WASP
Critical Design Review

November 24th, 2020

ASEN 4018-011 Team 9

Company Customer:
Sierra Nevada Corporation (SNC)

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Presentation Outline

1. Project Overview - Samuel Felice
2. Design Solution - Matthew Zola, Bailey Roker
3. Critical Project Elements - Aidan Kirby
4. Design Requirements Satisfaction - Samuel Felice
5. Risk Analysis - Foster Greer
6. Verification & Validation - Aidan Kirby
7. Project Planning - Foster Greer, Aidan Kirby, Emma Markovich, Matthew Zola

Project Overview

Project Overview

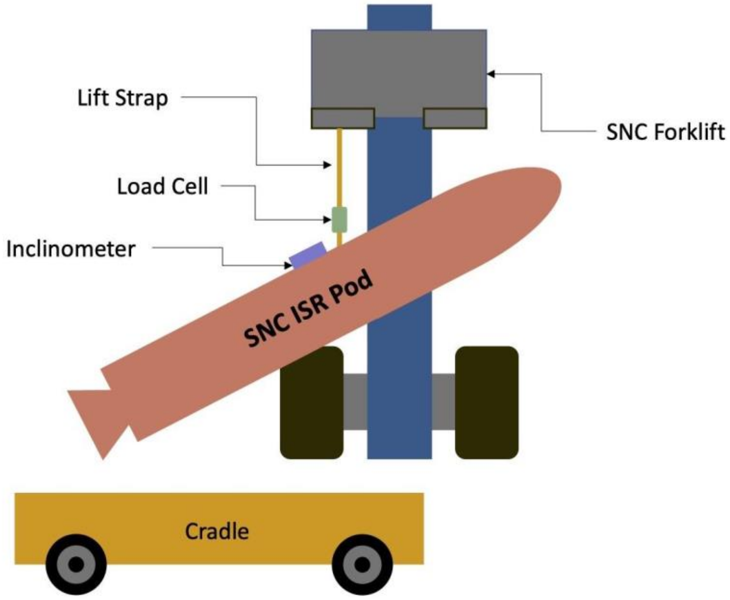
Background:

- **Sierra Nevada Corporation's ISR, Aviation, and Security (SNC IAS) division** needs a better way of **measuring the weight and CG** of their Intelligence, Surveillance, and Reconnaissance (ISR) pods.

Motivation:

- **Effective:** Current method of finding weight and CG is challenging.
- **Safety:** ISR Pods and Engineers are at risk with current method.

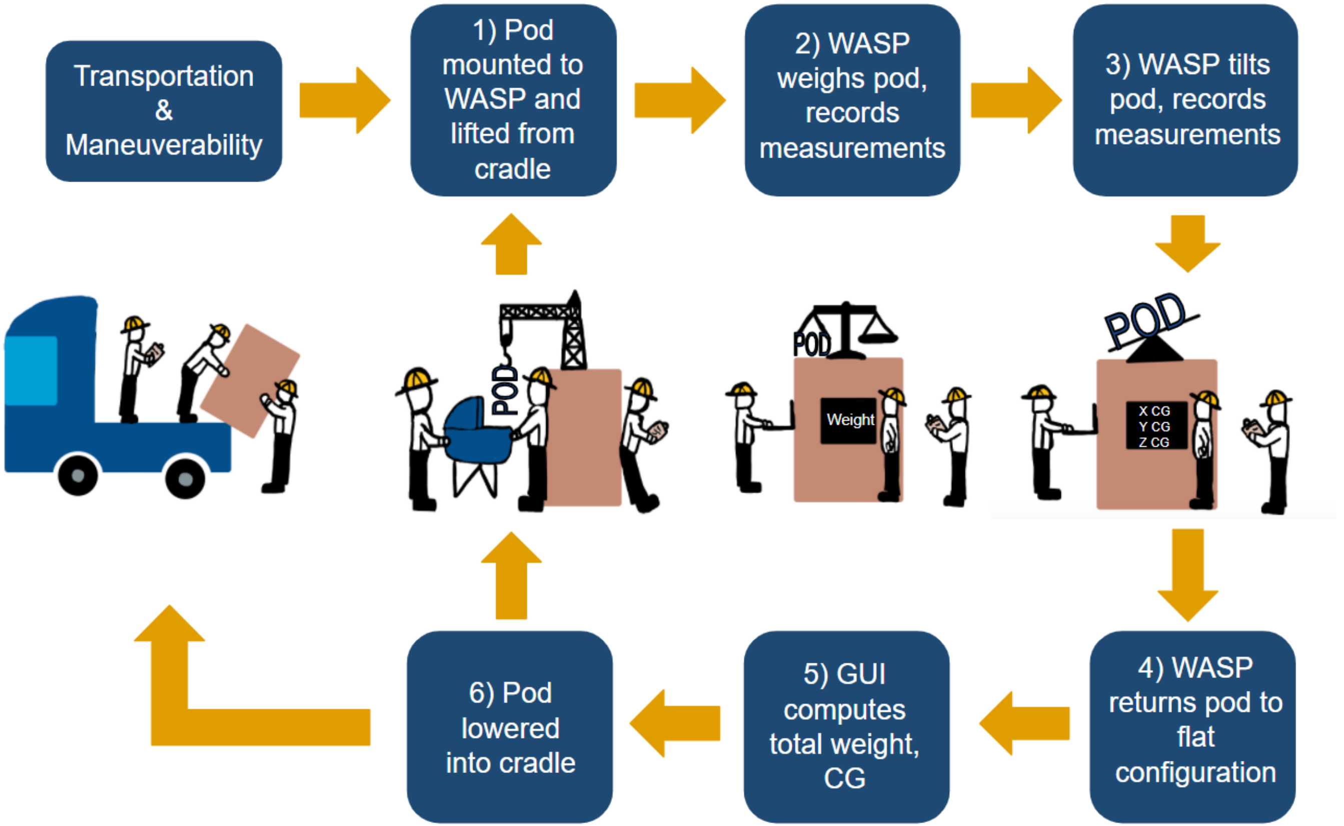
SNC's Current Method



Primary Project Objectives

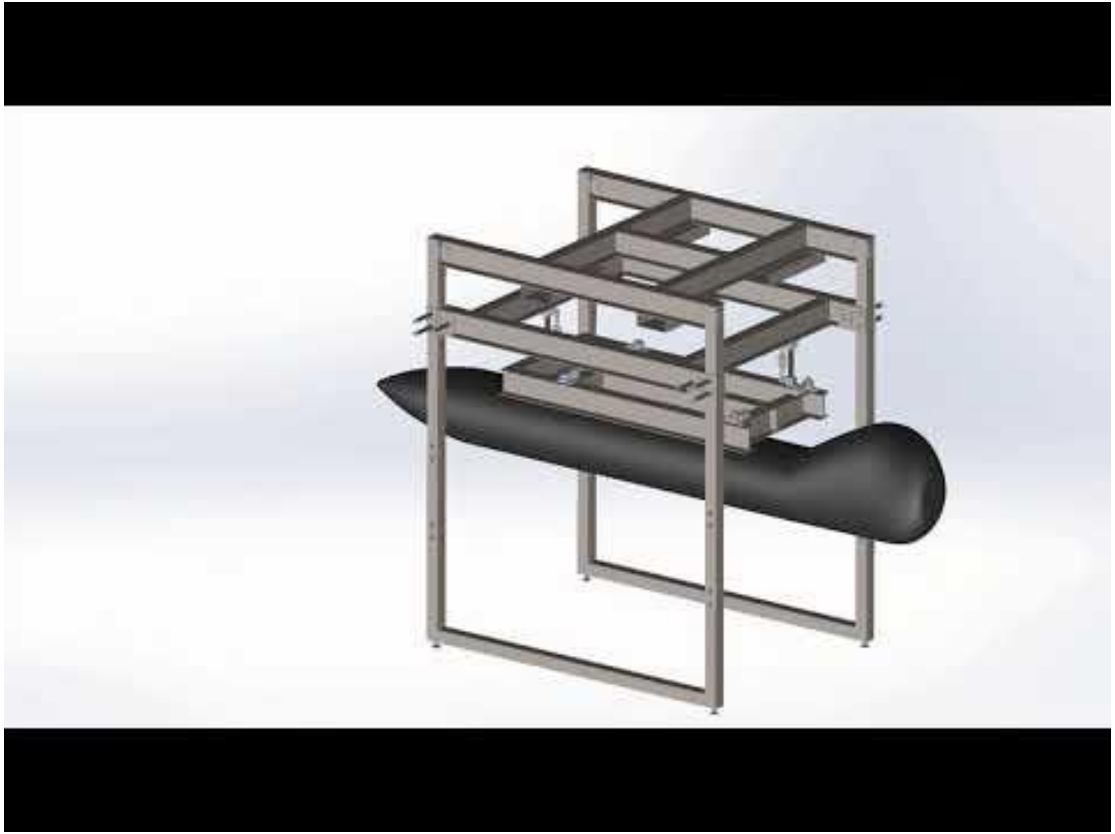
1. Measure the **weight** and **CG location** of SNC ISR Pods to an accuracy of **±0.1%** and **±0.1 inch**, respectively.
2. Be able to use WASP for pods weighing up to **2000 lbs**.
3. Be able to accomodate pods with **14-inch** and **30-inch** lug spacing configurations.
4. Develop a measurement procedure for WASP that is feasible for SNC test engineers (**30-minute** test duration, **2 engineers**)

Concept of Operations

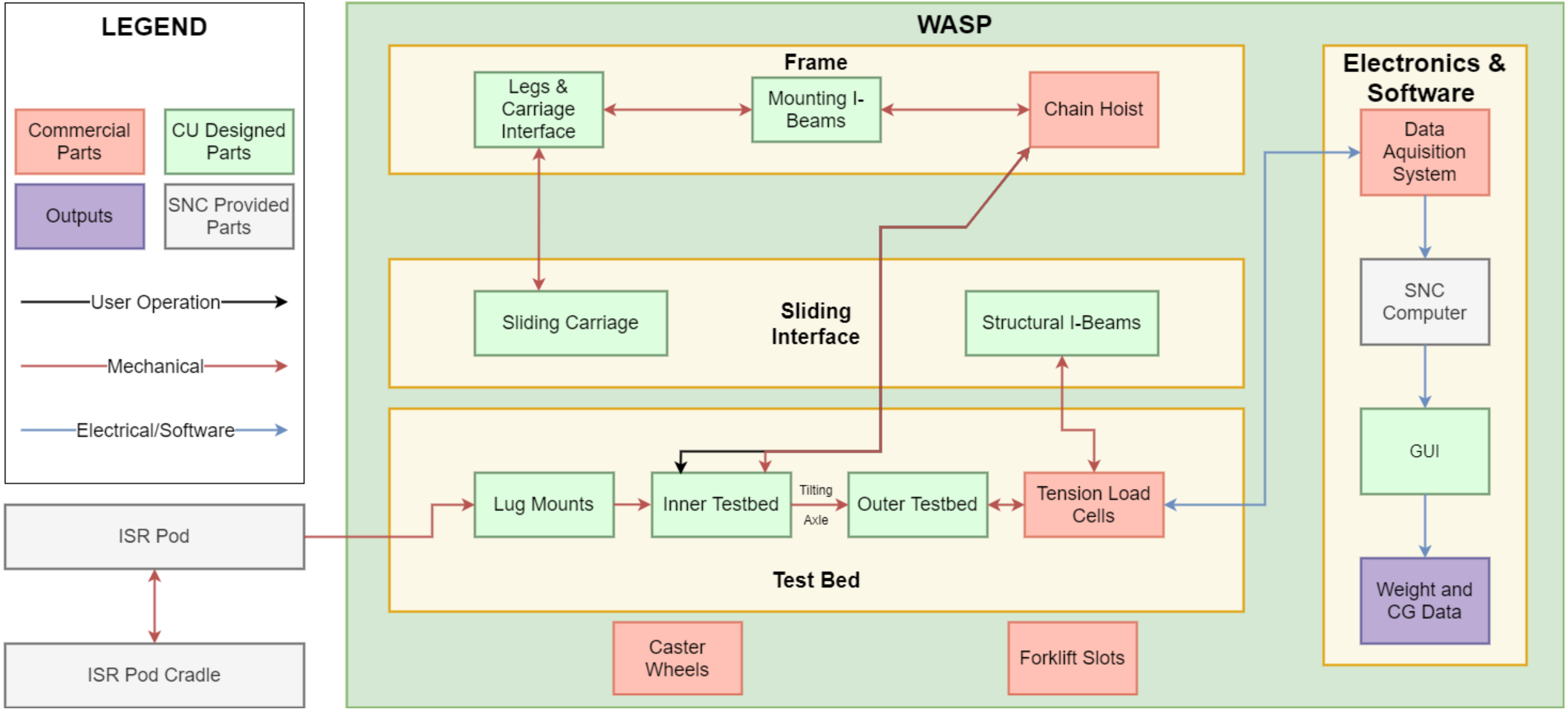


Design Solution

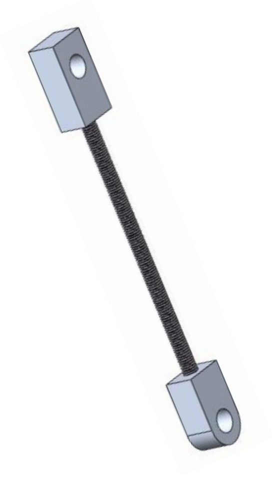
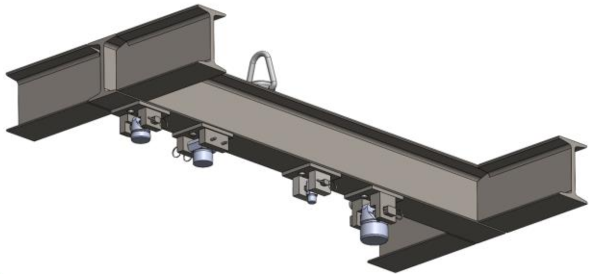
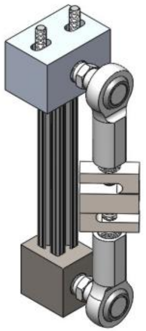
Structural Design Details - Animation



