Test Frame Design for Characterization of Additive Manufacturing Compliant Materials

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Chair:

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CEDAR CLEMSON ENGINEERING DESIGN APPLICATIONS AND RESEARCH

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Overview

- Background
- Motivation of Design
- Research Questions
- Research Method
- Singularity Work
- Design Solution
- Solution Justification
- Discussion of Solution
- Conclusions
- Future Work
- References

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Background of Parallel Manipulators

- Classification by: DOF, kinematic structure, drive technology
  - This design: 6-DOF, closed-loop, electrohydraulic [Tsai]
- 3 types of parallel manipulators
  - Planar → 3-DOF = 3 limbs
  - Spherical → 3-DOF = 3 limbs
  - Spatial → 6-DOF = 6 limbs
- This work → Spatial parallel manipulator

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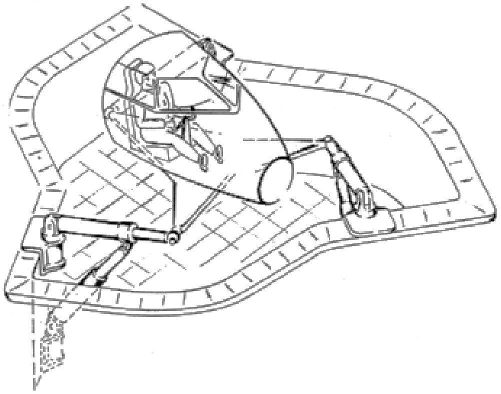
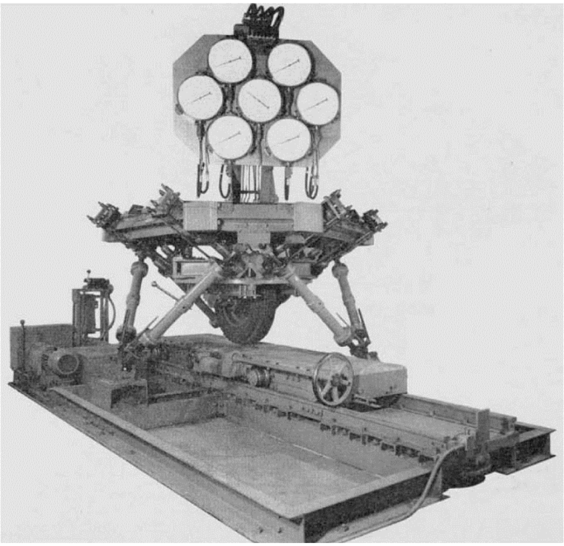
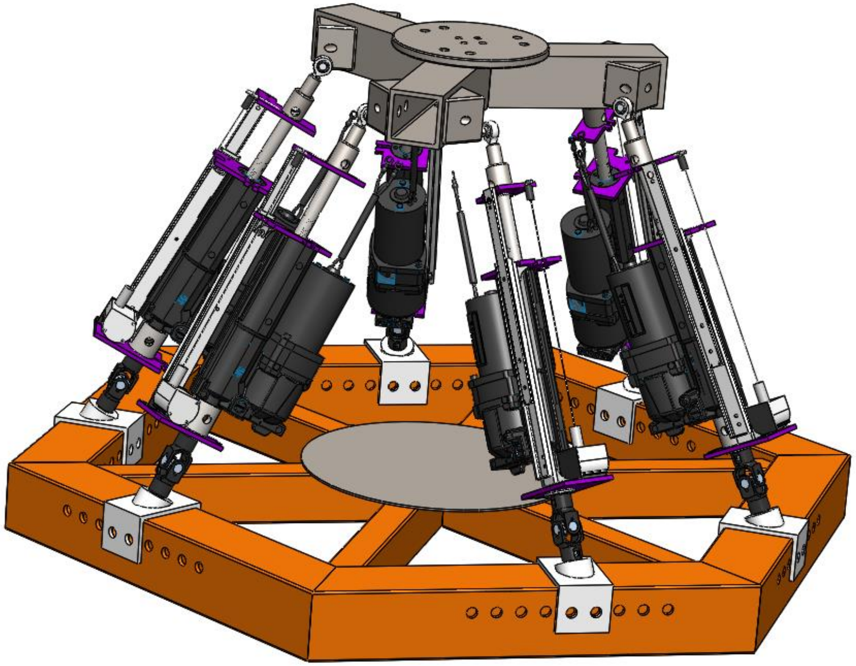
Background: Stewart-Gough Platform

- First published paper by Stewart in 1965 (right)
  - Flight simulator for helicopter pilots
- Gough developed similar platform before Stewart (bottom left)
  - Tire testing machine
- SPU configuration (bottom right)
  - Spherical → Prismatic → Universal







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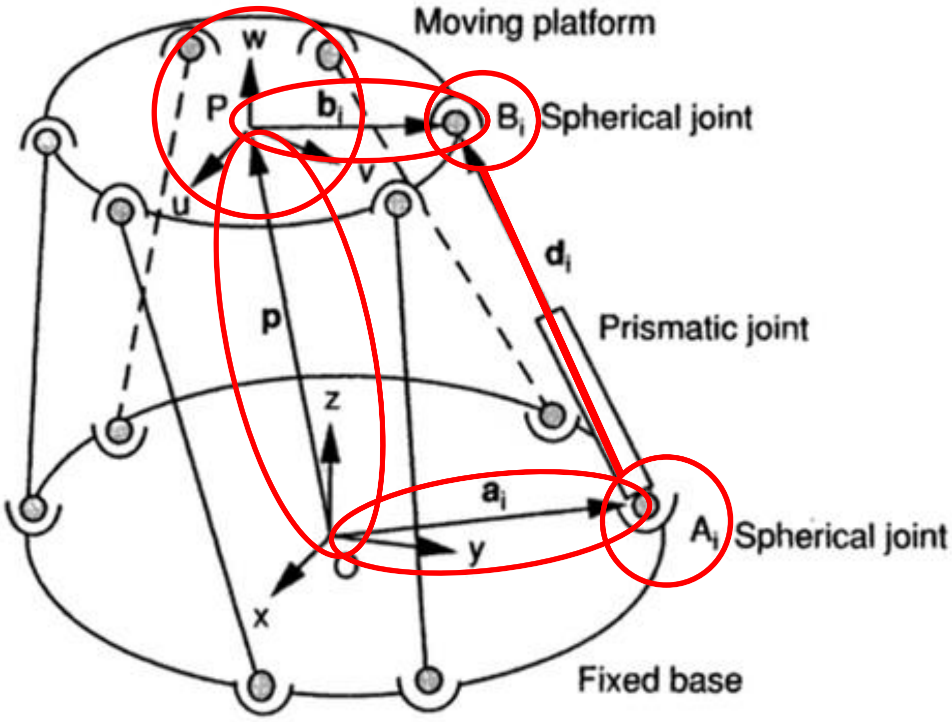
Background: Stewart-Gough Platform

- Vector-loop equation:
  - $\overline{A_i B_i} = \boldsymbol{p} + R_B^A \boldsymbol{b}_i^B - \boldsymbol{a_i}$
- Rotation Matrix:
  - $R_B^A = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix}$
- Leg length: Inverse Kinematics
  - $d_i^2 = \overline{A_i B_i}^T \overline{A_i B_i}$
- Jacobian
  - $\boldsymbol{s_i} =$ unit vector of $\overline{A_i B_i}$



$$J = \begin{bmatrix} \boldsymbol{s}_1^T & (\boldsymbol{b}_1 \times \boldsymbol{s}_1)^T \\ \vdots & \vdots \\ \boldsymbol{s}_6^T & (\boldsymbol{b}_6 \times \boldsymbol{s}_6)^T \end{bmatrix}$$

