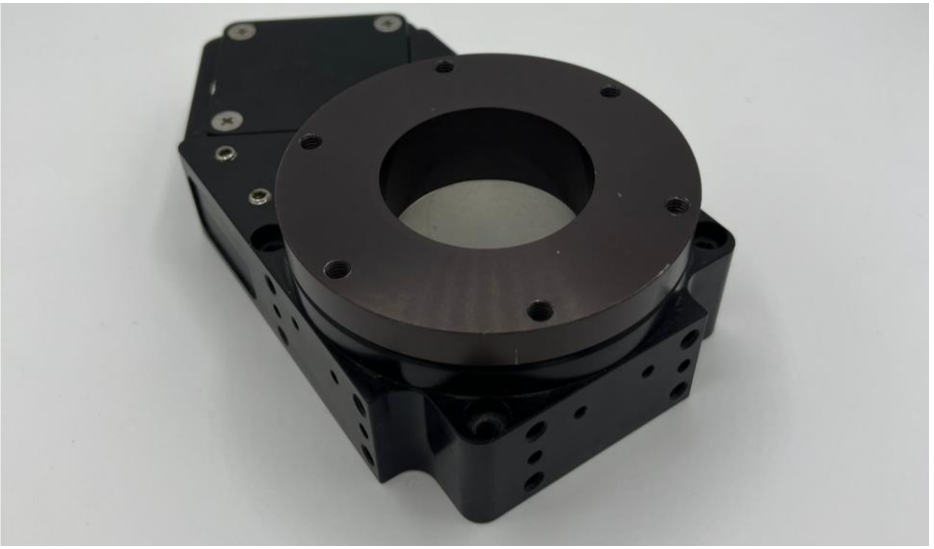
2. Resists moments
    a) Cantilever beam
    b) FEA – 4140 Steel



Final Results

Initially:
17 mm deflection at the build plate

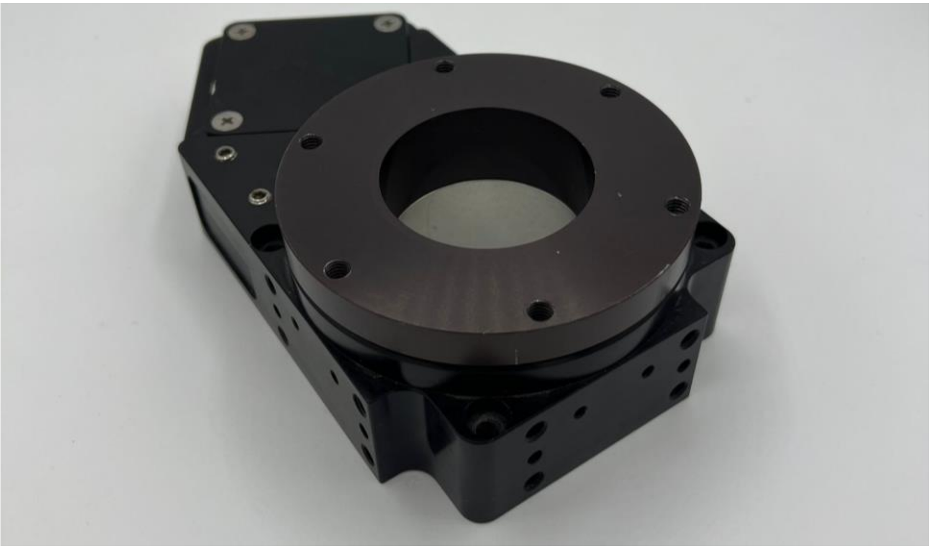
Now:
Measured Stiffness = 1600 Nm/rad
Predicted Stiffness = 4700 Nm/rad
Calculated deflection at the build plate = 1 mm