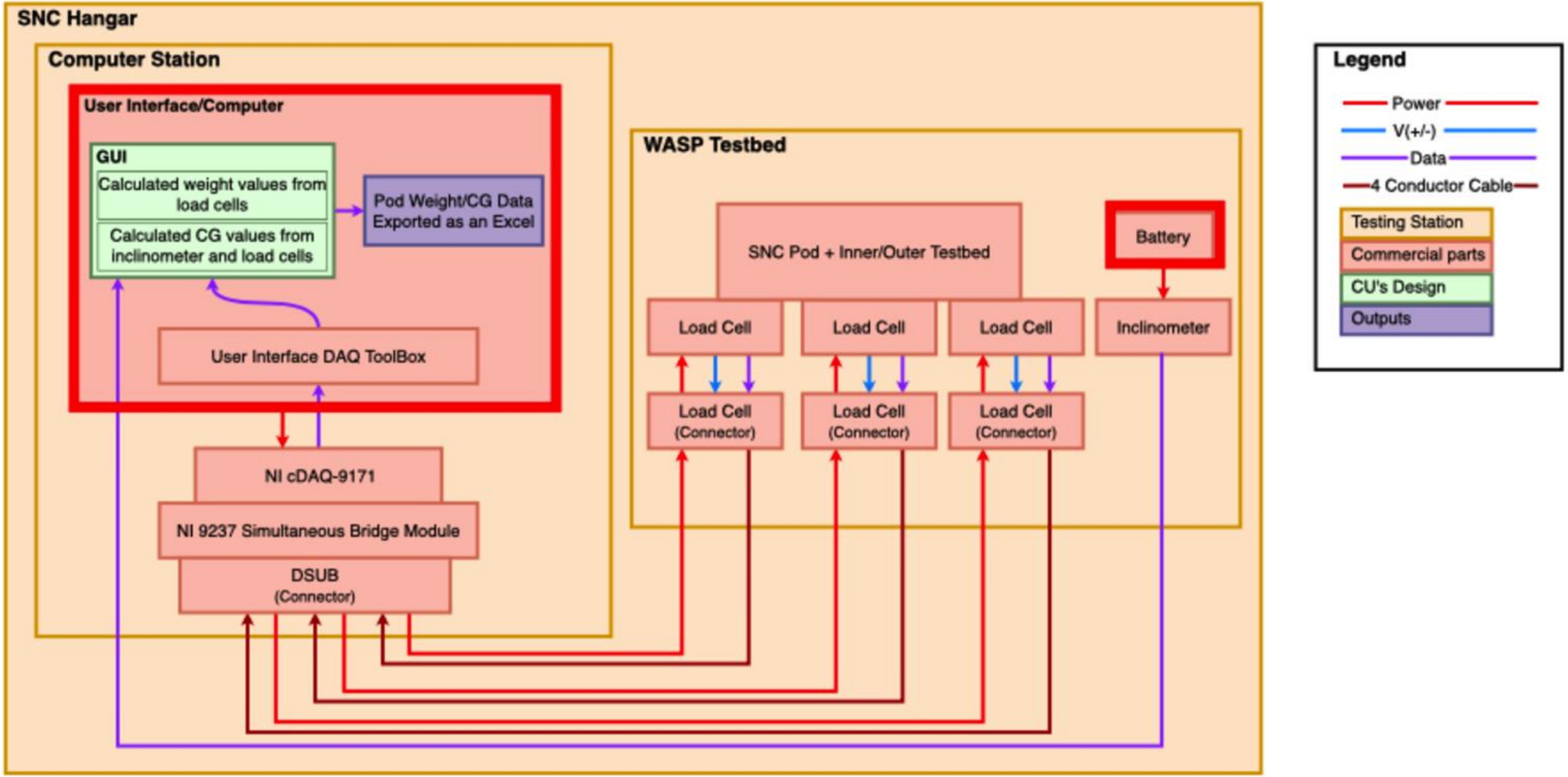
Functional Block Diagram



Structural Design - Key Detailed Components

	Lifting	Tilting	Pod Mounting	Force Measurement
Component	Chain Hoist, Trolley	Hard Stops	Lug Mounts	Load Cells, Socket Joints, Attachment Blocks
Visual				

Electronics Functional Block Diagram



Electronic Hardware Details

Hardware List	Product Names	Specification(s)	Value
Load Cells	Omega LC103B [8]	Accuracy Class	C3: ±0.023%
Inclinometer	Wyler Clinotronic Plus [10]	Limits of Error	< 1.5 Arcmin (~ <0.025 deg)
Simultaneous Bridge Module	NI 9237 DAQ [14]	Sampling, Signal Conditioning	50 kS/s (per channel), 8th order filtering
CompactDAQ Chassis	NI cDAQ 9171 [15]	FIFO size, Timing Accuracy, Timing resolution	127 samples, 50 ppm of sample rate, 12 ns

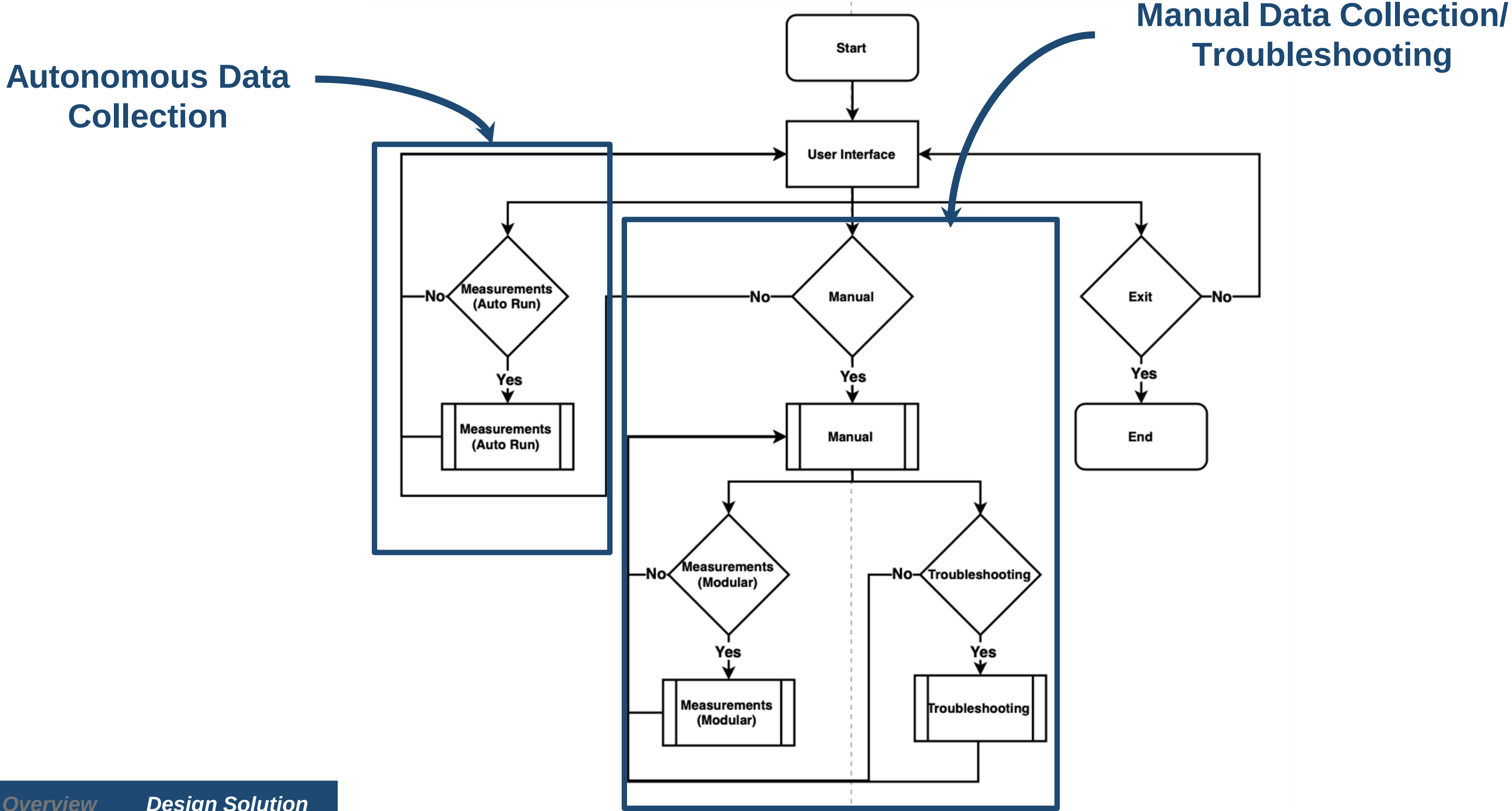

Omega LC103B

Wyler Clinotronic Plus


NI 9237 DAQ


NI cDAQ 9171

User Interface and Software Details



Critical Project Elements

Critical Project Elements

CPE	Icon	Description	FR
E1		All static possible loading must be handled by the frame. It must be portable and support at least 2000 lbs.	FR3, FR4
E2		WASP should rigidly interface with lugs for all pod types.	FR3
E3		WASP must be capable of weight measurements with ±0.1% of true value; CG measurements within ±0.1" of true value.	FR1, FR2
E4		Testing procedures for weight and CG calculations must be well-developed.	FR5
E5		Since heavy loads are involved, both the pods and WASP operators should be safe from harm.	FR5

Design Requirements Satisfaction

Driving Requirements

Requirement Number	Requirement Summary	CPE	Satisfied?
FR1, FR2	Weight and CG Measurement		
FR3	Structural Integrity		
FR4	Maneuverability		
FR5	User Procedure		

Weight and CG Measurement Accuracy (FR1, FR2)

DR 1.1: WASP shall measure the pod weight within a tolerance of ±0.1% of the total pod weight

DR 2.1: WASP shall measure the pod X, Y, & Z CG of each pod with an accuracy of ±0.1 in.