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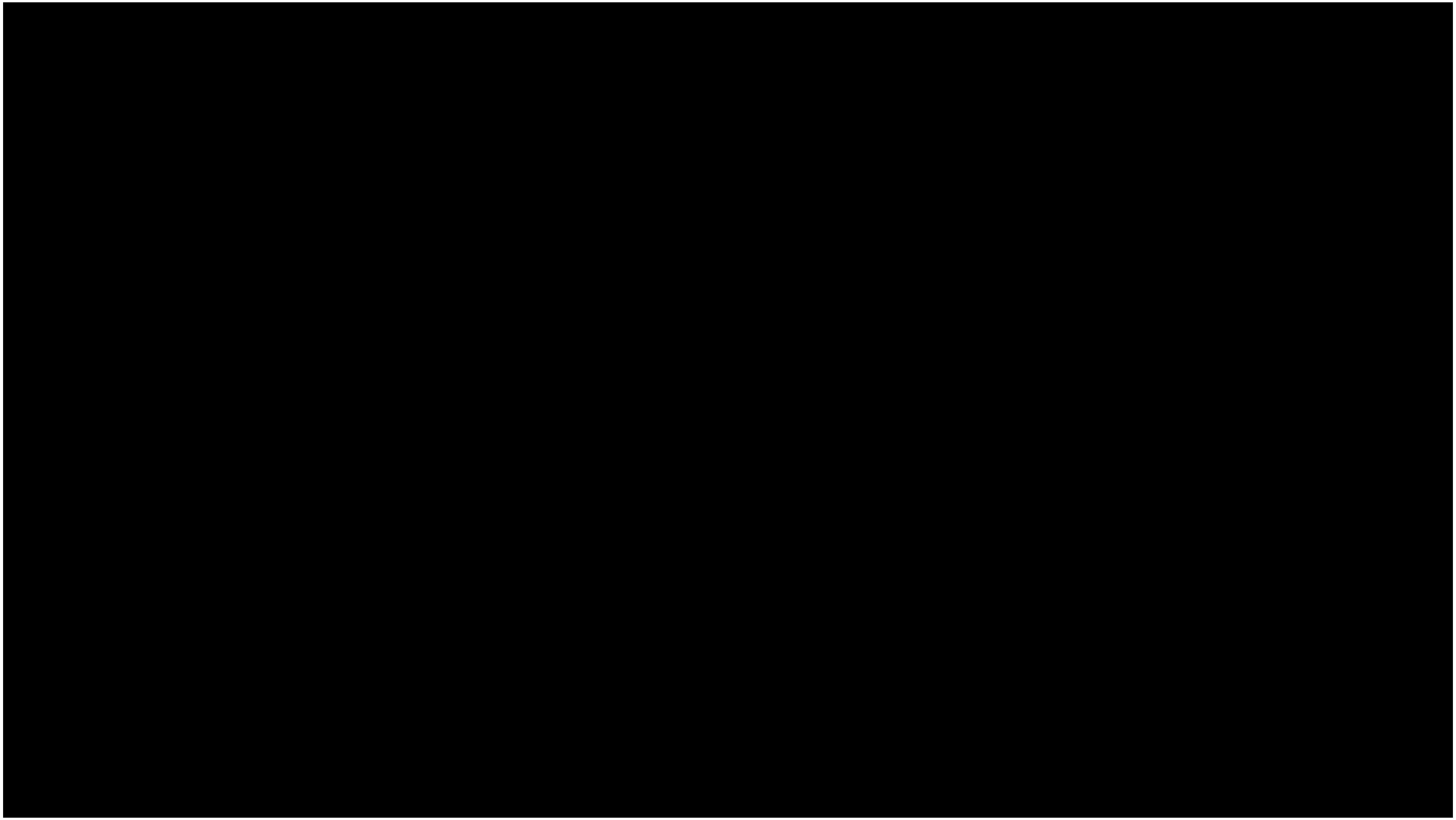
Background: Previous Work

- Naval Research Laboratory (NRL) at Washington, DC
- “Real-time” characterization of anisotropic composite materials [1-3]
  - Full field strain measurements
  - ~ 2 meters tall
  - ~ 1.5 m platform diameter
  - ~ 170 cm stroke

NRL 66.3 [4]

Background: Previous Work



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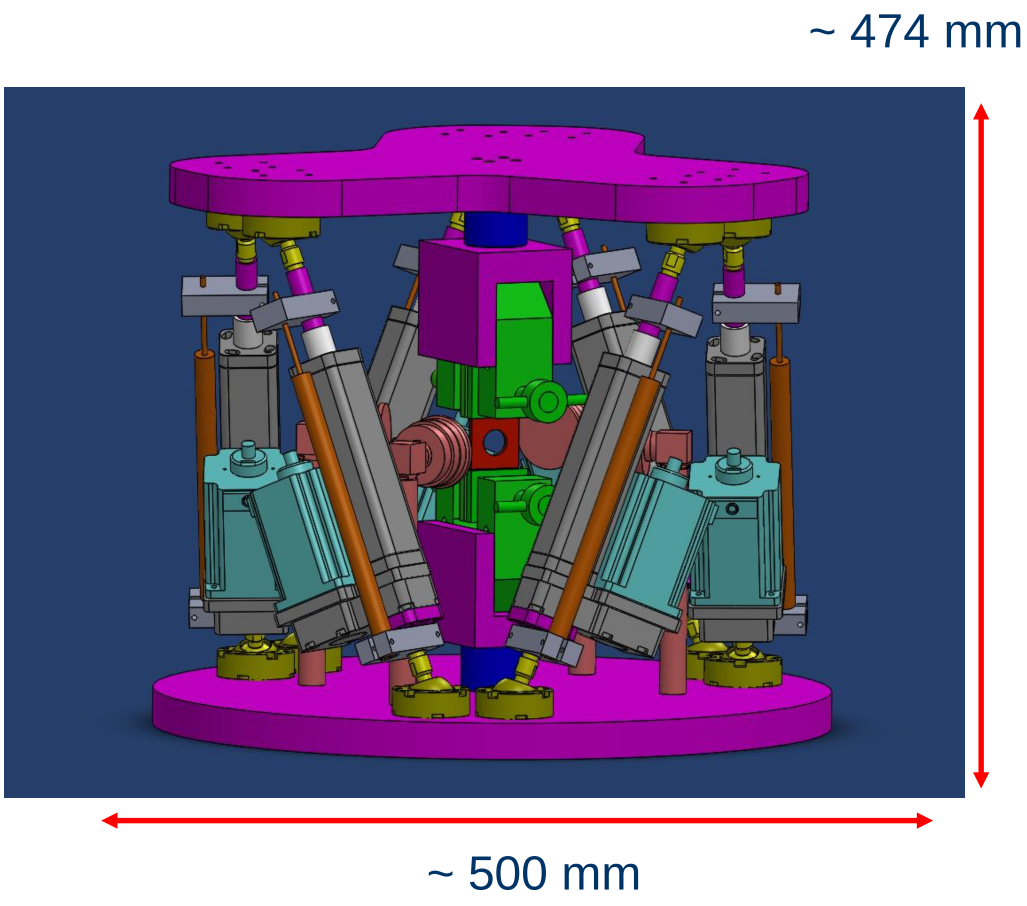
Background: Previous Work

- Developed by senior design team at Colorado School of Mines
  - 30 weeks
- Several issues
  - SPS configuration
  - Platform is too heavy and compliant for testing
    - Metallic or composite materials
  - "Home" position → nearly singular
  - Forces and displacements of specimen → sensitive to variations in geometry of platform
  - Grips not suitable for:
    - bending/torsion tests
    - metals
  - Stroke length is insufficient (60 mm)
    - Load rating: 1349 lbf.
    - Bending test: Slope ~ 42°



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Motivation for Design

- Need for a more in depth knowledge of characterization of nonlinear anisotropic materials
  - Change load dynamically for greater excitation of properties
- 6-DOF test frame = greater movement than traditional stands
  - Reduces the amount of specimens → reduces cost
- Small scale design is more efficient
  - Reduces weight, cost, space, resources
  - Easier transportation

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Research Questions

1. How suitable is the given design for…
   1. With respect to workspace
   2. With respect to FEA
   3. With respect to some metallic AM materials
2. How can the design be improved for a larger workspace for more compliant materials?
3. How can the singularities be better understood in the parallel manipulator?

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Research Methods

- Background research
- Recommendations for Naval Research Laboratory (NRL)
- Overview of given design
- Kinematic analysis of general SG platform
- Singularity analysis
- Analysis of specimen design
- Optimization of design
  - Design for modularity
  - Reduce weight
  - Minimize deflection
  - Maximize workspace

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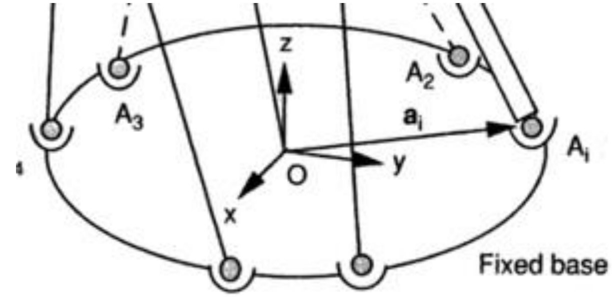
Singularity Work: Jacobian Normalization

- Condition number varies with units

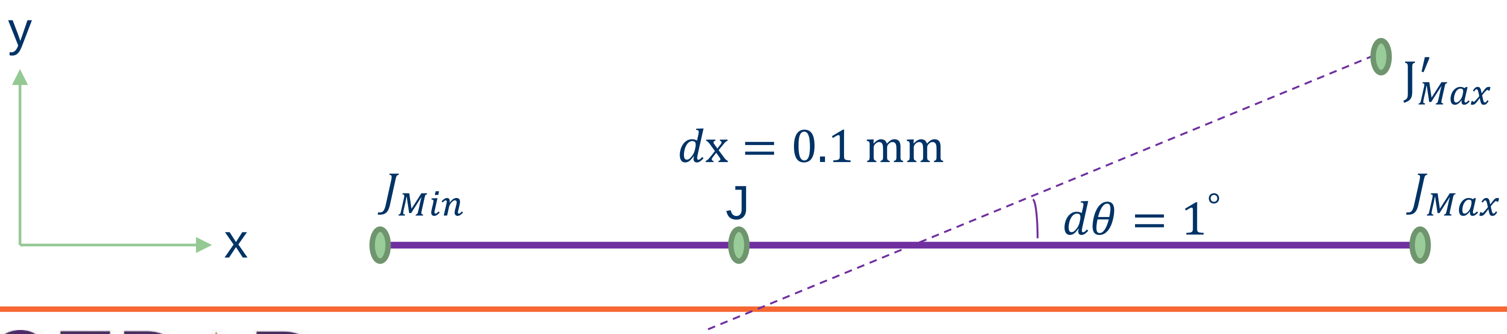
$$J = \begin{bmatrix} \boldsymbol{s}_1^T & (\boldsymbol{b}_1 \times \boldsymbol{s}_1)^T \\ \vdots & \vdots \\ \boldsymbol{s}_6^T & (\boldsymbol{b}_6 \times \boldsymbol{s}_6)^T \end{bmatrix}$$