Next Steps

1. Increase stiffness to predicted value
    - Reseat the bearings as recommended by SKF

2. Continue working on mass measurement system



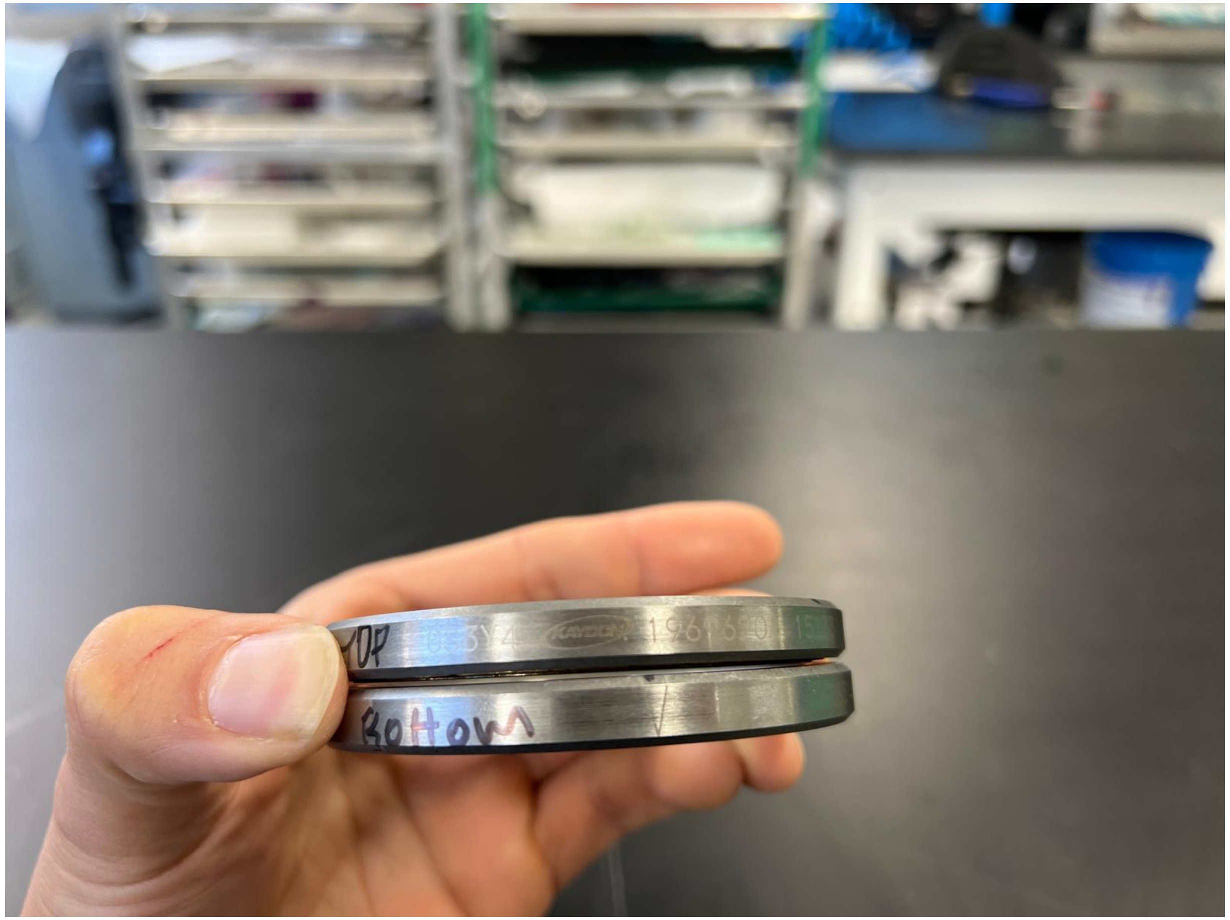
Thank you!