Updates to model since PDR:

- **Inclinometer accuracy = ±0.025°**, Wyler Clinotronic Plus [10]
- Load Cells Error distribution model
  - Mean = 0.0 % FSO
  - **Std. Dev. = (1/2.4)*(0.02% FSO)** [1]
- Worst-case scenario - model evaluated at **maximum** expected error:

W: 0.18% → 6.7σ
XCG: 0.05 in → 3.0σ
YCG: 0.07 in → 10.4σ
ZCG: 0.14 in → 3.3σ

	Load Cell Sensor Full-Span	
Pod Weight [lbs]	**500 lbs**	**1000 lbs**
200	> 95%	> 95%
300	> 95%	> 95%
350	> 95%	> 95%
400	X	> 95%
500	X	> 95%
600	X	> 95%
700	X	> 95%
800	X	> 95%
850	X	>95%
900	X	> 95%
1000	X	> 95%

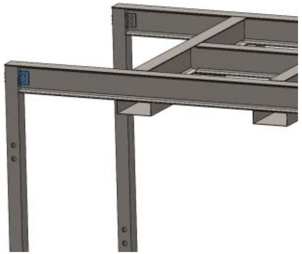
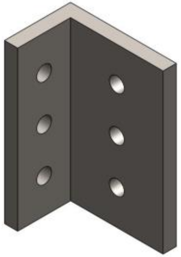
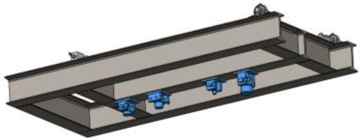
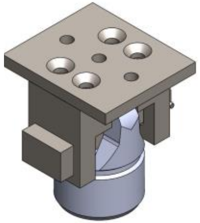
Expected Success Rate for Satisfying Accuracy Requirements for Weight and CG vs. Pod Weight

(From Monte Carlo Simulations with N = 10000)

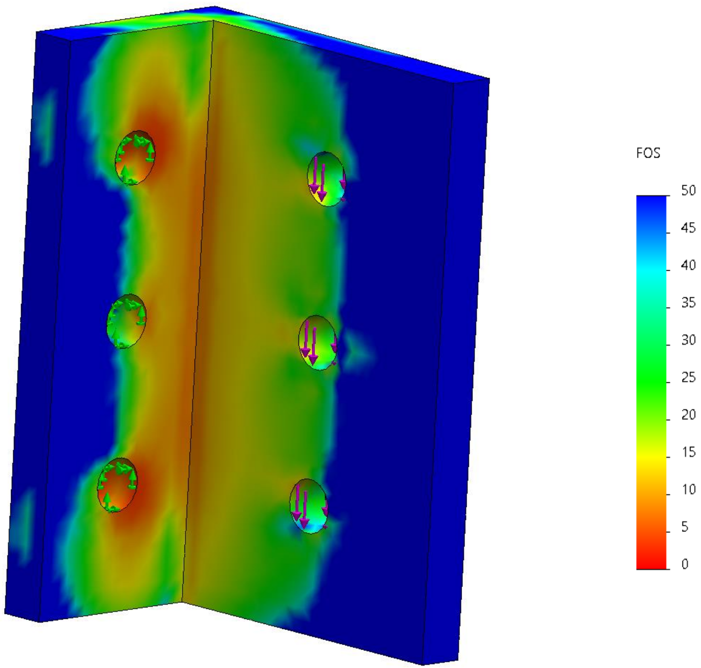
Structural Integrity (FR3)

DR 3.1: WASP shall support pods of 2000 lbs with a FOS of 2.0 to make safe and accurate measurements

Components with Safety Factors Less Than 4.0

Critical Component	Min FOS (FEA)	Min FOS (BOTE)	Consequence of Failure	Visuals
Frame Cleats	3.1	N/A	**Mild** Welds attach legs to top frame as well	 
Lug Mounts	3.0	3.1	**Severe** Pod can fall to the ground (up to 5 feet).	 

Leg Cleat - FEA

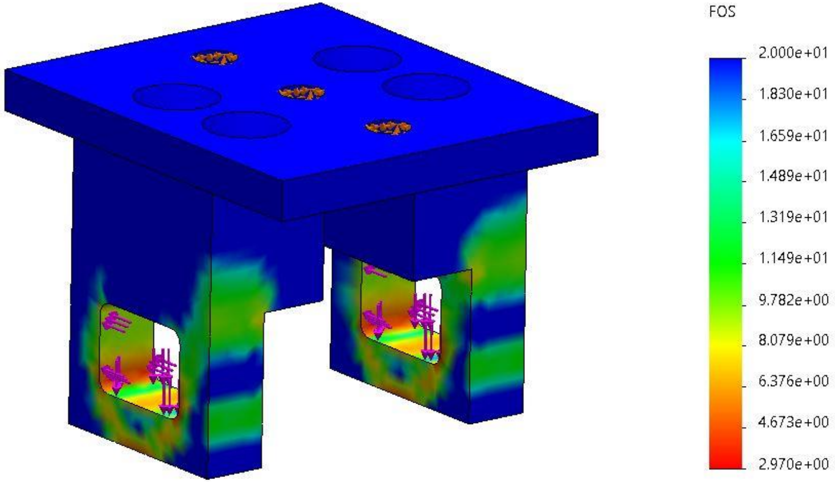


Min Factor of Safety: 3.1

*FEA done in Solidworks Simulation [3]

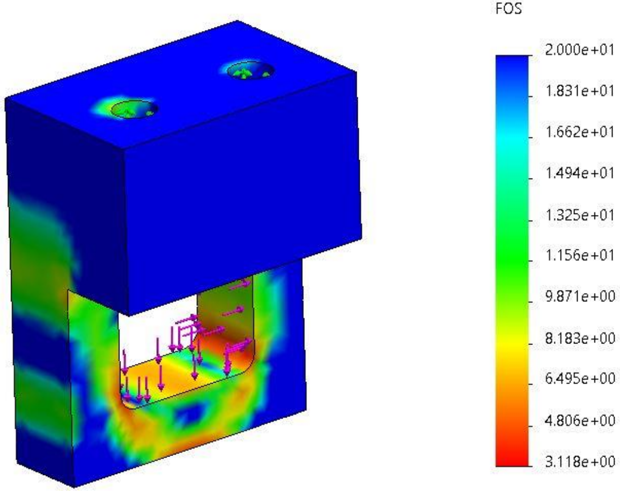
Lug Mounts - FEA

Lug Mount Assembly



Min Factor of Safety: 3.0

Isolated Flange



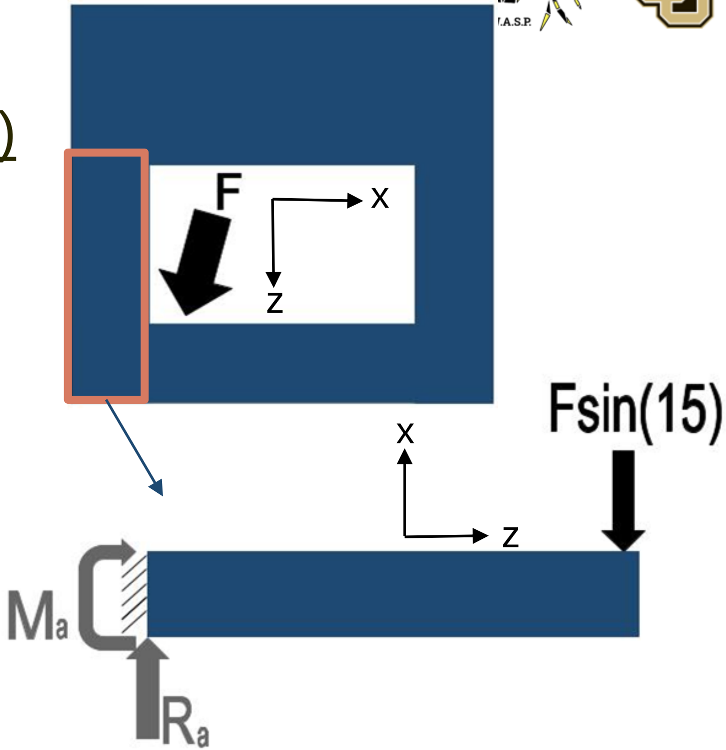
Min Factor of Safety: 3.1

*Assumes one mount supports the entire pod weight

Lug Mounts - BOTE

Flange Bending (Tilted, Cantilevered Beam)

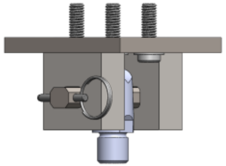
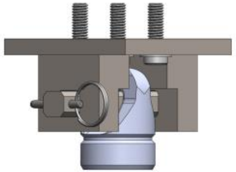
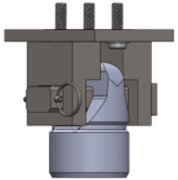
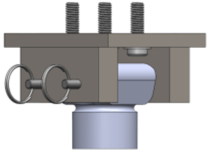
- Part of the force (sin(15)) acts in the x-direction
  - Due to the 15 degree tilt
- Cantilevered beam problem [4]
- Modeled with a point load on the end of the beam
- Second area moment of inertia: 0.00383 in^4
- Maximum moment: -214.82 lb-in
- Maximum normal stress: 11.89 ksi
- Safety factor: 3.05
- This is a very conservative oversimplification
  - The “beam” is not truly free on the bottom
  - The load is not concentrated at the very edge of the “beam” as modeled here
  - Entire pod weight is on one of the two mounts



Design Requirement	Minimum Safety Factor	Requirement Satisfied
DR 3.1 (FOS > 2.0)	3.05	Yes

Structural Integrity (FR3)

DR 3.2: The WASP mounting interface shall support all current SNC pod mounting types.

Lug Type	100 lb	1000 lb	2000 lb	TP lug
Image				
Requirement Satisfied	Yes	Yes	Yes	Yes

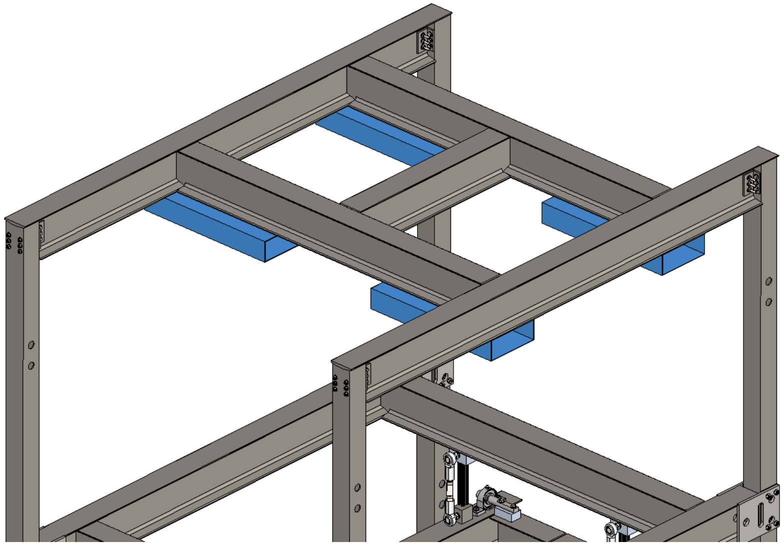
DR 3.3: WASP shall lift pods out of their cradles.

Lifting Solution	Specs	Requirement Satisfied
Chain Hoist	4000 lbs Loading Capability	Yes

Maneuverability (FR4)

DR 4.1: WASP shall have a transportation mechanism.

Current Transportation Solution:
Forklift Slots



Future Transportation Solution:
Leveling Caster Wheels

User Procedure (FR5)

DR 5.1: WASP shall complete a single weight and balance test (defined as the moment after the pod is first loaded until the pod is back in its cradle) in no more than 30 minutes.

Time-Reducing Design Features:

- **Autonomous Software**
  - Load Cell data read directly into software for computation purposes
- **Hard Stops**
  - Additional tolerances built into pins/pin houses for easier insertion
- **Wyler Clinotronic Plus Inclinometer**
  - Accurate within ±0.025° [6]
  - Allows for fewer measurement sets

Procedure	Time
Chain Hoist Lift/Lower	12 mins
Pin Insertion/Removal	10 mins
User Interface & Computation	2 mins
Pod Mount/Demount	6 mins
Total (3 measurement sets)	30 mins

Driving Requirements Satisfaction

Requirement Number	Requirement Summary	CPE	Satisfied?
FR1, FR2	Weight and CG Measurement		Yes
FR3	Structural Integrity		Yes
FR4	Maneuverability		Yes
FR5	User Procedure		Yes

Project Risks

Risk Scoring Definitions

Scoring - Impact		
Value Range	**Level**	**Description**
1	***Low***	**DRs Met**
3	***Mild***	**1 DR Failed**
6	***Medium***	**More than 1 DR failed**
8	***High***	**FR(s) Failed**

Scoring - Likelihood		
Value Range	**Level**	**Description**
1	***Low***	**Not Likely**
3	***Medium***	**Somewhat Likely**
8	***High***	**Very Likely**

Risk Table

	Number	Risk Description	Effect
Super Critical	1	Load Cell Placement *(Manufacturing)*	• Inaccurate measurements
	2	Budget Exceeds $5000 *(Finance)*	• Failure to complete project • Functional failure
Critical	3	Structural Component Failure *(Structures)*	• Fail accuracy requirements • Safety concerns
	4	Structural Interface with Pods via Lug Mounts *(Structures)*	• Functional failure
	5	Misalignment of Frame Members from Welding *(Manufacturing)*	• Structural failure • Inaccurate measurements
	6	Human-Induced Error due to Deviations from Intended Use *(Safety)*	• Functional failure • Safety concerns
	7	Manufacturing implications due to COVID-19 *(Manufacturing)*	• Can’t manufacture WASP

Pre-Mitigation Risk Matrix

RISK KEY

1. Load Cell Placement
2. Budget Exceeds $5000
3. Structural Component Failure
4. Structural Interface with Pods via Lug Mounts
5. Misalignment of Frame Members from Welding
6. Human-Induced Error due to Deviations from Intended Use
7. Manufacturing implications due to COVID-19

		Impact Level			
Likelihood Level		*Low*	*Mild*	*Medium*	*High*
	High			5	1
	Medium				2 3 4 6 7
	Low				