- To normalize the Jacobian values within the workspace of the manipulator

$$J_N = \frac{J - J_{Min}}{J_{Max} - J_{Min}}$$



  - Taking a "slice" of the x-y plane at "home" z value
    - Min and max Jacobian taken from both ends of the line ($0 \leq \theta \leq 180$)

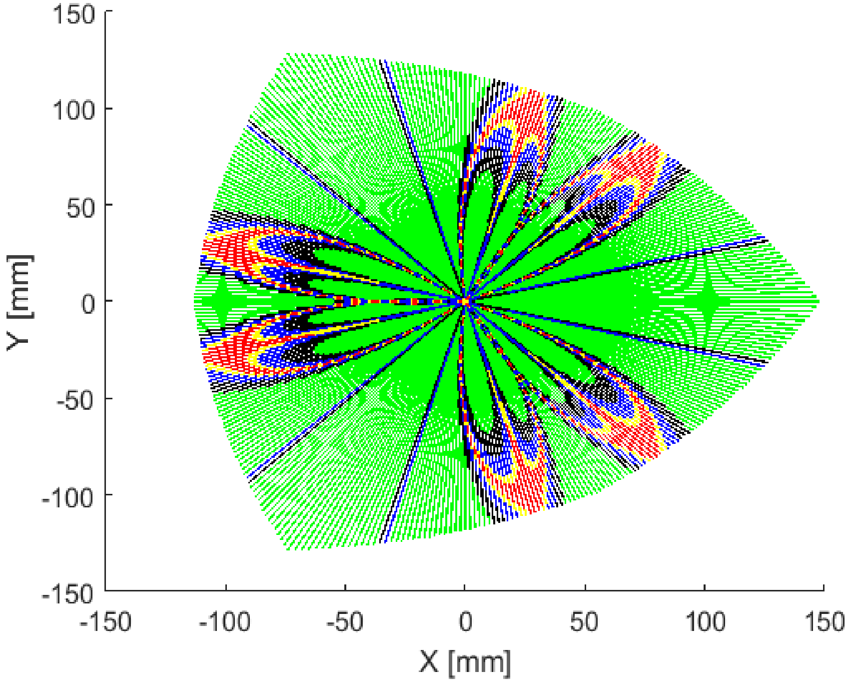


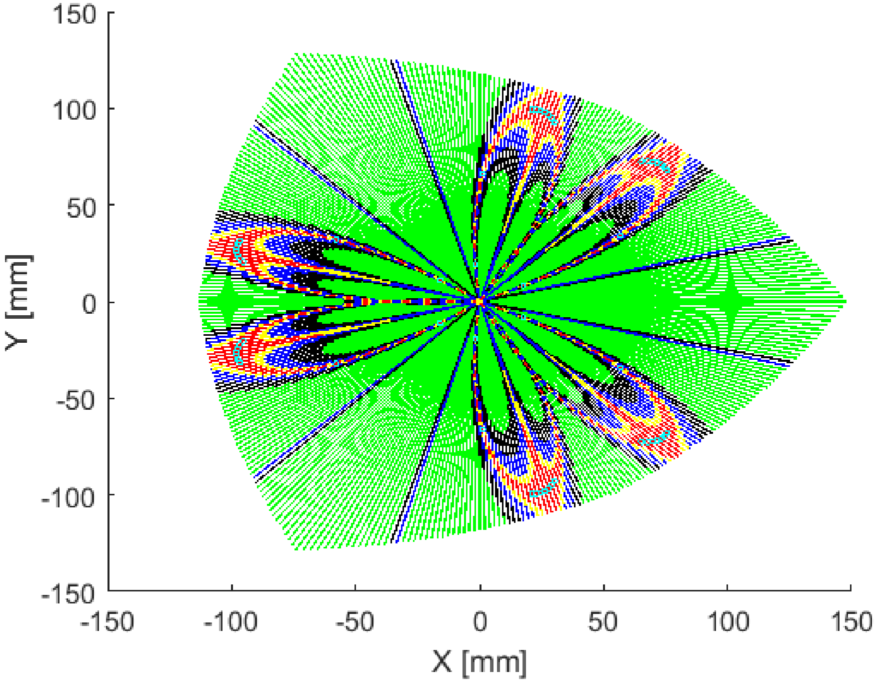
Jacobian Normalization Results

Color coding scheme	
Color:	Condition Number Range
Green	<= 50
Black	> 50 & <= 100
Blue	> 100 & <= 250
Yellow	> 250 & <= 500
Red	> 500
Cyan	> 100000

GOOD

BAD





- Plotting normalized Jacobian values vs the movement of centroid, P

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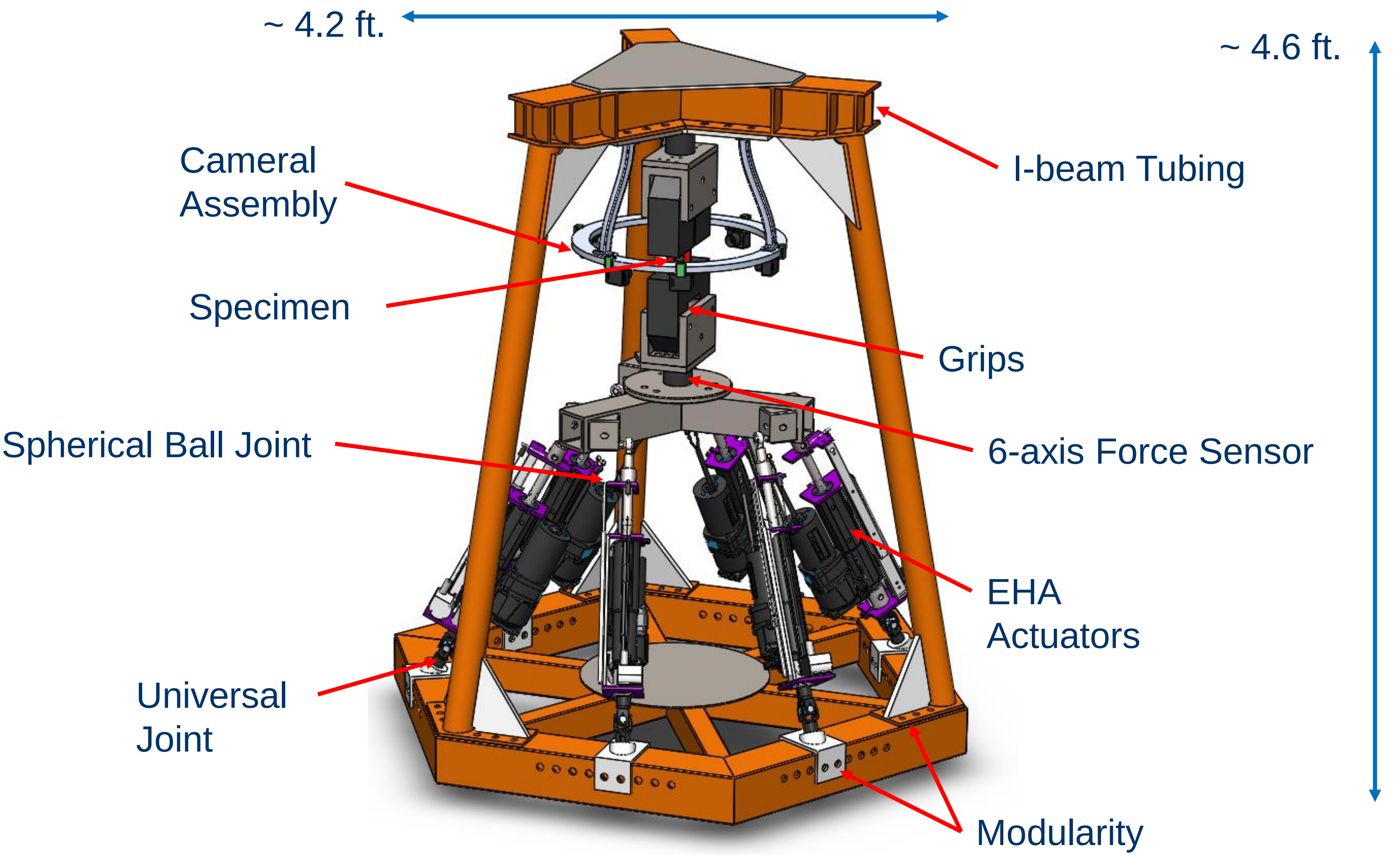
Overall View of Design Solution