Fundamentals

- Abbe Errors
- Saint Venant’s
- Structural Loop
- F=kx

Backup

Outer race lack of damage



Measuring Stiffness

Measuring Dimensions

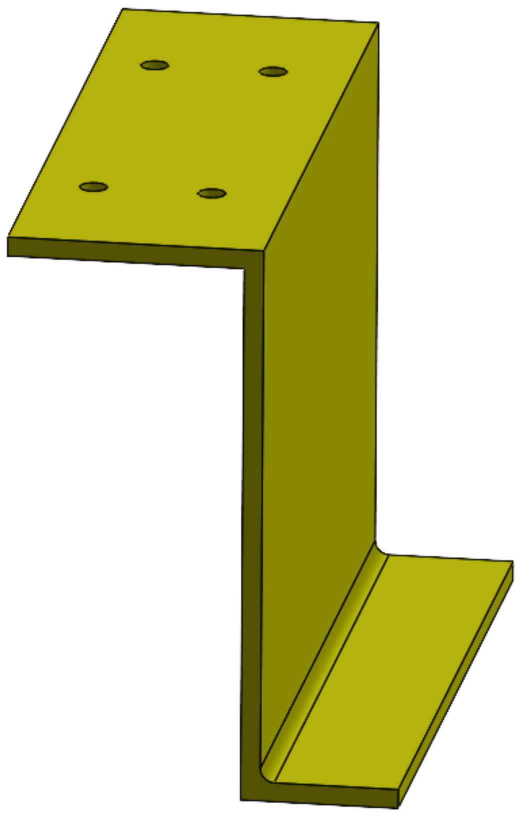
Machining

Kinematic Mount for crucible

Kelvin Kinematic Design

Ball size = 1” Diameter tool steel (Bal-Tec)

Groove Material = 6061 Aluminum

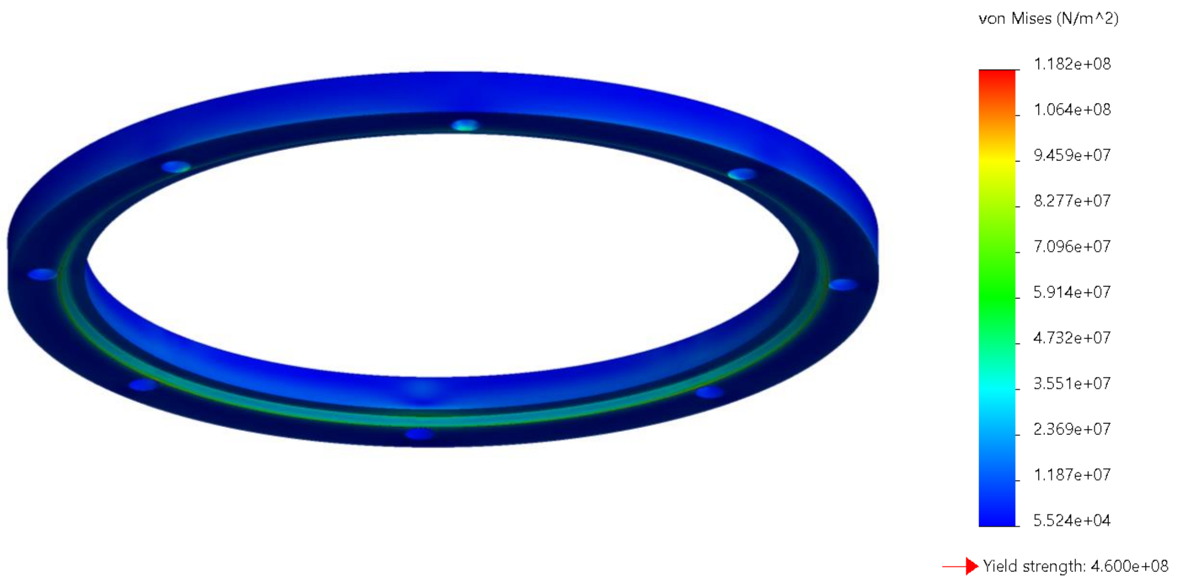


Design constraints and sizing

Analysis:

1. Clearance
    a) Tolerance analysis

2. Resists moments
    a) Cantilever beam
    b) FEA – 4140 Steel
        a) Stiffness: 4064 Nm/rad
        b) Max Stress: 120 MPa