Post-Mitigation Risk Matrix

RISK KEY

1. Load Cell Placement
2. Budget Exceeds $5000
3. Structural Component Failure
4. Structural Interface with Pods via Lug Mounts
5. Misalignment of Frame Members from Welding
6. Human-Induced Error due to Deviations from Intended Use
7. Manufacturing implications due to COVID-19

MITIGATION

1. Margin for tolerance, Slotted for adjustability, Manufacturing procedures
2. Finalized master equipment, Management reserves, Student discount/grad funding
3. Modelling, Testing, Manufacturing procedures
4. Careful design, Testing/verification
5. Manufacturing procedures, measurements
6. User manual, tag equipment
7. Buffer time, At-home manufacturing,

		Impact Level			
		Low	*Mild*	*Medium*	*High*
Likelihood Level	*High*			5	1
	Medium		5	2 7	2 7 3 4 6
	Low		1		3 4 6

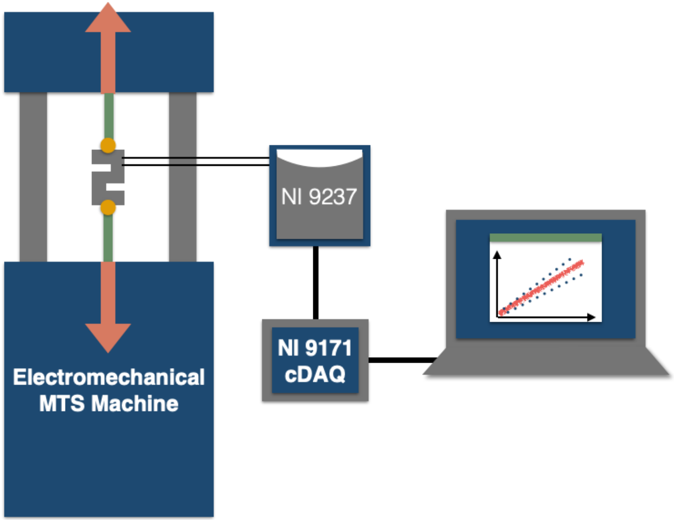
Verification & Validation

Component Validation - Load Cell Characterization

DR 1.1.3: Sensors shall be calibrated such that measured values are accurate within ±0.1% of the pod's true total weight

DR 2.1.3: Sensors shall be calibrated such that measured values are accurate within ±0.1 in. of the pod's true CG

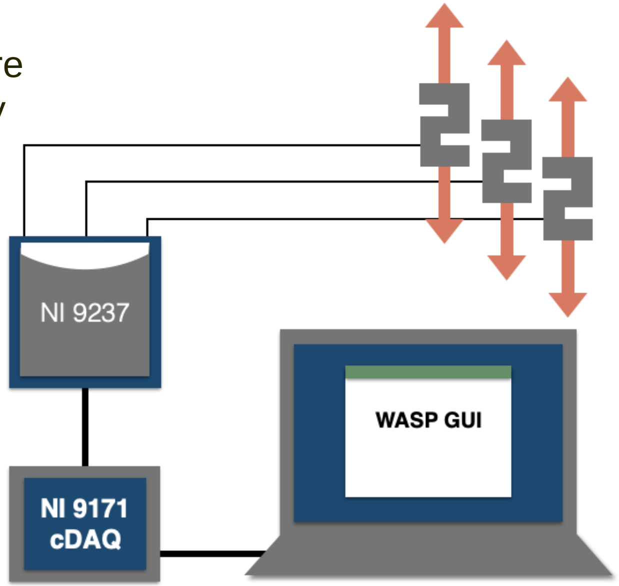
- **Objective:**
  - Calibrate software to sensors
  - Confirm load cells perform within accuracy tolerance
- **Plan:**
  - Apply tensile load in 100 lb increments using Electromechanical MTS machine (Pilot Lab)
  - Record measured force in WASP UI
- **Measurements:**
  - Applied load from MTS machine
  - Measured load from LC103B load cells
- **Pass Criteria:**
  - Load cells measure force within error tolerances
  - Load cell measurements are linear within FSO



Subsystem Verification - Electronics & Software

DR 8.1: WASP shall have a computer based tool that interfaces with the sensors

- **Objective:**
  - Prove functionality of software and compatibility of hardware
  - Verify data acquisition for multiple channels simultaneously
- **Plan:**
  - Connect 3 load cells to WASP DAQ System
  - Extract data from load cell
  - Calibrate NI DAQ System
- **Measurements:**
  - NI 9237 Signals
- **Pass Criteria:**
  - All hardware connected correctly
  - Convert sensor response into data
    - Converts analog input into digital value
  - Filter/sample/amplify signal

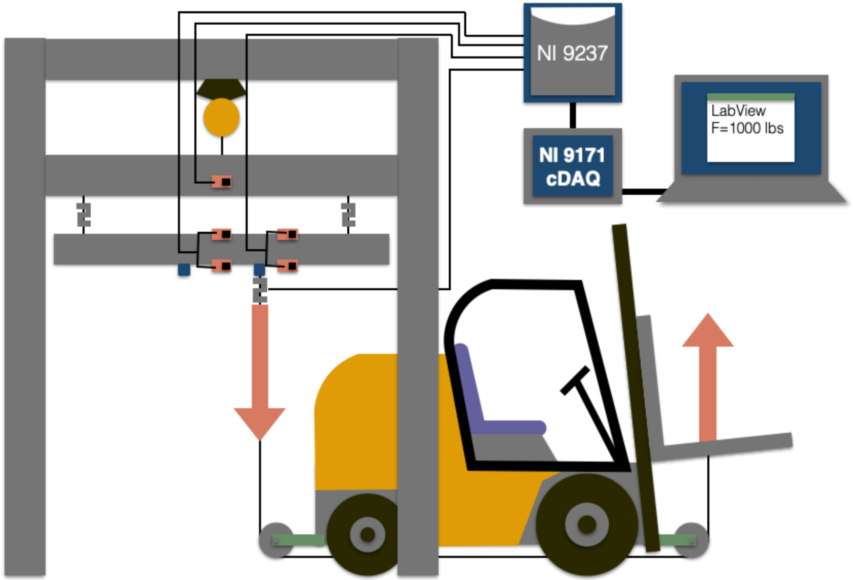


Subsystem Validation - Structural Integrity

DR 3.1: WASP shall support pods of 2000 lbs with a FOS of 2.0 to make safe and accurate measurements

DR 3.3: WASP shall lift pods out of their cradles

- **Objective:**
  - Verify structure can support pods up to 2000 lbs for all possible CG locations
- **Plan:**
  - Incrementally load up to 1000 lbs
  - Validate/modify SolidWorks FEA model
  - Predict FOS for 2000 lb loads
- **Measurements:**
  - 5 x CEA-06-250UW-350 strain gauges [11]
  - 1000 lb FSO tension load cell
- **Pass Criteria:**
  - No yielding

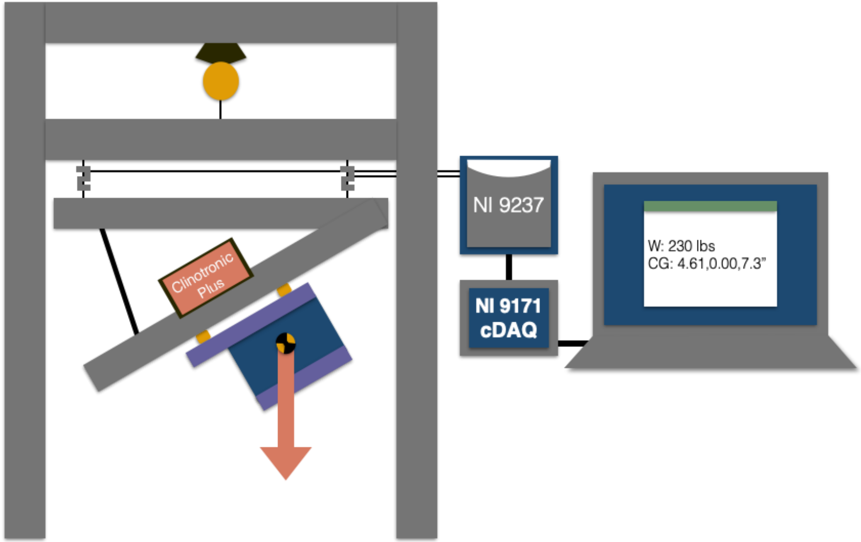


System Verification - Measurement Accuracy

DR 1.1: WASP shall measure the pod weight within a tolerance of ±0.1% of the total pod weight

DR 2.1: WASP shall measure the pod X, Y, & Z CG of each pod with an accuracy of ±0.1 in.

- **Objective:**
  - Verify successful integration of subsystems
  - Compare Weight & CG measurements with model
- **Plan:**
  - Perform full test with SNC test article
  - Calibrate WASP
- **Measurements:**
  - Weight & CG
- **Pass Criteria:**
  - Measured weight within ±0.1%
  - Measured CG within ±0.1 in.

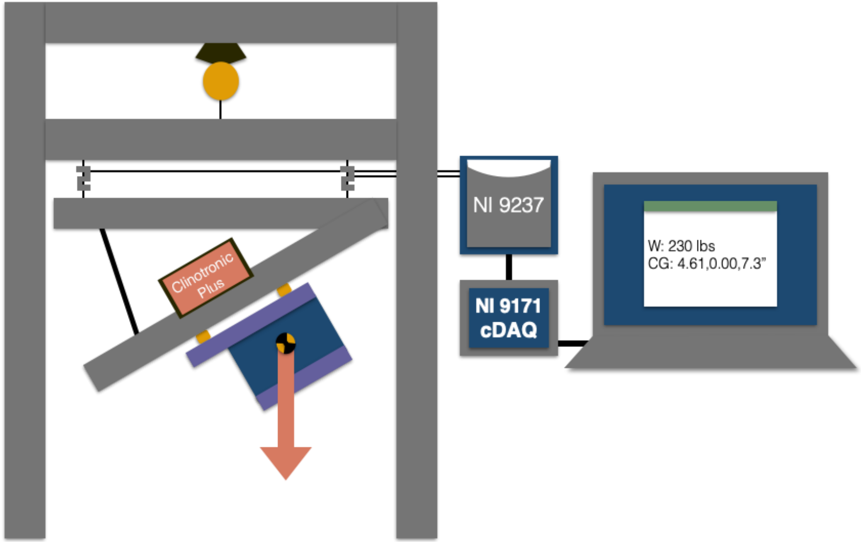


System Verification - Operations Tests

DR 5.1: WASP shall complete a single weight and balance test in no more than 30 minutes

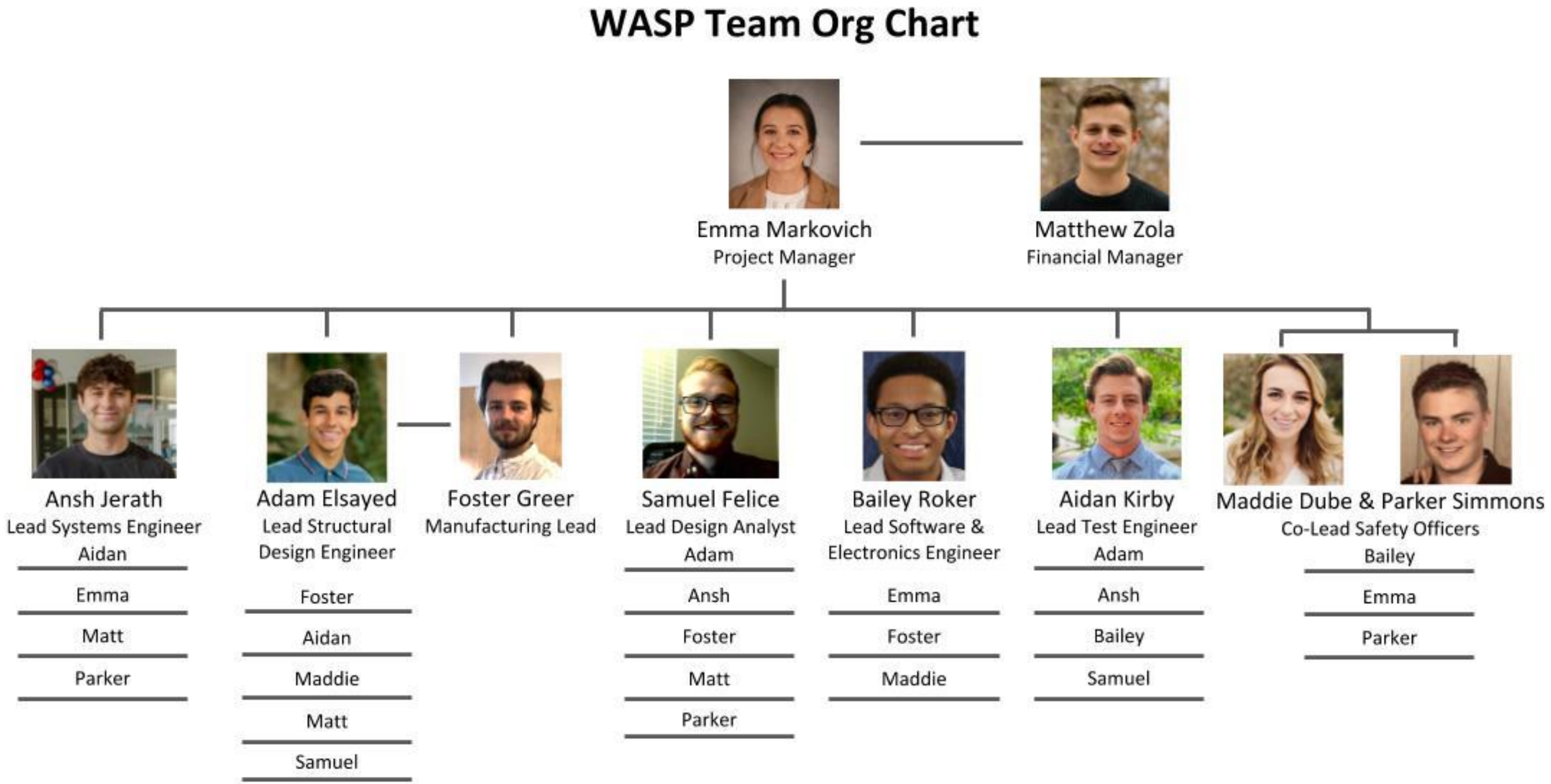
DR 5.2: WASP shall require no more than two engineers to complete one test