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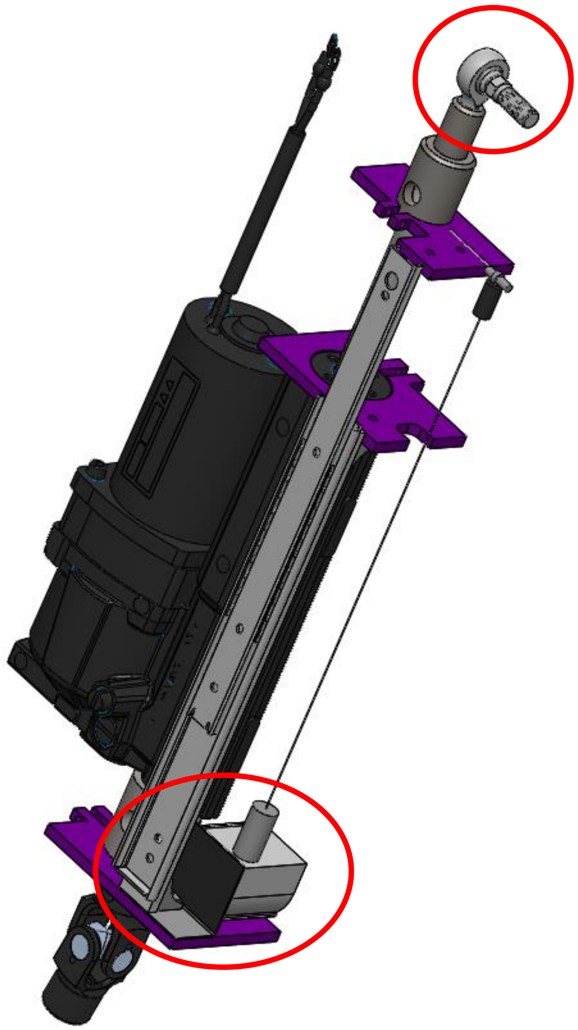
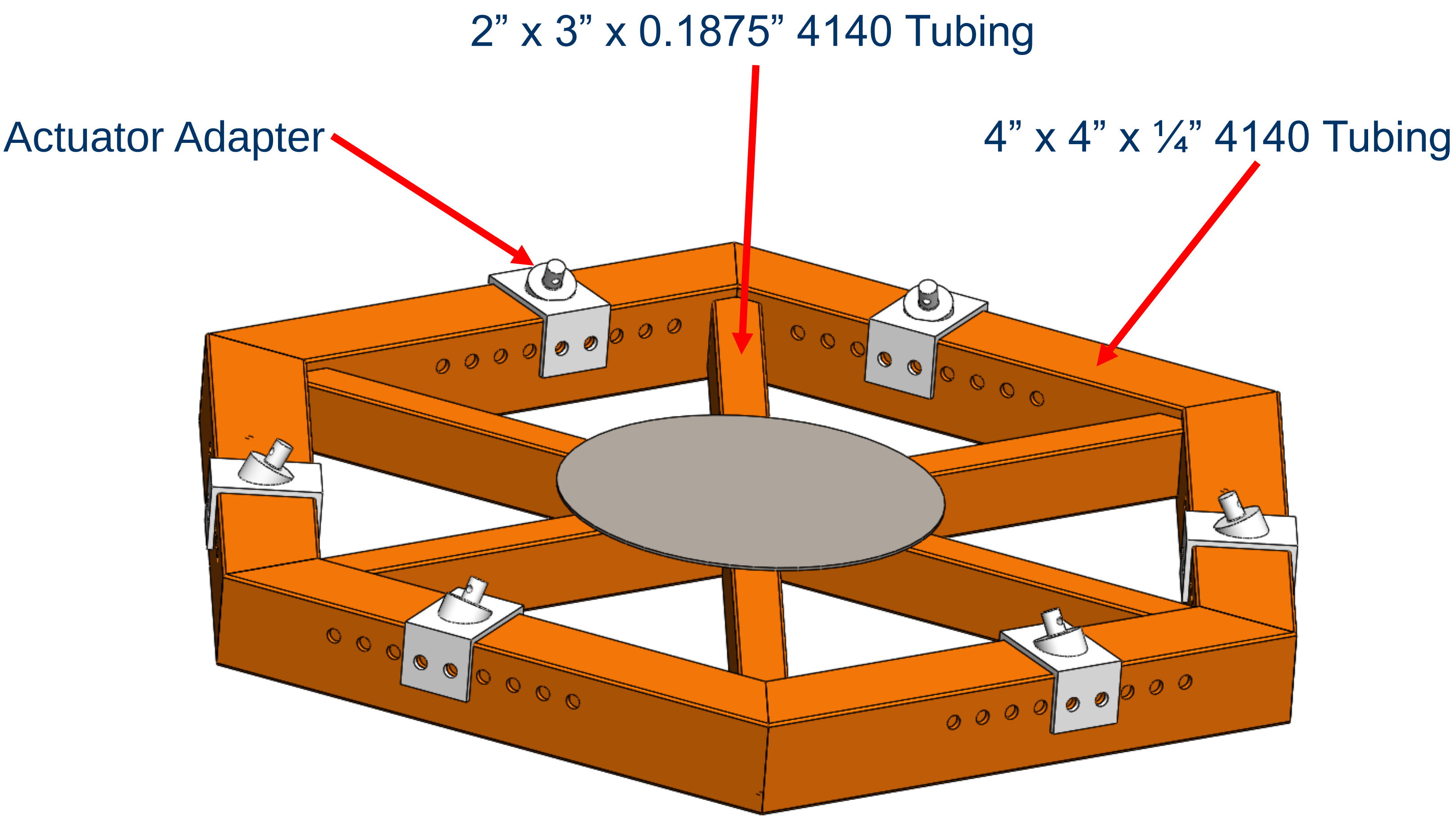
Design Solution: EHA Actuators

- Electrohydraulic actuators (EHA)
  - 8 in. stroke
  - Capacity: 4800 lbs. (x6 = 28,800 lbs.)
  - Speed: 1.3 in/s
- Drawer slide & aluminum plates
  - Why?
- Linear Motion Position-Measuring Transmitters (LMPMT)
  - Stroke: 12.5 in.
  - Accuracy Range: -0.25% - 0.25%
  - Repeatability Range: -0.05% - 0.05%
- Spherical ball joint
  - Static radial load: 10,250 lbs.
- Universal Joint
  - Max Torque: 5,500 in-lbs.



Design Solution: Bottom Frame Assembly



- Can adjust bottom joint locations for change in workspace

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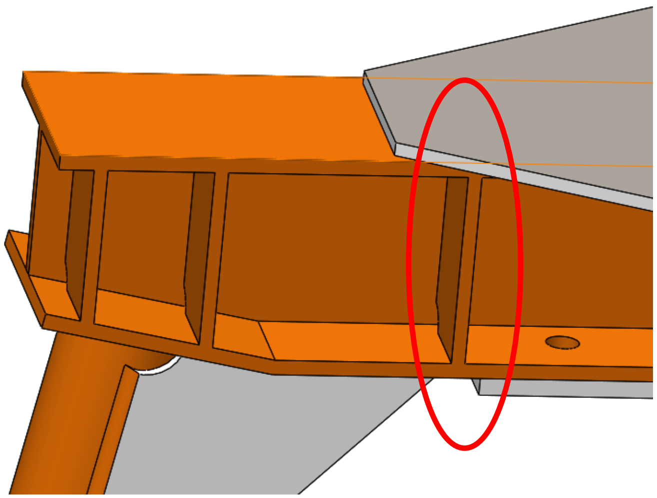
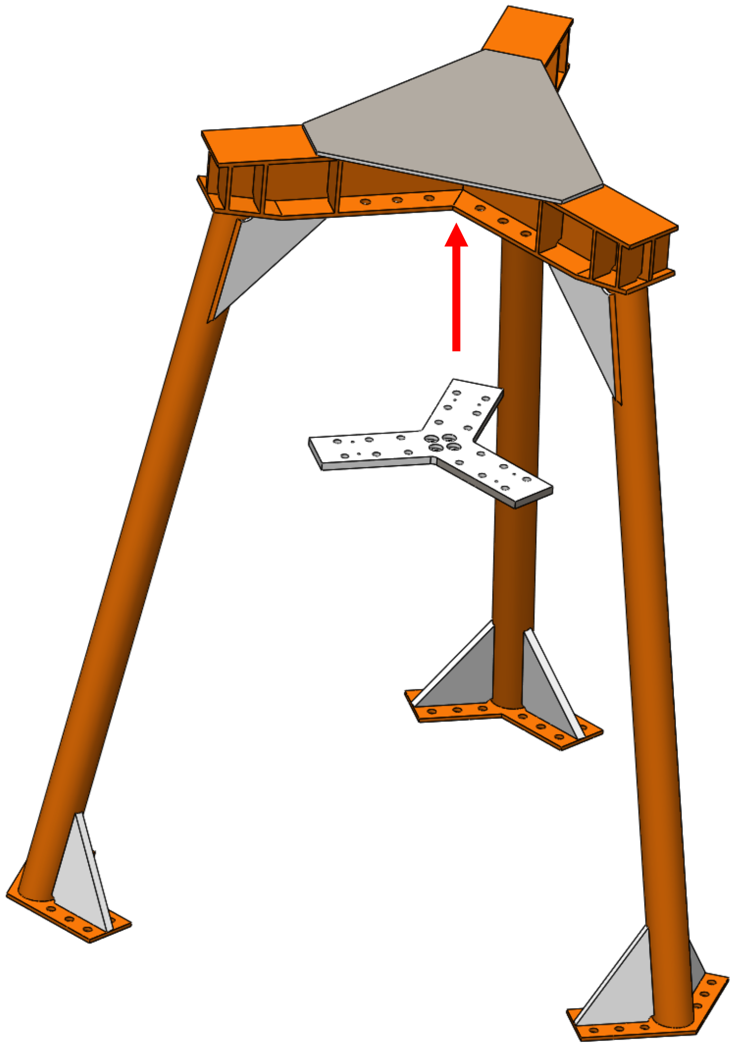
Design Solution: Top Frame