SKF Solution Code

Symptom D: Excessive shaft movement

Possible cause	Solution code
Looseness	
• Inner ring loose on the shaft	30
• Outer ring excessively loose in the housing	31
• Bearing not properly clamped on the shaft or in the housing	32
Surface damage	
• Wear from ineffective lubrication	1, 2, 3, 4
• Spalls in raceways and/or rolling elements due to fatigue	37
• Spalls in raceways and/or rolling elements due to surface initiated damage	38
Incorrect internal bearing clearance	
• Bearing with wrong clearance installed	11
• Bearing not properly clamped on the shaft or in the housing, excessive endplay	33

SKF Solution Code

Outer ring creeps (turns) in the housing seat

Worn or oversized seat

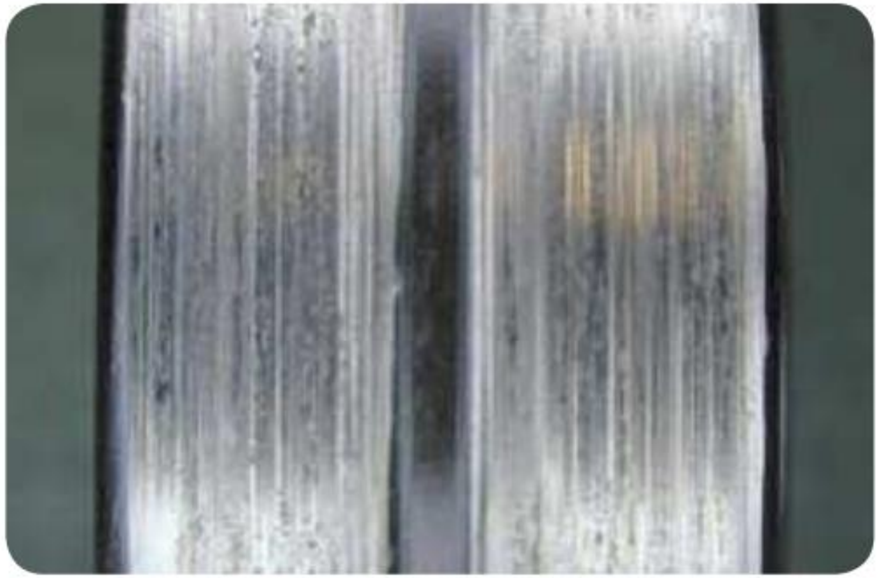
Considerations about fits or creep:
- Most applications have a stationary housing where the load is unidirectional. This is considered a stationary outer ring load and, under most conditions, the outer ring can be held in place with a loose fit.
- However, an outer ring can creep or turn in its housing seat if the seat is oversized or worn.
- This leads to increased noise and vibration levels as well as wear.

Actions:
- Metalize and regrind the housing seat to the appropriate size.
- For large housings, machining the seat to a larger diameter and using a cartridge sleeve might be a solution.