- **Objective:**
  - Verify CONOPS
  - Determine test time, engineers required
- **Plan:**
  - Perform full setup of WASP
  - Perform full tests with SNC test article
- **Measurements:**
  - Weight & CG
- **Pass Criteria:**
  - Accurate test performed with 2 engineers
  - Accurate test performed in 30 minutes
  - Accurate test performed with non-WASP engineers

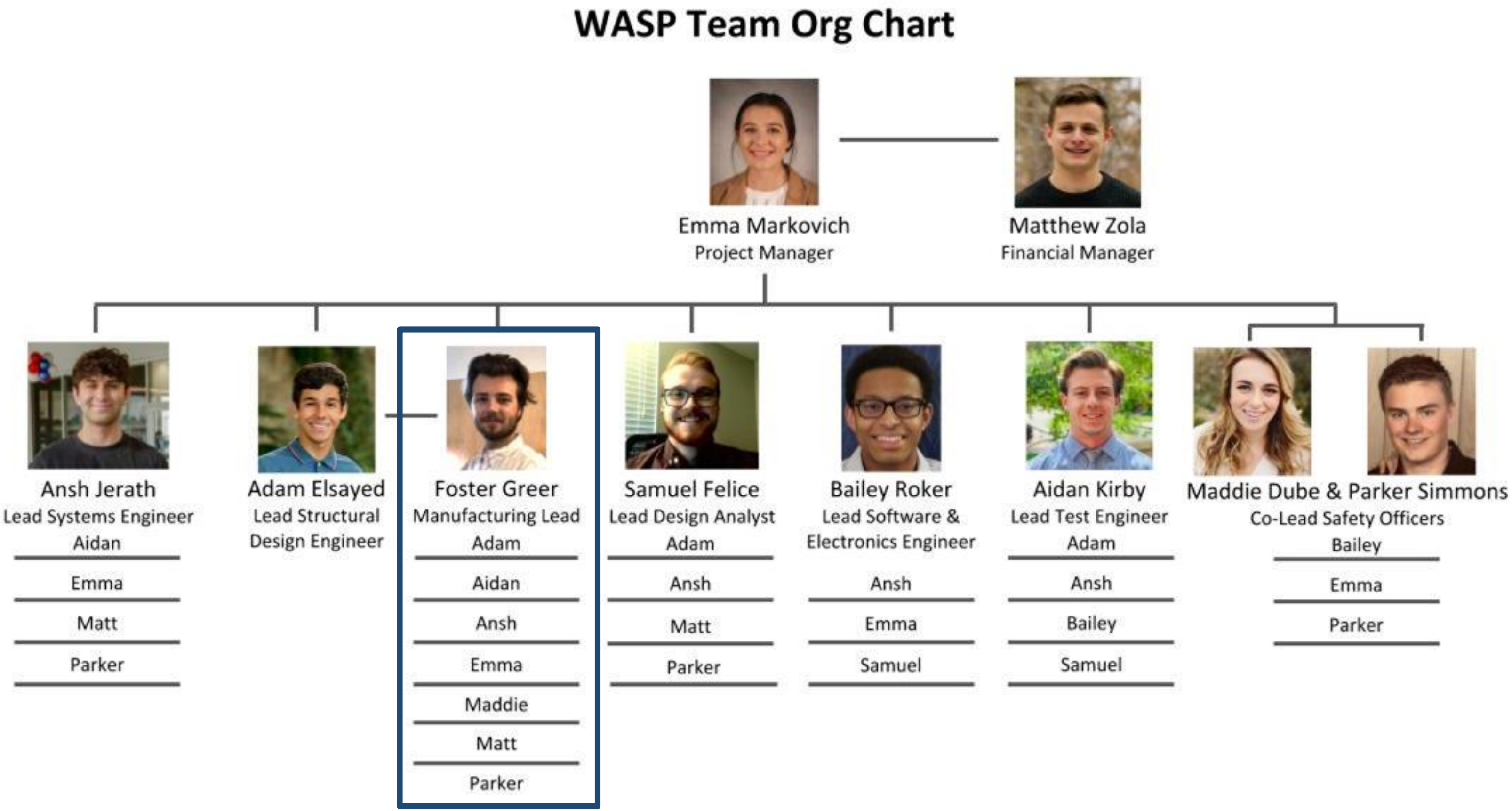


Project Planning

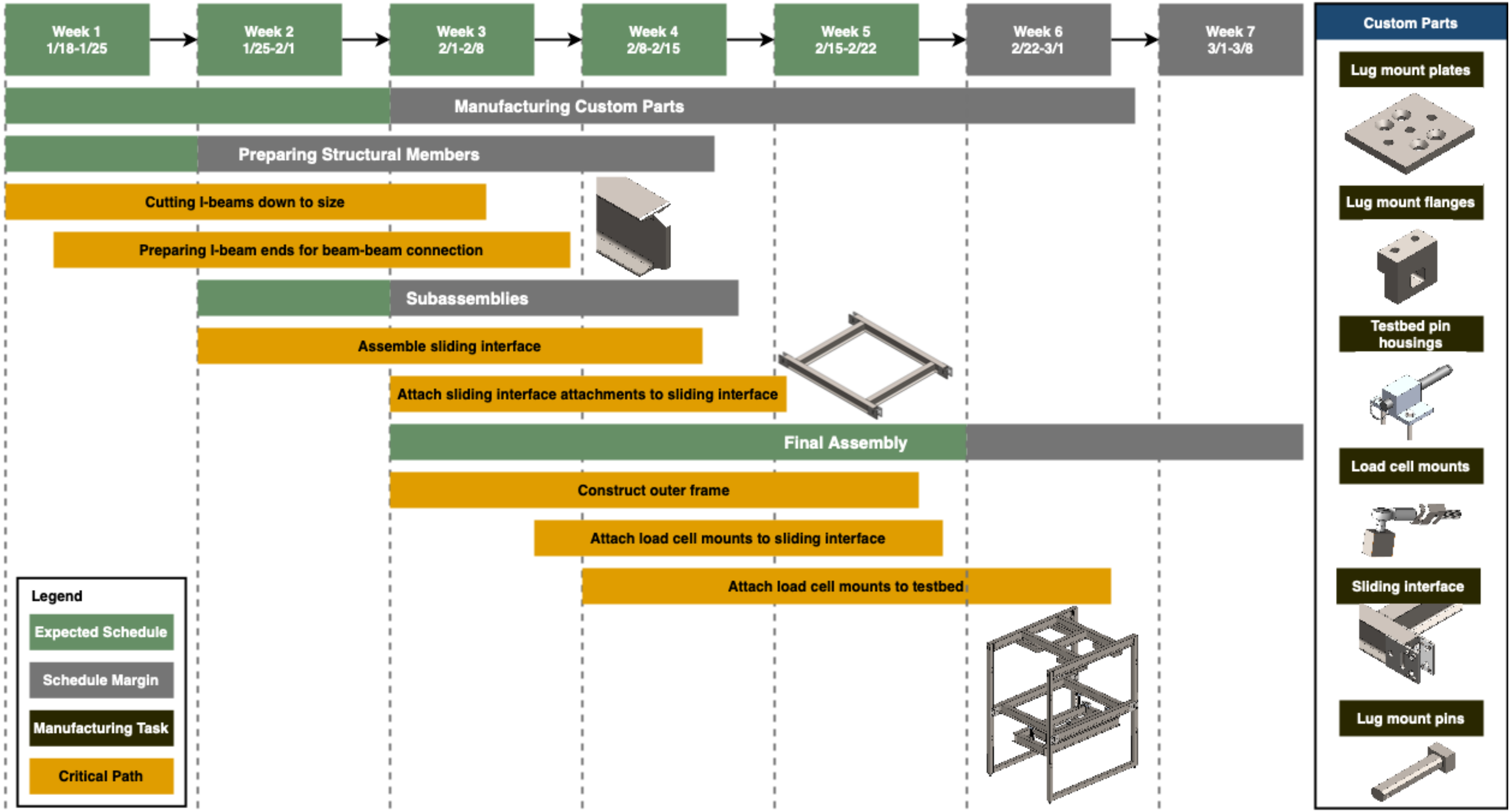
WASP Organizational Chart - Fall 2020



WASP Organizational Chart - Spring 2021



Manufacturing Plan



Test Plan

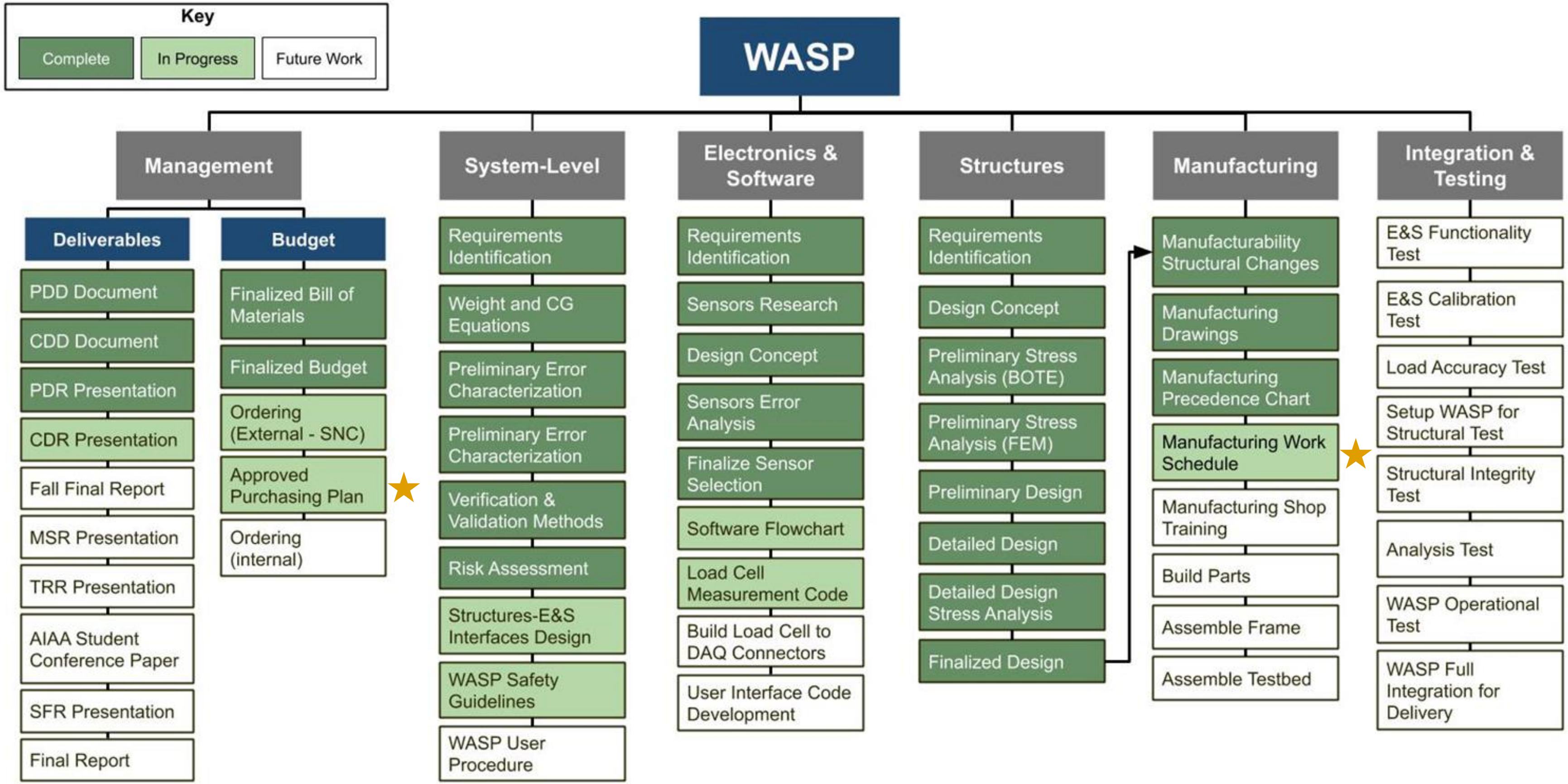
Test Name	CPE Addressed	Scheduling		
		Location	Anticipated Date	Hazards or Challenges
Sensor Characterization		Pilot Lab	January 2021	Heavy Loads (1000 lbs)
E&S Functionality		Pilot Lab	December 2020	N/A
Structural		Machine Shop	March 2021	Heavy Loads (1000 lbs)
Accuracy		Machine Shop	April 2021	N/A
Operations		Machine Shop	April 2021	N/A