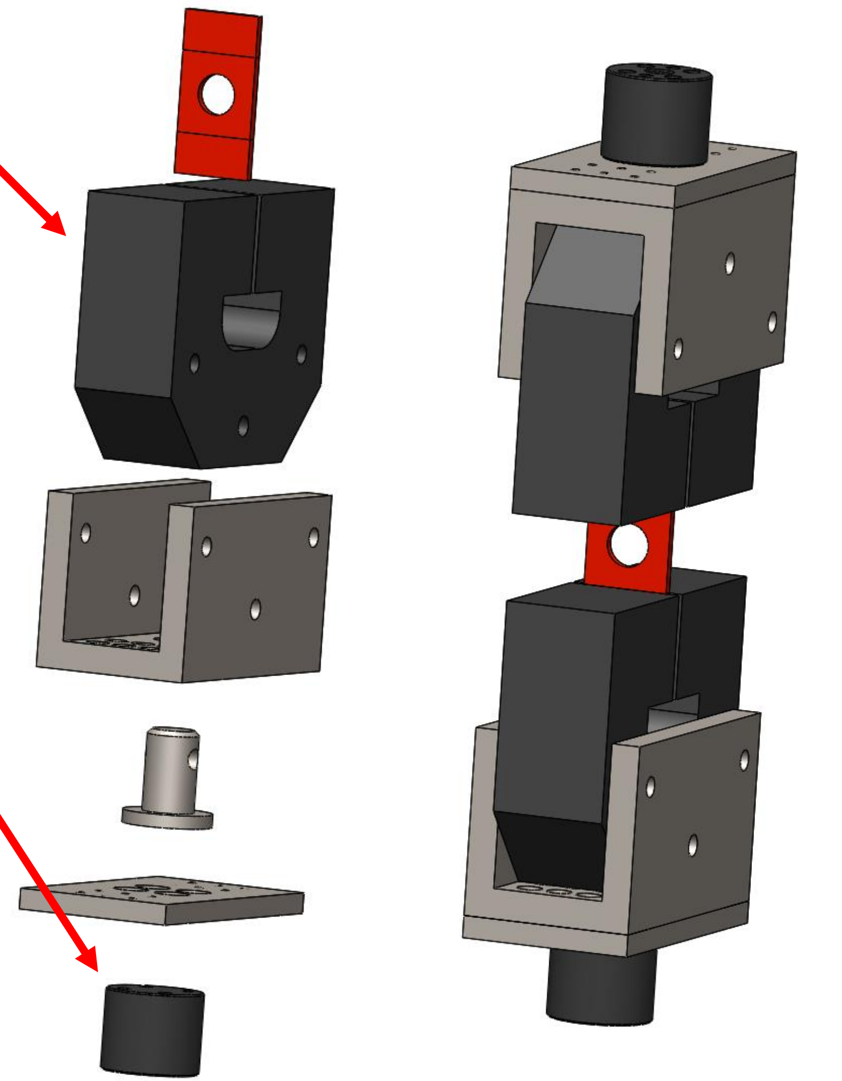




- All welded
  - Except exploded portion
- Modified H-beams for additional stiffness
  - Account for in-plane bending

Design Solution: Grips

- Grips (black): ADMET GV-50T
  - Tensile Force: 50kN
  - Plain clamping surface
  - Opening size 0 – 30 mm
- Adapter (grey) from force sensor to grip
- 6 axis force/torque sensor
  - Sunrise Instruments: M3943
  - Non-linearity: 1%
  - Hysteresis: 1%
  - Fx & Fy: 16200 N
  - Fz: 32400 N
  - Mx & My: 660 Nm
  - Mz: 530 Nm



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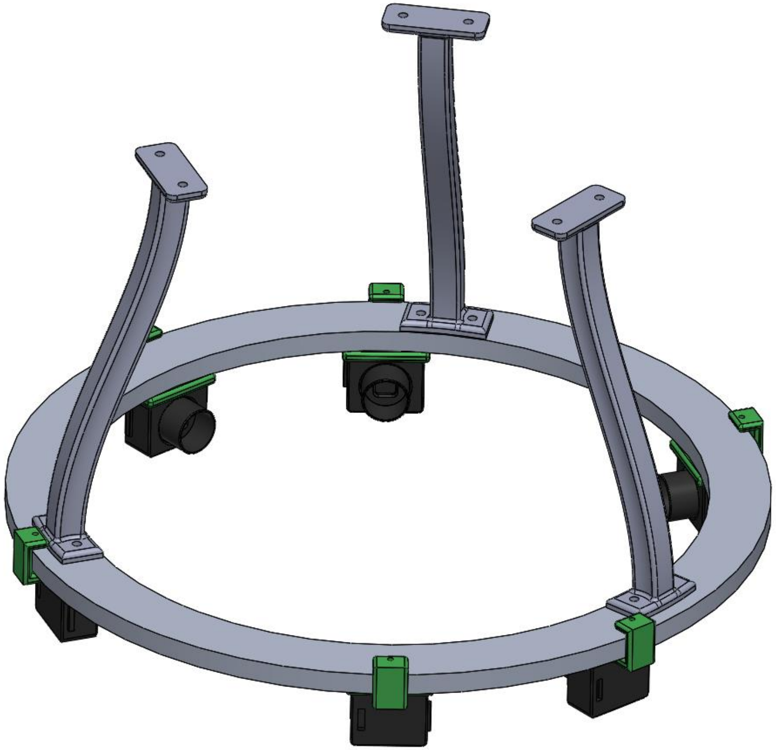
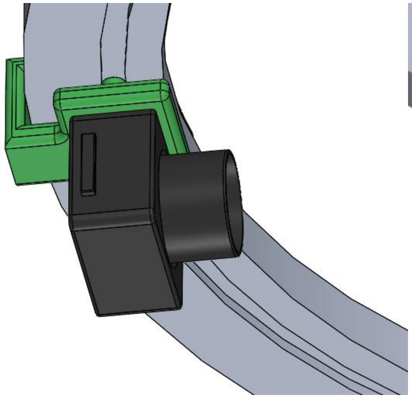
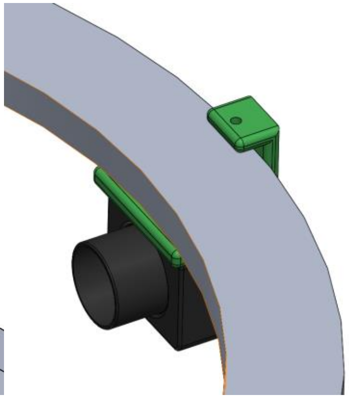
Design Solution: Camera Assembly

- Aluminum ring
- 3D printed camera adapter (green)
  - Slot design for stability (bottom left)
- Cameras (black)
  - FLIR: Chameleon 1.3 MP Color
  - 1280 x 1024 res; 149 FPS
- 3D printed legs







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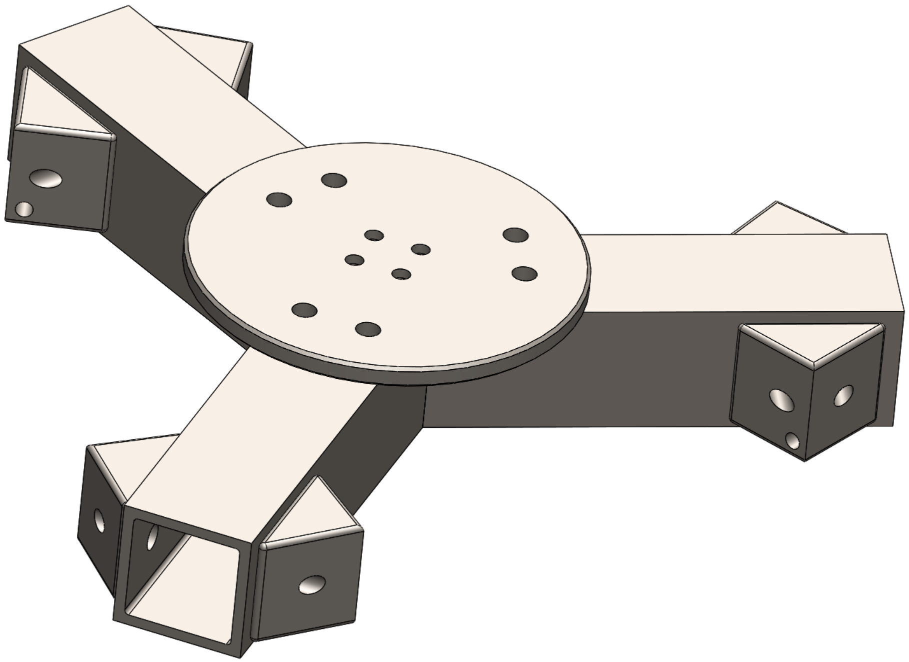
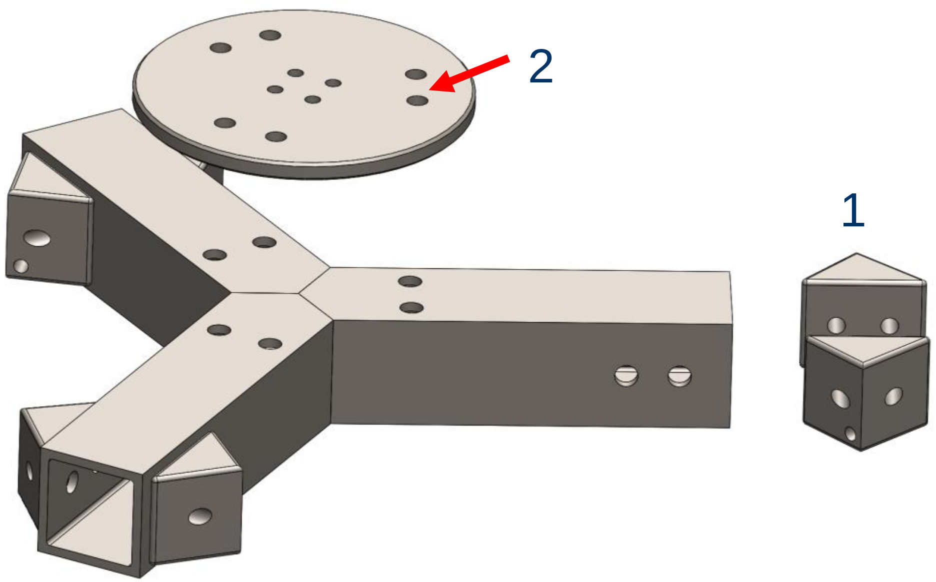
Design Solution: Top Plate