Unbalanced load

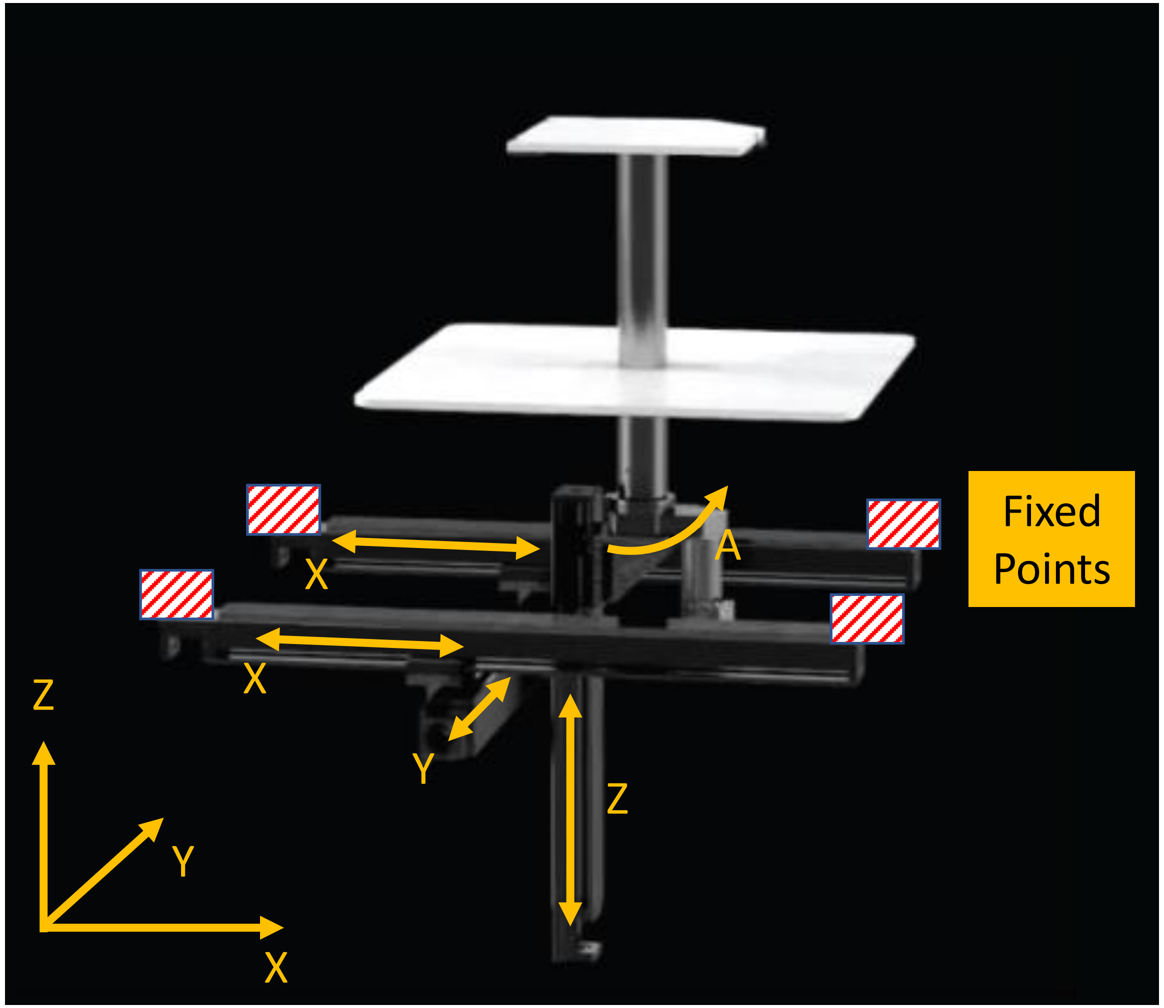
Considerations about fits or creep:
- Loads resulting from an unbalanced shaft can cause outer ring creep, even if the fits are correct.

Actions:
- Eliminate the source of the unbalance.
- Rebalance the machine.



https://cdn.skfmediahub.skf.com/api/public/0901d1968064c148/pdf_preview_medium/0901d1968064c148_pdf_preview_medium.pdf