Cost Plan

Subsystems Overview		
Subsystem	Expenses	Percentage
Raw Materials	$1,847.85	36.96%
Hardware	$1,627.22	32.54%
Electronics	$145.68	2.91%
Other Expenses	$500.00	10.00%
Management Reserves	$879.25	17.59%
Total	**$5,000.00**	

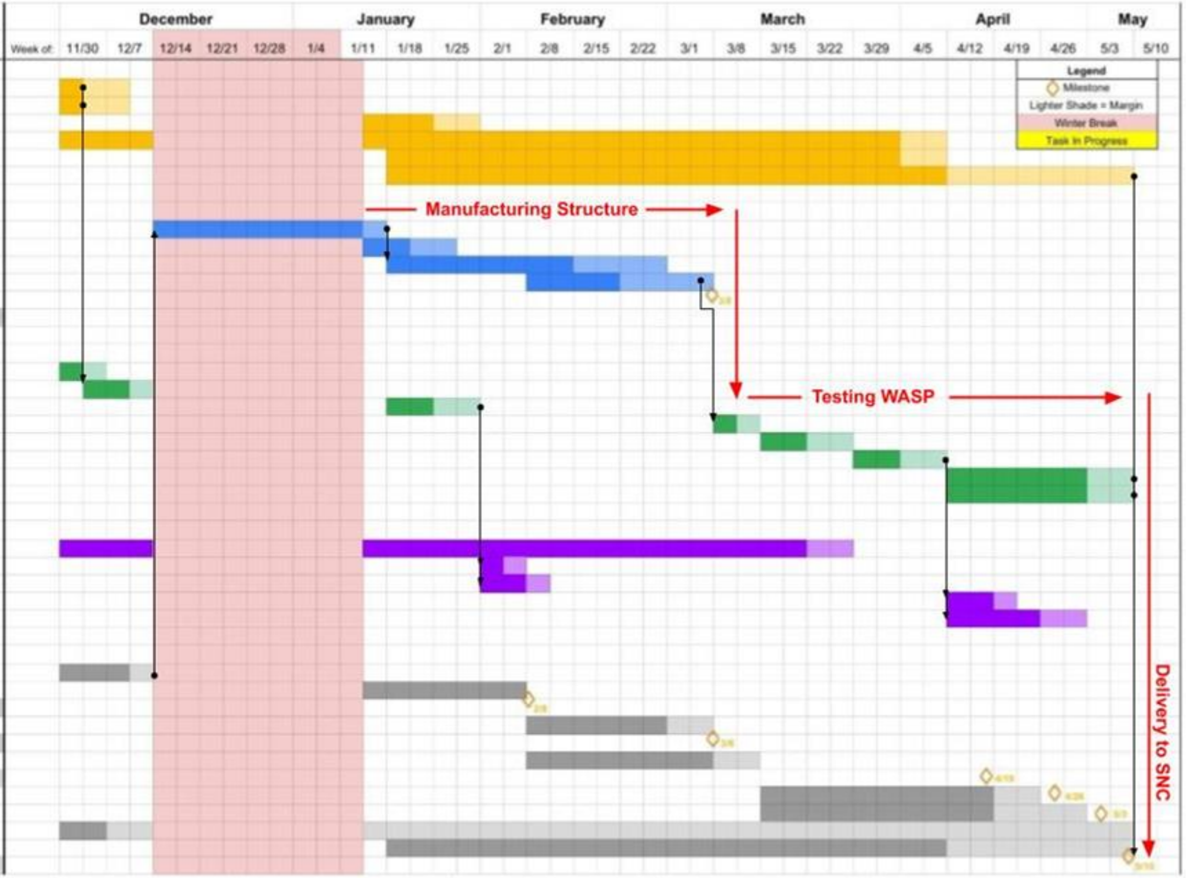
Management Reserves			**$ 879.25**
S6x17.25 A36 I-Beam (10' length)	$ 164.20	1	$ 164.20
3"x.120" A36 Square Tube (96" length)	$ 45.86	1	$ 45.86
Shipping	$ 100.00	1	$ 100.00
Extra Fasteners	$ 50.00	1	$ 50.00
Manufacturing Consumables	$ 200.00	1	$ 200.00
Electrical Connectors	$ 50.00	1	$ 50.00
Unallocated Reserves	$ 269.19	1	$ 269.19

Work Breakdown Structure



Timeline for Spring Semester

WASP Task	Duration (weeks)	Margin (weeks)	Planned Start Date	Actual Start Date	Planned End Date	Deadline Date	Actual End Date
Electronics & Software							
Build Connectors to DAQ	1	1	11/25		12/2	12/9	
Build Cable Harnesses	1	1	11/25		12/2	12/9	
Build Connectors to Load Cells	1.5	1	1/14		1/24	1/31	
User Interface Code	10	1	10/28	10/28	4/5	4/12	
Git Repository			11/23		4/5	4/12	
E&S System Manual	12	4	1/18		4/12	5/10	
Manufacturing							
Materials Ordering/Shipping	4	1	12/14		1/11	1/18	
Training	1	1	1/14		1/21	1/28	
Manufacturing Parts	4	2	1/18		2/15	3/1	
Assembly	2	2	2/8		2/22	3/8	
Manufacturing Completed	7		1/18		3/8	3/8	
Last Machining Day							3/22
Integration & Testing							
etup E&S Suite for Functionality Test	0.25	0.25	12/2		12/3	12/5	
E&S Functionality	1	0.5	12/5		12/12	12/16	
Load Cell Characterization Test	1	1	1/18		1/25	2/1	
Setup WASP for Structural Test	0.5	0.5	3/8		3/11	3/15	
Structural Test	1	1	3/15		3/22	3/29	
Analysis Test	1	1	3/29		4/5	4/12	
WASP Operational Test	3	1	4/12		5/3	5/10	
WASP Full Integration for Delivery	0.5	0.5	4/12		4/15	5/10	
Analysis							
Create FMEA Document	16	1	11/30		3/22	3/29	
Update MCS with Load Cell Data	0.5	0.5	2/1		2/4	2/8	
Load Cell Characterization	1	0.5	2/1		2/8	2/11	
Stress Extrapolation	1	0.5	4/12		4/19	4/22	
WASP Error Characterization	2	1	4/12		4/26	5/3	
Deliverables							
Finalized Budget + Approval	5	0.5	11/4		12/9	12/12	
MSR Slides	2		1/25		2/8	2/8	
MSR Presentation						TBD	
TRR Slides	3	1	2/8		3/1	3/8	
TRR Presentation						TBD	
AIAA Conference Paper	4	1	2/8		3/8	3/15	
Symposium						4/19	
Spring Final Review	5	1	3/15		4/19	4/26	
Project Final Report	5	2	3/15		4/19	5/3	
Safety Guidelines Document	4	16	11/9		12/7	5/10	
User Procedure Document	12	3	1/18		4/12	5/10	
WASP Delivery to SNC						5/10	



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Questions?

References

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Supporting Material

Acronym List

Acronym	Definition
ACC	Accuracy
BC	Boundary Conditions
BOTE	Back of the Envelope (Hand-derived)
CAD	Computer-Aided Design
CG	Center of Gravity
COMPAT	Compatibility
CONOPS	Concept of Operations
COTS	Consumer Off-The-Shelf

Acronym	Definition
CPE	Critical Project Element
DAQ	Data Acquisition System
DR	Design Requirement
E&S	Electronics and Software
FEA	Finite Element Analysis
FOS	Factor of Safety
FSO	Full Span of Operation
FR	Functional Requirement

Acronym List

Acronym	Definition
GUI	Graphical User Interface
IAS	ISR, Aviation & Security
ISR	Intelligence, Surveillance, & Reconnaissance
NIST	National Institute of Standards and Technology

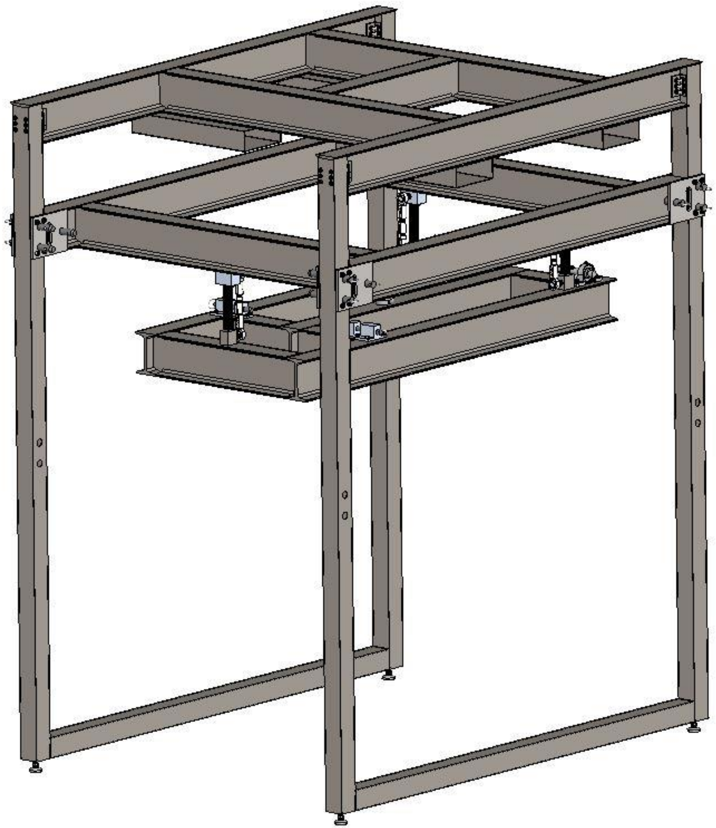
Acronym	Definition
PDR	Product Design Review
SNC	Sierra Nevada Corporation
TP	Third Party
UI	User Interface
VBA	Visual Basic for Applications
WASP	Weight Analysis of Surveillance Pods