- 3” x 3” x ¼” 4140 Tubing
  - Welded together
- 1 connected by M14 screws
- 2 connected by M14 screws through all





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Solution Justification: Deflection

Top Frame					
6061-T6 Specimen					
Value	Unit	Direction	Location	Value	Units
Shear					
0.3453	mm	In-plane shear, one leg	Grips	3000	N
	mm	in-plane shear, two legs	Grips	3000	N
Tensile					
0.3305	mm	Tensile	Grips	30000	N
Torsion					
0.001335	mm	Y-direction	center of i-beam leg	30	Nm
FIXED	mm	y-direction	Grips	30	Nm
Moment					
	mm	neg Z direction	Grips	26	Nm
0.007857	mm	pos X direction	Grips	100	Nm
	mm	neg X direction	Grips	100	Nm

Top Plate					
6061-T6 Specimen					
Value	Unit	Direction	Location	Value	Units
Shear					
0.3517	mm	In-plane shear, one leg	Grips	3000	N
0.3965	mm	in-plane shear, two legs	Grips	3000	N
Tensile					
0.1798	mm	Tensile	Grips	30000	N
Torsion					
0.003258	mm	y-direction	outer edge	30	Nm

- “Value” column
  - Taken from specimen FEA
- Aluminum specimen vs. polymer specimen
- Coordinate system based on SW

Bottom Frame Assembly					
6061-T6 Specimen					
Value	Unit	Direction	Location	Value	Units
Shear					
3.671	mm	In-plane shear, one leg	Joints	3000	N
3.671	mm	in-plane shear, two legs	Joints	3000	N
Tensile					
0.502	mm	Tensile	Joints	30000	N

Solution Justification: Workspace

- Rotation data → Z direction
  - Can reach ~ 102° total
- Moments measured from center frame of specimen
- Translational movement
  - X & Y: ± 200 mm
  - Z: ~ ± 100 mm

Rotation Data		
About +X	28.7	Deg
About -X	-31.5	Deg
About +Y	25.8	Deg
About -Y	-25.8	Deg
About +Z	51.1	Deg
About -Z	-51.1	Deg

Pure Bending Limits	
Direction	Degree
My (-)	28.813
My(+)	28.675
Mx (-)	29.012
Mx (+)	28.869

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Discussion of Solution

- Limitations of design
  - Grips: Slippage, pressure on specimen, specimen setup
  - Not a “table-top” design
  - Metallic specimen redesign
- Singularity analysis theoretical only
  - Testing to compare experimental results
  - Does not account for rotation of the top plate
  - Suitable condition number and determinant values are not well known
- May need additional cameras for compliant materials

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Conclusion

- Solution addresses the problems of previous design
  - Workspace
  - Singularities
  - Stiffness
- In-plane shear and in-plane bending account for most of the deflection
- More work and testing is needed for analysis of singularities

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Future Work

- Finish building test frame
- Getting test frame to move
- Getting sensors to work
- Getting results (without calibration)
  - Compare bulk material with printed specimen
- Calibrate test frame
- Run with various materials and different printing styles

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QUESTIONS?

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BACKUP SLIDES

Singularities

- What are singularities?
  - Boundary of workspace
  - Poorly understood within workspace
  - Condition Number/Determinant of Jacobian
  - Heavily determined by geometry

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Singularities Cont.

- Types [5]
  - Inverse kinematic singularities
  - Direct kinematic singularities
  - Combined singularities

$$\underline{J_x}\dot{\boldsymbol{x}} = J_q\dot{\boldsymbol{q}}$$

- Inverse kinematic singularities
  - Occur at the workspace boundary
  - Do not occur within workspace
  - J_q = Identity matrix
- Direct kinematic singularities
  - Impossible to find all singularities
  - Can be examined by Jacobian matrix of platform velocity
  - Depends on geometry
    1. Top plate geometry is similar to bottom plate geometry
    2. Point at which all the leg lengths are equal
    3. Legs are parallel to each other
- Combined singularities do not happen for SG-platform

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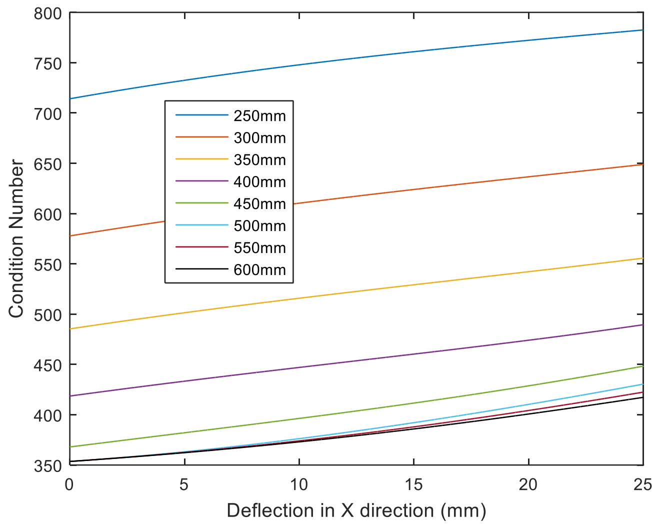
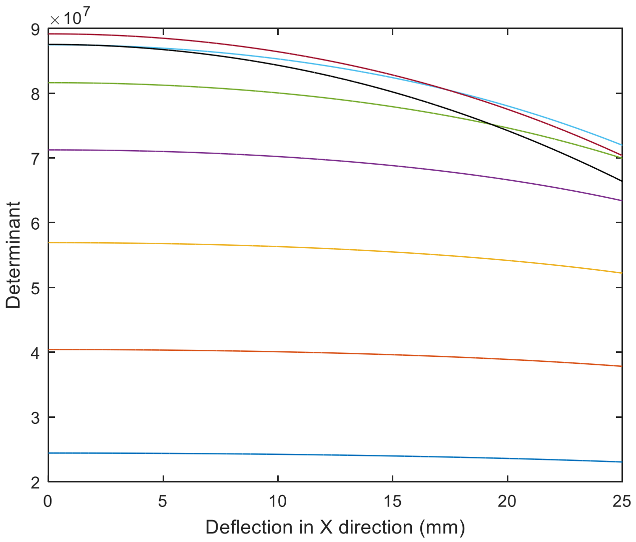
Condition Number & Determinant

- Suitable scenarios
  - Condition number = 1
  - Higher the determinant, the better
- Unsuitable scenarios
  - Condition number goes to infinity
  - Determinant = 0

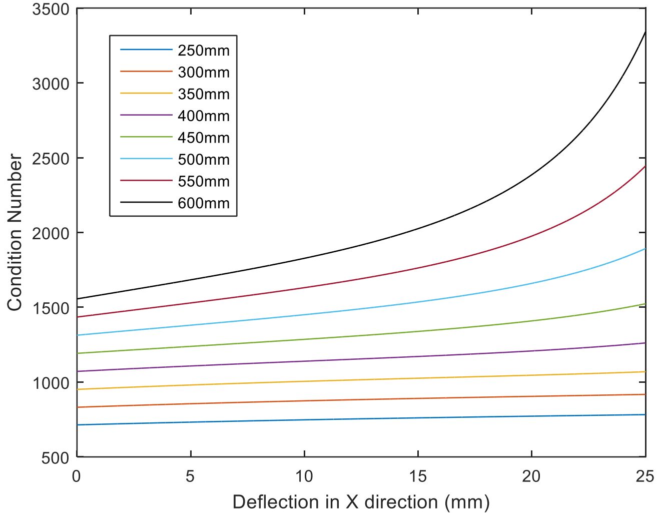


- Pure bending results of ABS-ESD7 [6]
  - Using platform geometry of initial design
  - 25 mm deflection
  - Increasing bottom plate radius
  - Constant top plate radius (250 mm)

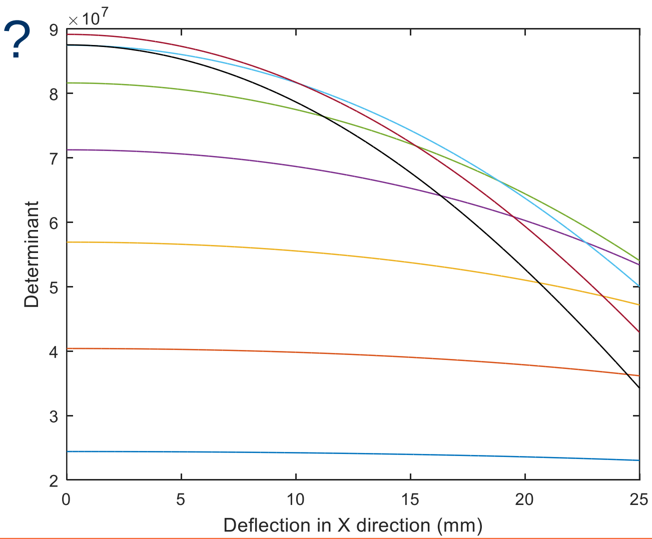


Condition Number & Determinant Cont.