CNC Frame – Motion



https://oxman.com/projects/glass-ii

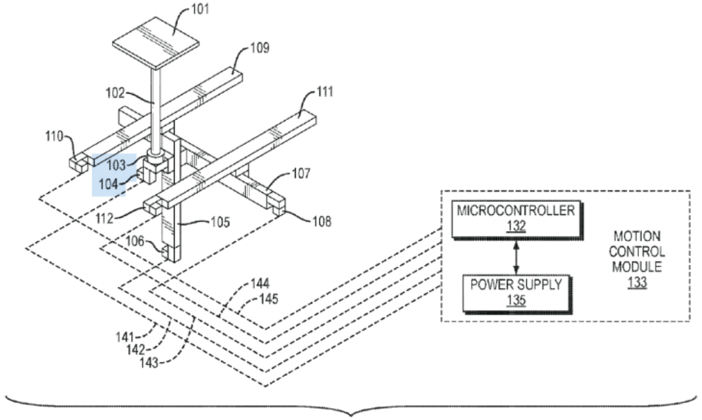
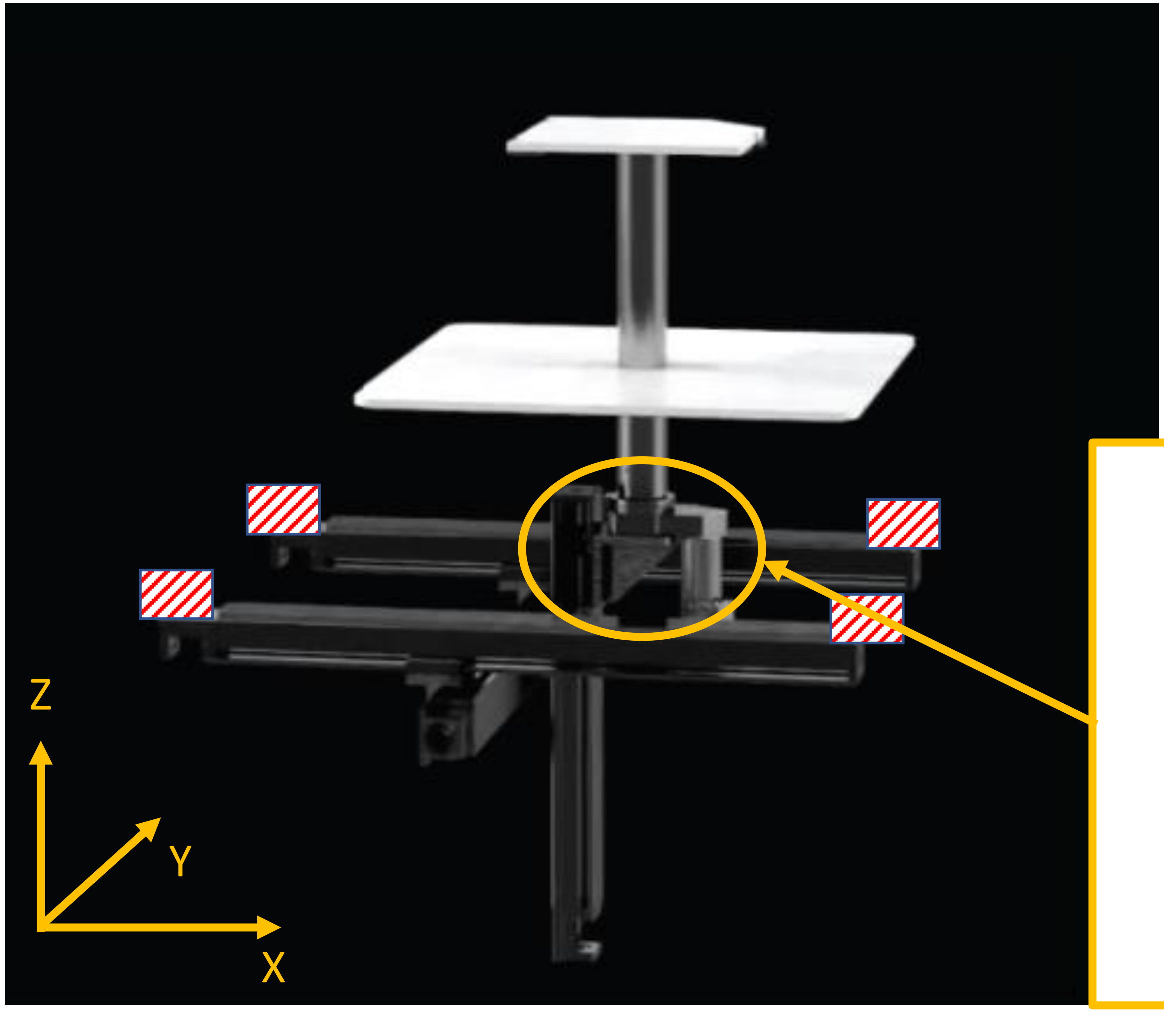