Key Terms Definition

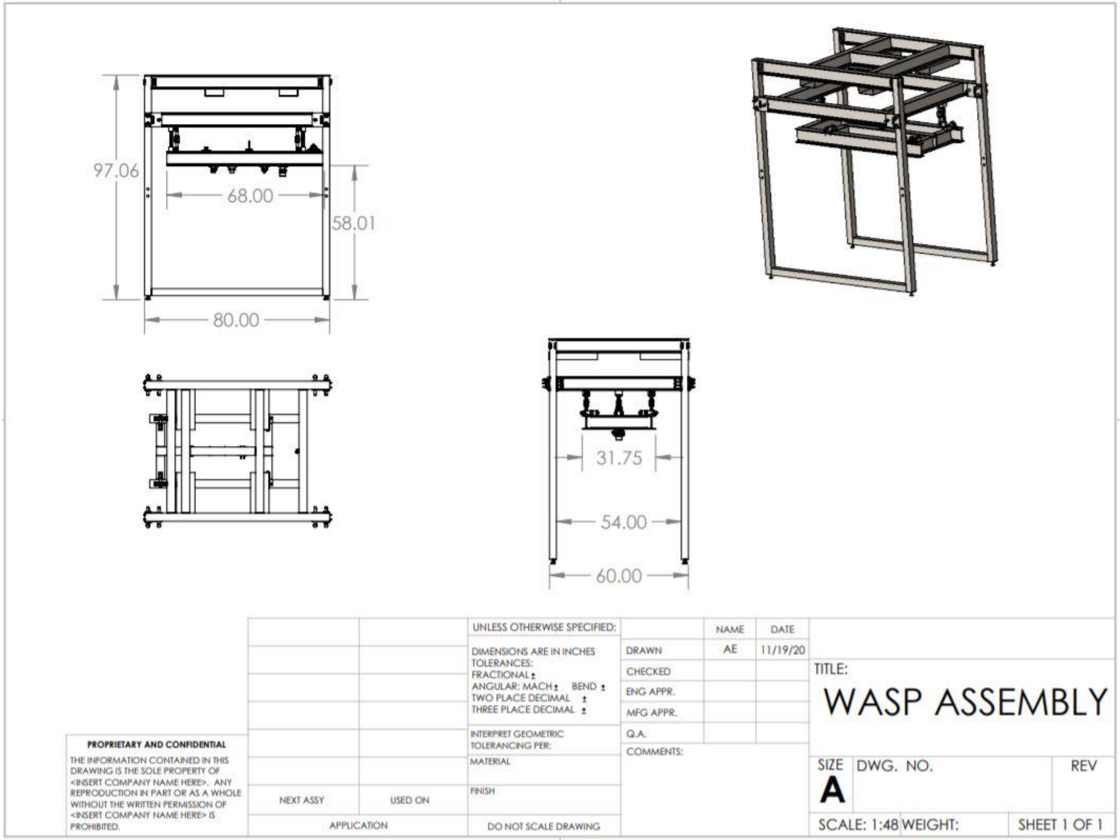
Term	Definition
Frame	The outer physical structure of WASP
ISR Pod/Pod	The physical object being measured by WASP, given by SNC.
Measurement Set	One recorded value for each sensor (load and inclination) in the flat and tilted configurations.
Test	The execution of a full procedure which starts after set-up and concludes when weight and CG values are output.
Tool	Equivalent to WASP.
User Procedure	Instructions document that describes transportation, maneuvering, and testing process for test engineers.
WASP	All elements of the final product/deliverable.