- Pure bending results of ABS-ESD7
  - Increasing top plate radius
  - Constant bottom plate radius (250 mm)



- What is considered an acceptable range?
  - Plug into direct kinematic equations
  - Compare results



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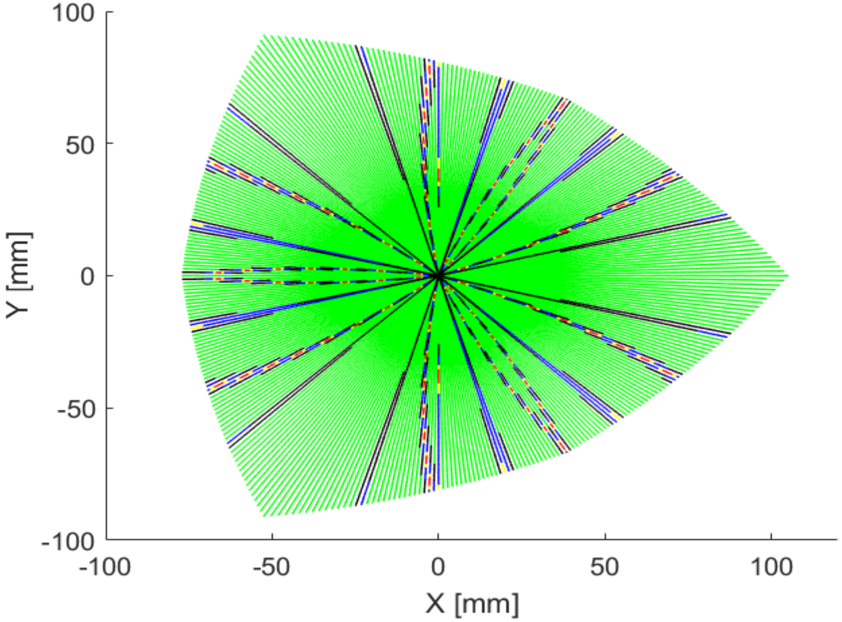
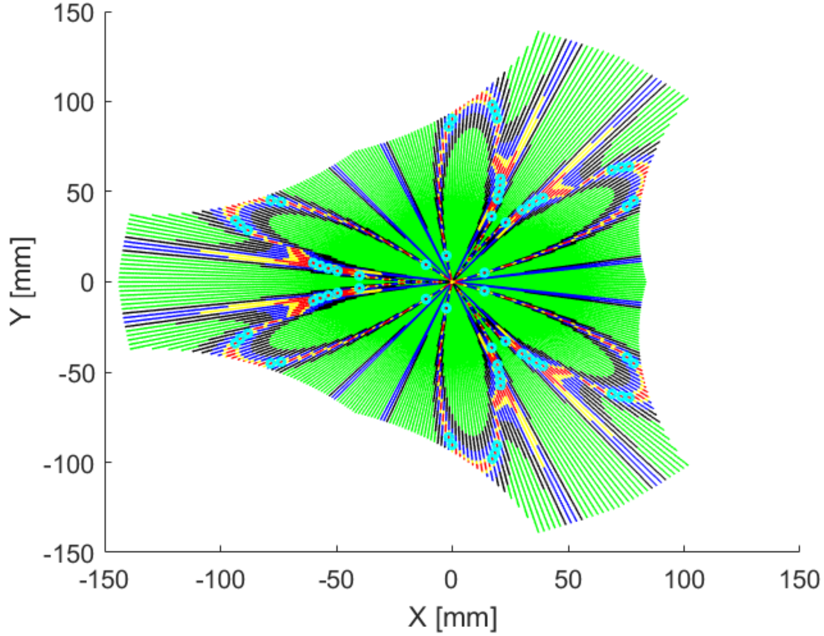
Jacobian Normalization Results

- 37.5 mm above “home” position



- 37.5 mm below “home” position



- Limitations and Issues
  - It is not known whether this method shows that singularities are actually there
  - Does not account for rotation of the top plate
  - Suitable condition number and determinant values are not well known

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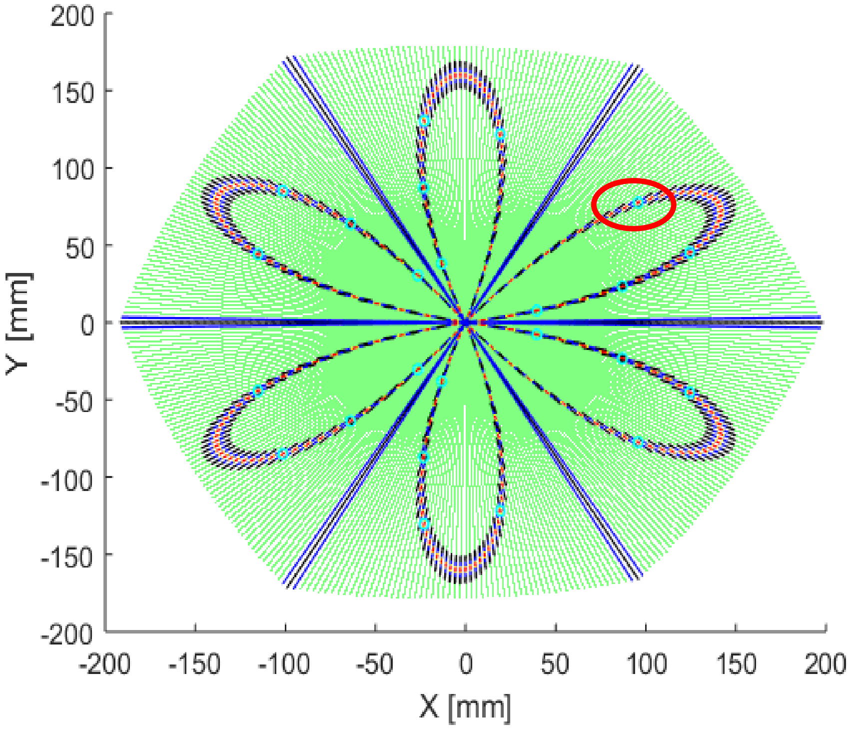
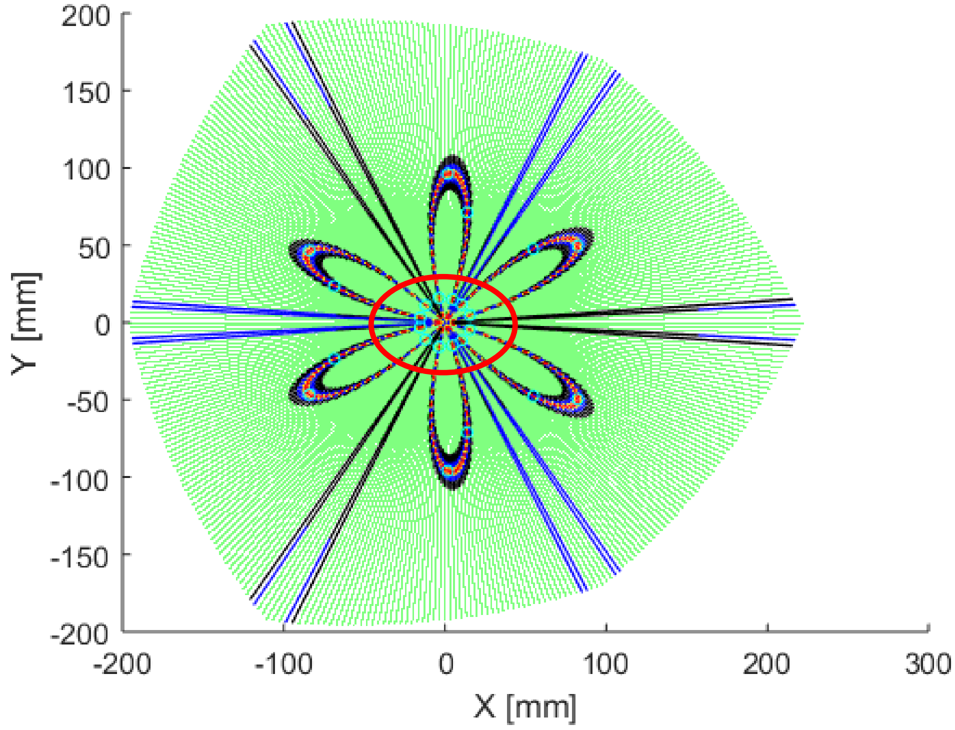
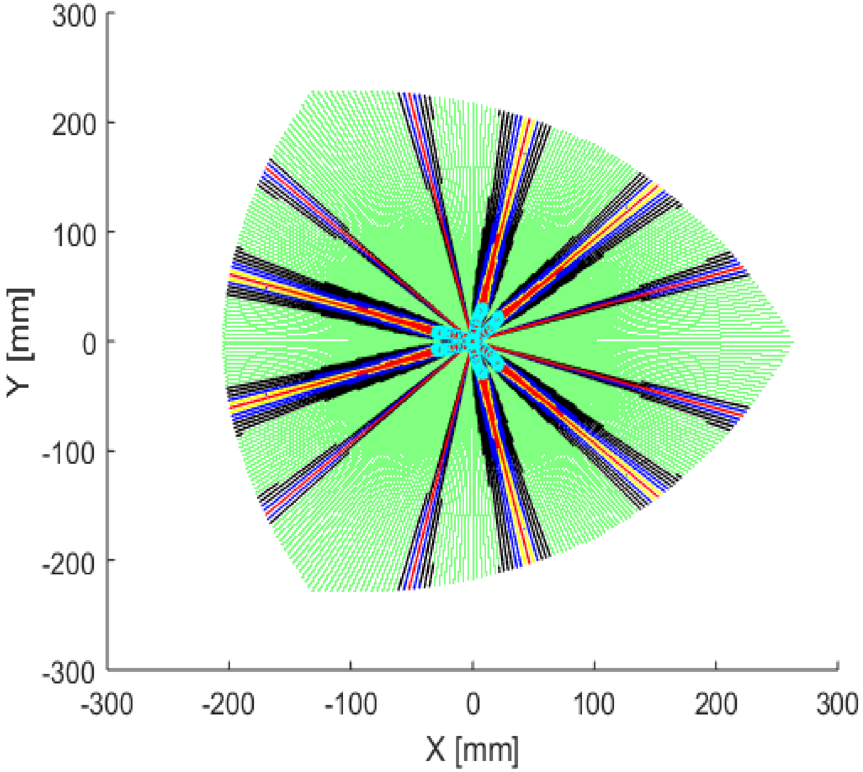
Other Findings