FIG. 1

Patent No. US 10,464,305

CNC Frame – Rotary Axis



https://oxman.com/projects/glass-ii

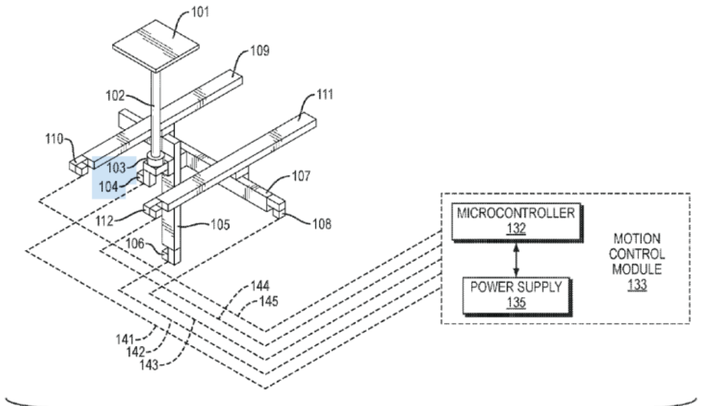


FIG. 1

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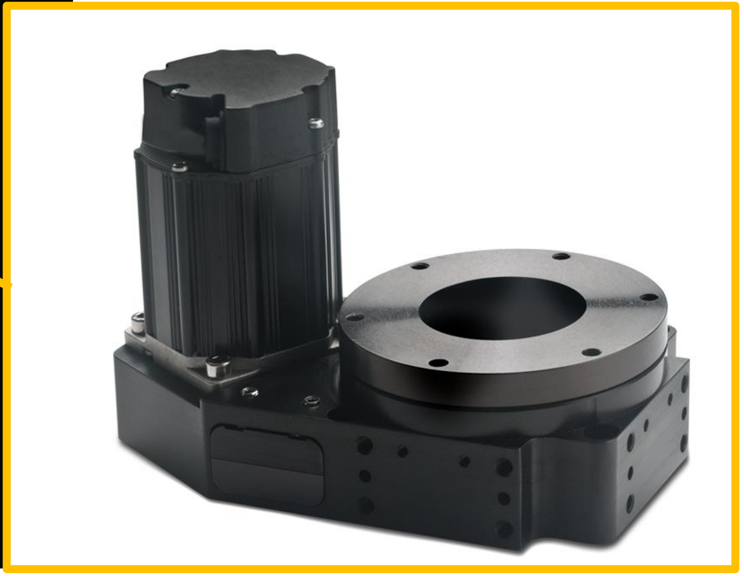
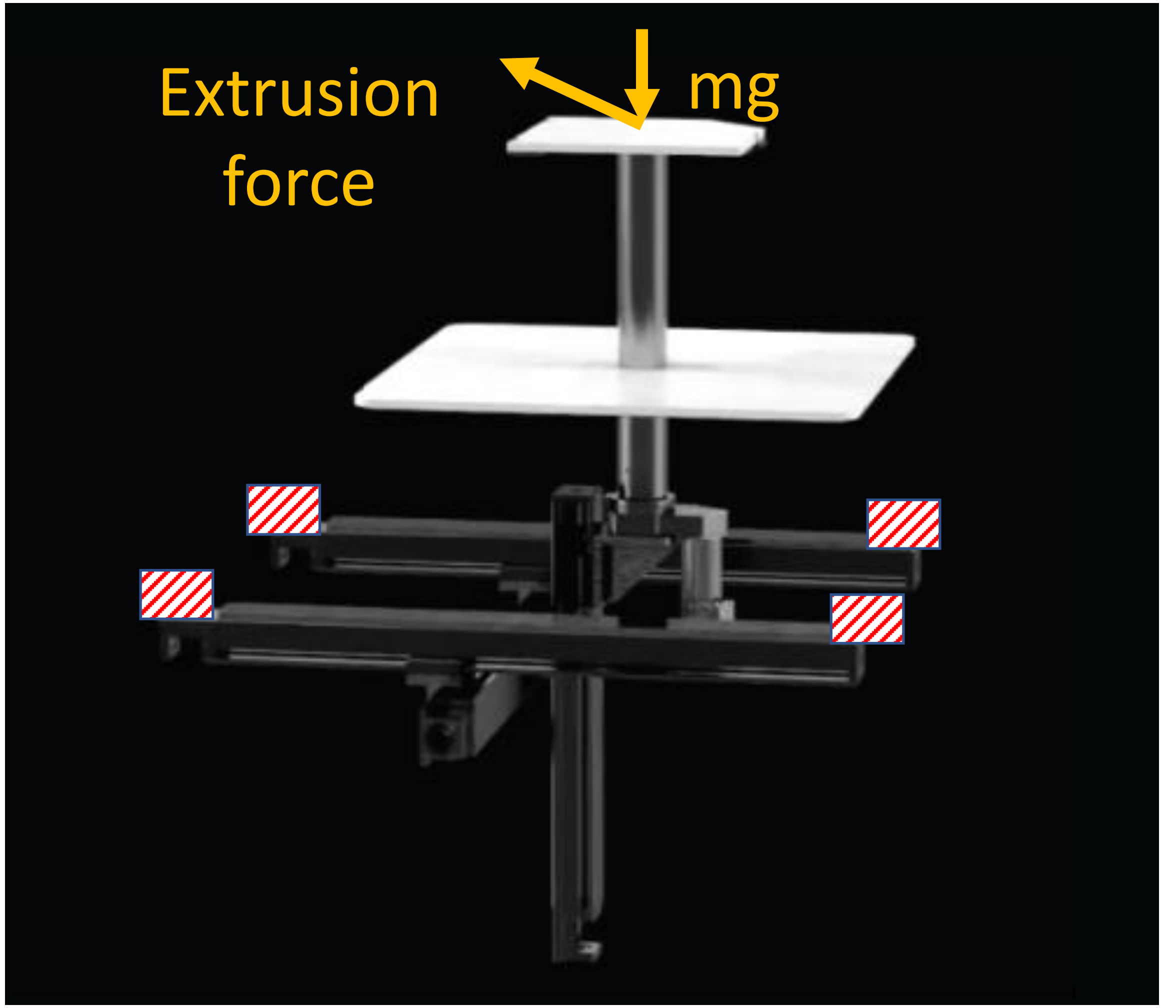