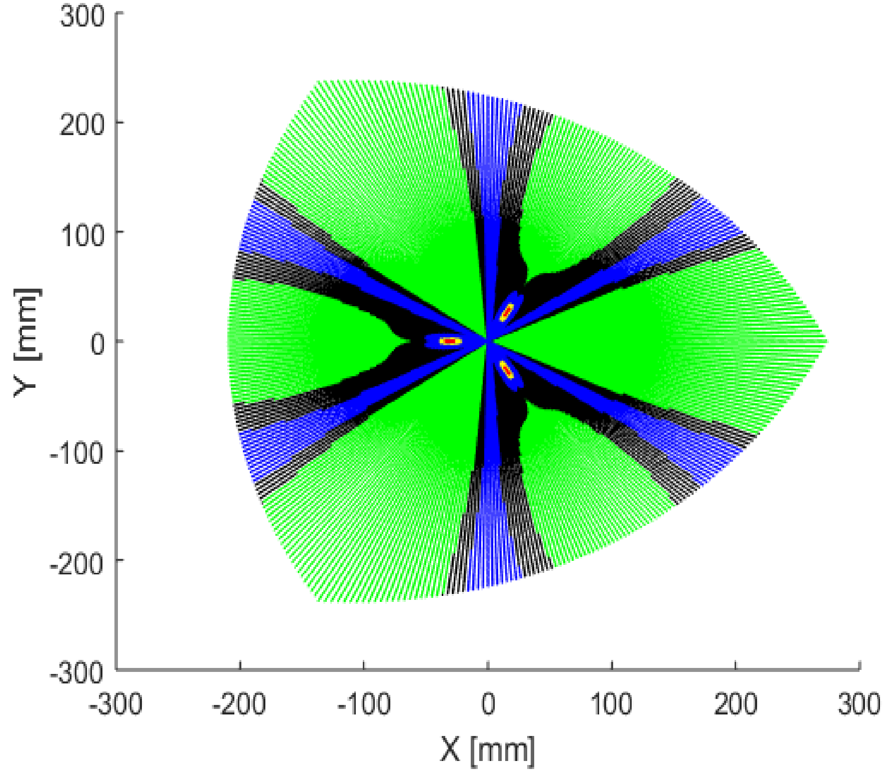
- Changed spacing between leg positions on top and bottom plate
- Initial location of leg joints with respect to angle from the x-axis





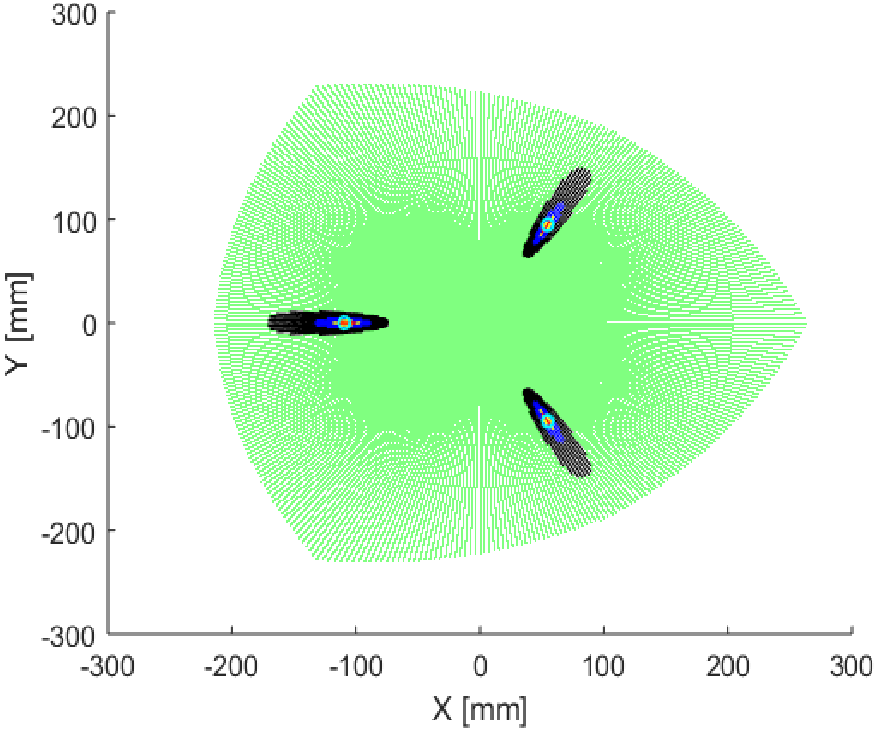
Other Findings

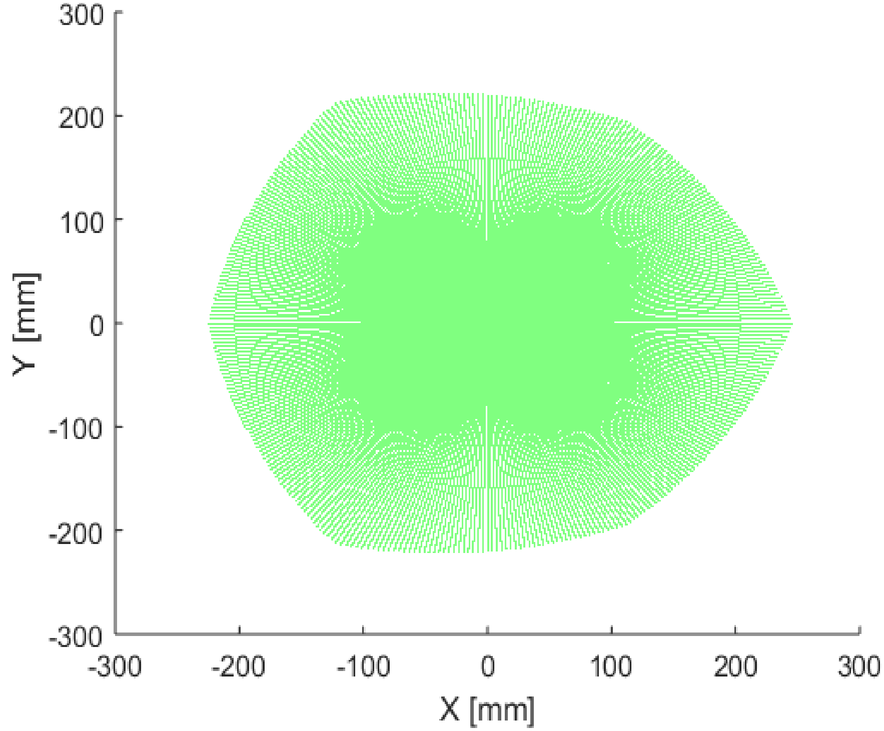




- Bad – singularities indicated near “home” position
- Good – No singularities, but there regions of higher condition numbers

Other Findings





- Bad – 3 singularities
- Good – No singularities and the condition number does not go above 50