Bell-Everman SBR-50 Rotary Table

https://www.bell-everman.com/products/rotary-positioning/servobelt-rotary-stage

“large full duplex, angular contact bearings”

Topic 2 – Statics FBD



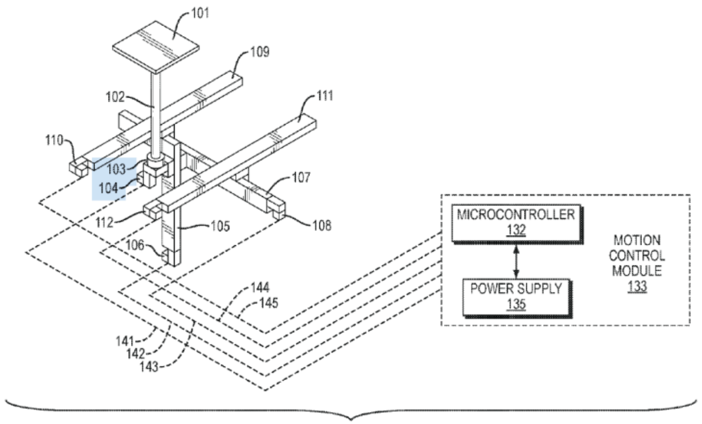


FIG. 1

Patent No. US 10,464,305

2. Integrate sensors to:
   a. Measure the weight of the extruded material
   b. Measure lateral loads and torques on z-shaft

Topics Summarized

1. Devise a new connection to Z-drive to:
   a. Avoid overloading the bearings of the rotary stage
   b. Improve stiffness
2. Integrate sensors to:
   a. Measure the weight of the extruded material
   b. Measure lateral loads and torques on the z-shaft