Structural Design

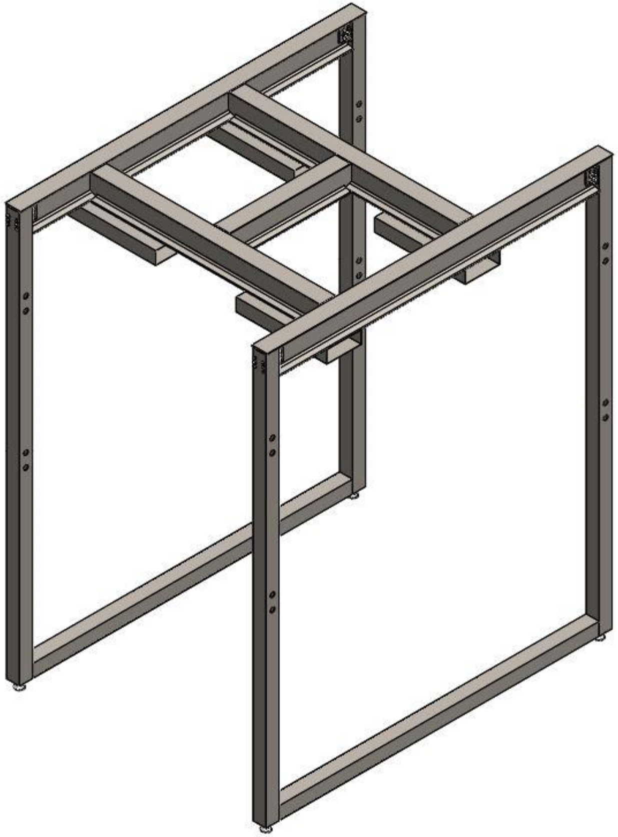
Structural Design - Isometric



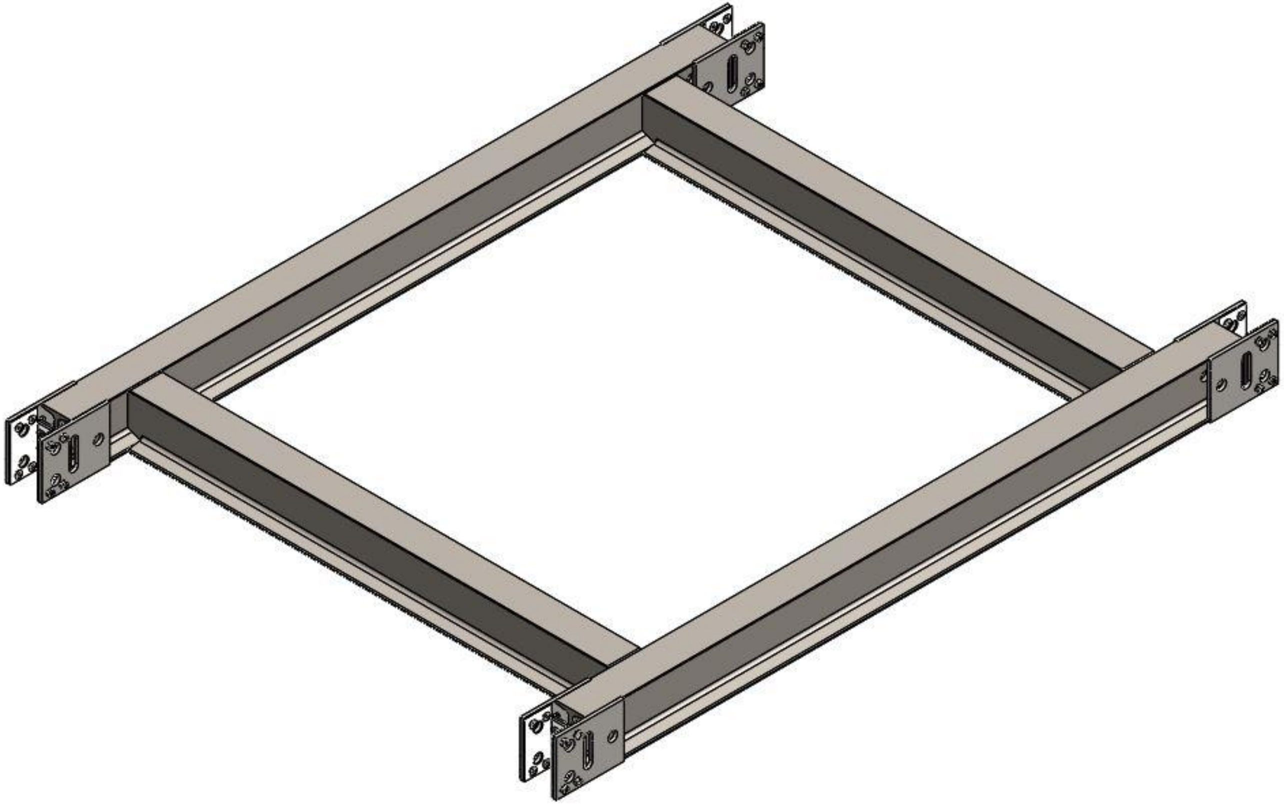
Structural Design - Basic Dimensions



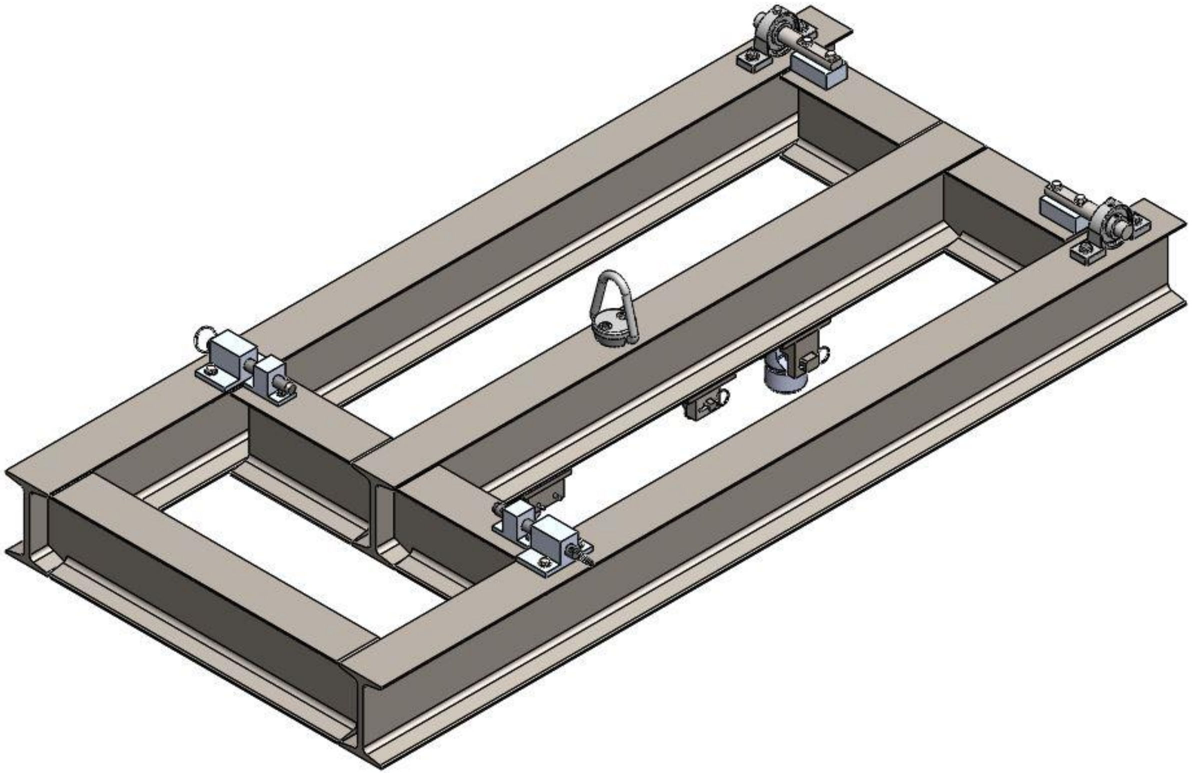
Structural Design - Outer Frame



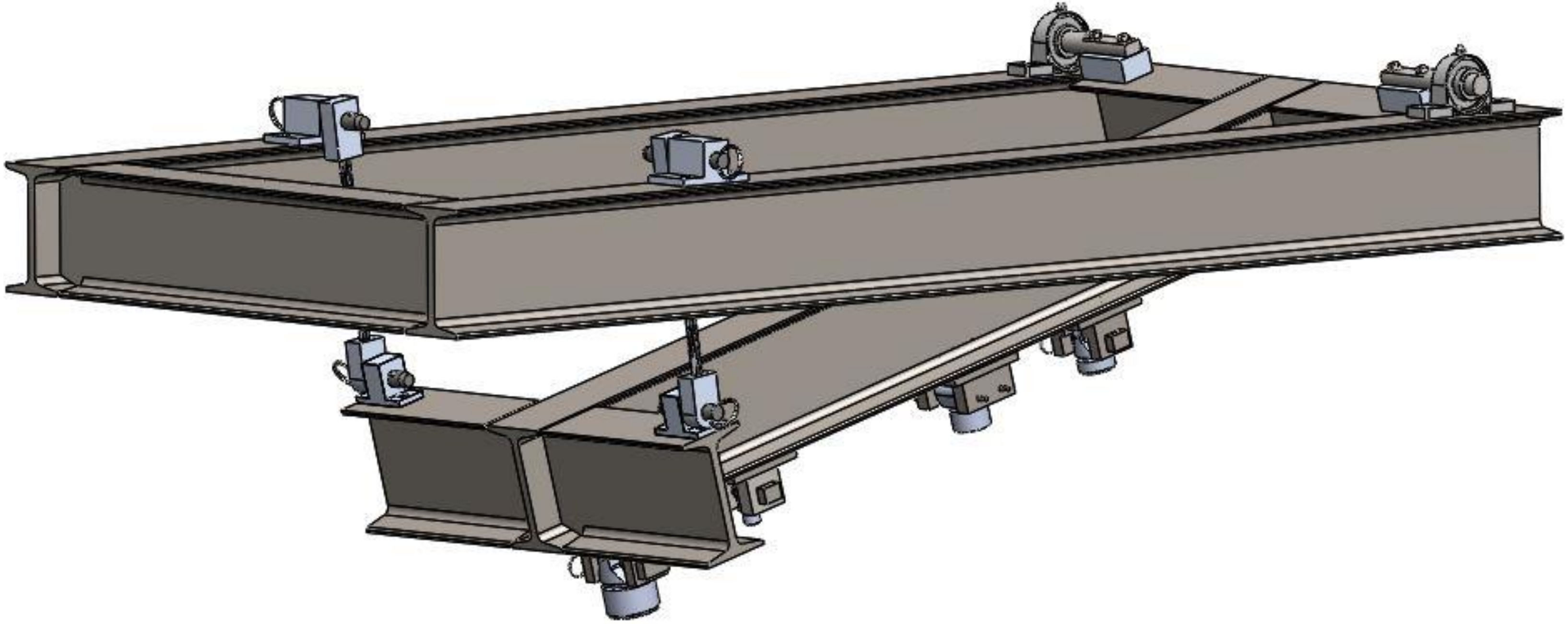
Structural Design - Sliding Interface



Structural Design - Level Testbed



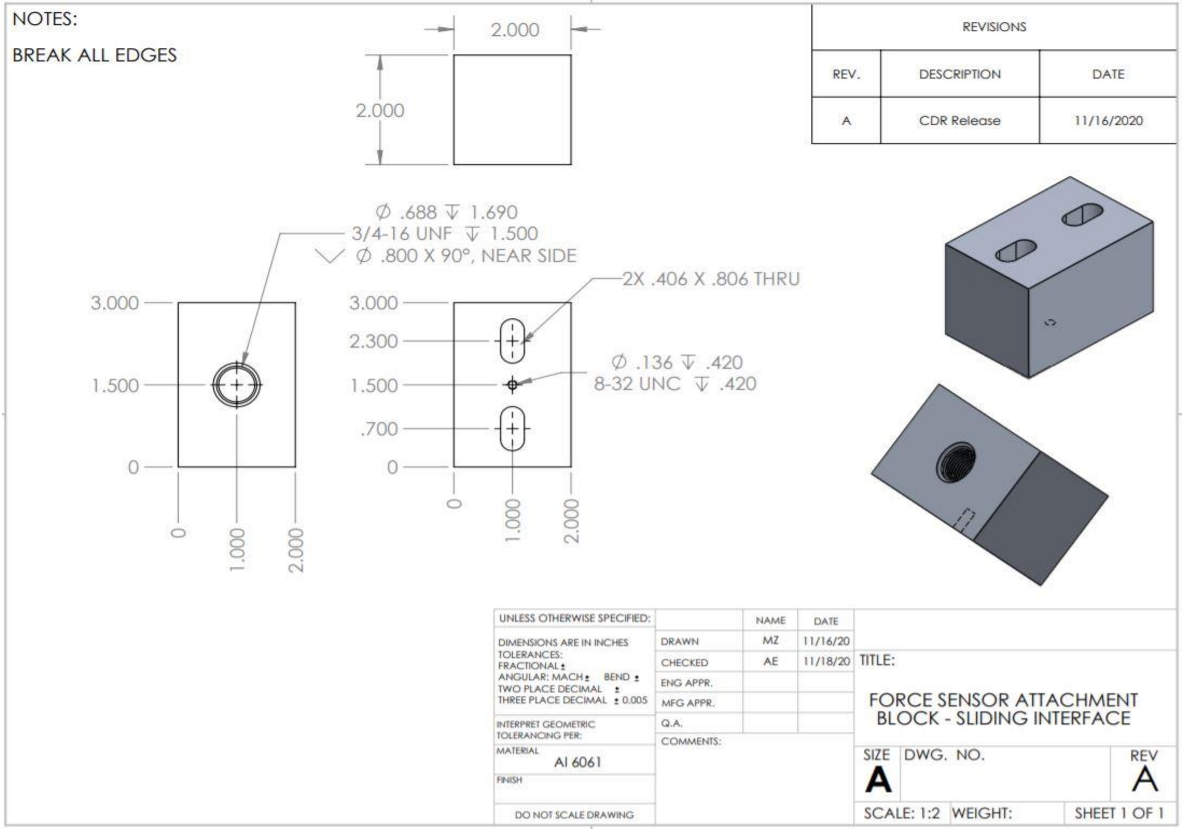
Structural Design - Tilted Testbed



Structural Design - Link to Mechanical Drawings

https://drive.google.com/drive/u/0/folders/1pGDeZoZGyrDvD-Qb2tOPaOz1nWZPimzU

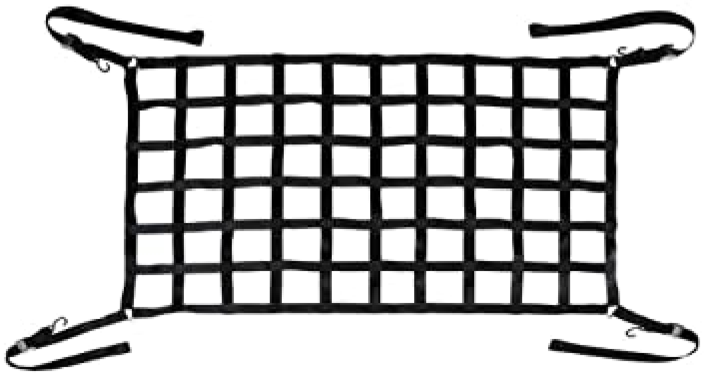
Structural Design - Sliding Interface Force Sensor Attachment Block



- Slots in bolt holes allow for some error in manufacturing to be tolerated

Structural Design - Safety Concept

- Can be attached to the legs of the outer frame
- Preliminary research:
  - Custom dimension orders can be made
  - Web breaking strength of 10000 lbs [16]
- If any structural components break, this system can either catch the pod or significantly reduce the energy with which it will hit the floor



Structural Analysis

Structural Analysis - Overall

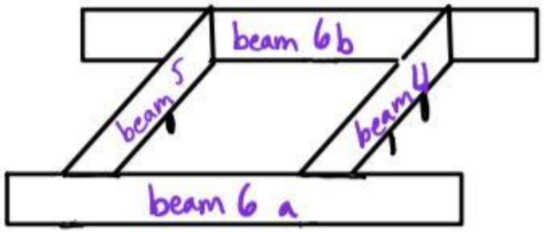
<u>Analyses</u>

- BOTE
  - Beam bending
  - Weld strength

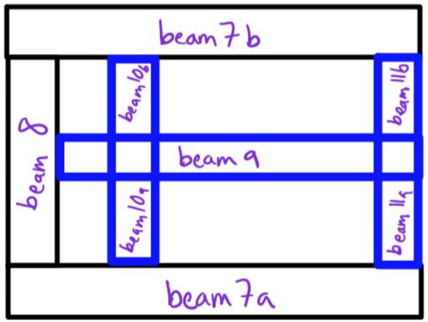
Overall Analyses - BOTE

Beam Bending

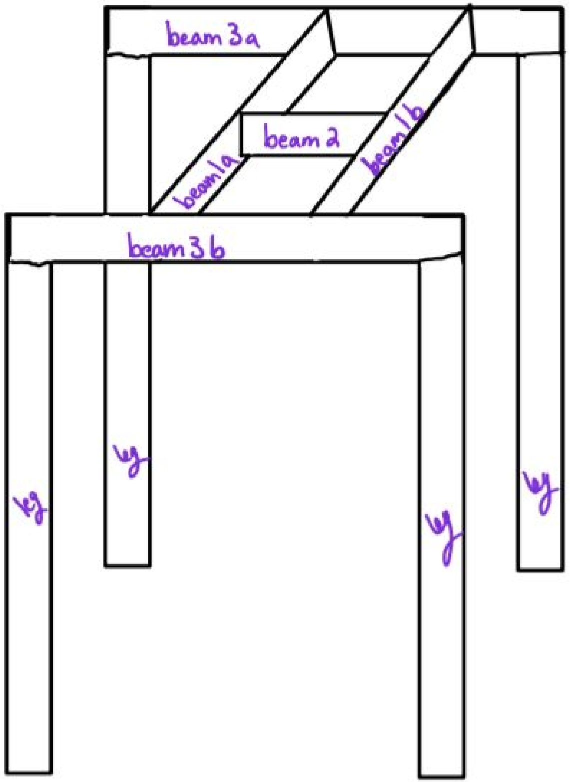
- This analysis is practically the same as it was for PDR with some updates - see the WASP PDR [5] for more information
    - Geometry and load cases have slightly changed
    - The beam numbering has been updated



Sliding Interface



Testbed



Top Frame and Legs

Overall Analyses - BOTE

Weld Strength

- The same welds are used on the sliding interface and testbed

Assumptions:

- Weld length: L_w = 8.75” (actual 21”)
- Weld yield strength: f_w = 64000 psi
- Max load: P = 2500 lbs
- Weld area is a conservative: a = ¼”

Results:

- FOS: 40

Equations:

$$f_v = P/(0.707 * L_w * a)$$

$$FOS = f_w / f_v$$

Overall - Results

Analysis	Displacement (in)	Maximum Stress (ksi)	Safety Factor
Weld Bead	N/A	1.60	40
Beam 1	0.0066	2.27	16
Beam 2	0.0011	1.91	19
Beam 3	0.0176	3.30	15
Beam 4	0.0099	2.59	14
Beam 5	0.0114	3.99	9.1
Beam 6	0.0050	0.698	52
Beam 7	0.0132	0.955	38
Beam 8	0.0008	0.981	37
Beam 9	0.0029	2.79	13
Beam 10	0.0004	0.908	40

Structural Analysis - Top Frame + Legs

Analyses

- BOTE
  - Leg compression and buckling
  - Cleat bolt shear
- FEA (SolidWorks Simulation)
  - Beam-leg cleats
  - Leveling Feet Mounting Plates
  - Top frame FEA

Top Frame + Legs - BOTE

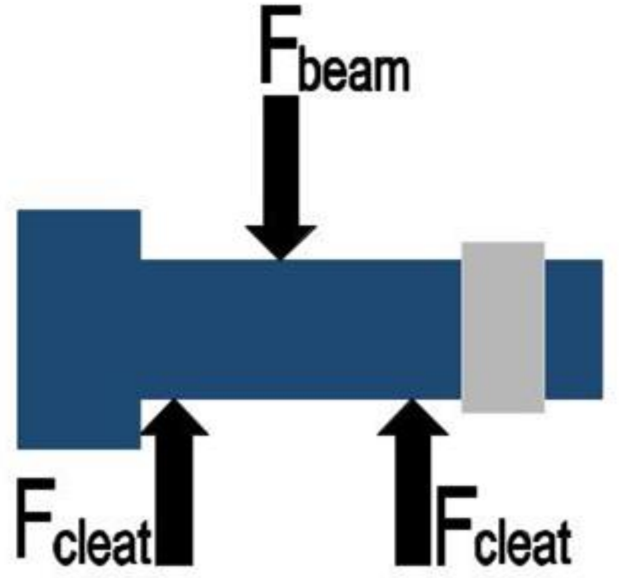
Leg Compression and Buckling

- As with beam bending, this analysis is practically the same as it was for PDR with some updates - see the WASP PDR [4] for more information

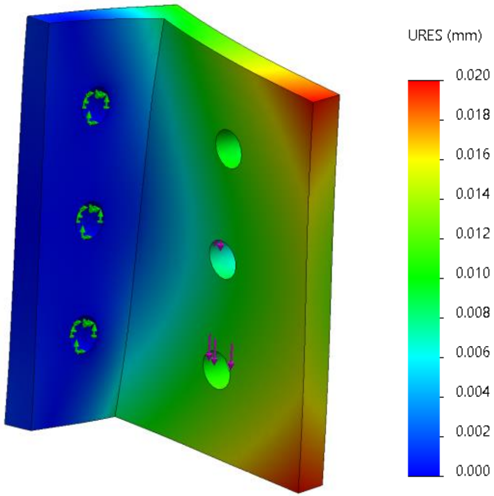
Top Frame + Legs - BOTE

Leg-Beam Cleat Bolt Shear

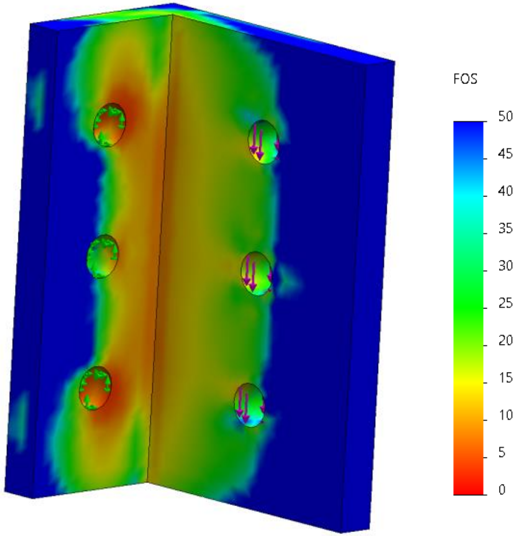
- Ignore the threads when calculating cross-sectional area: minor area (conservative)
- Ignores welds holding the legs to the upper beams
- A_c = 0.0269 in^2
- Load: 333 lbs
- Shear stress: 12.4 ksi
- Safety Factor: 7.0



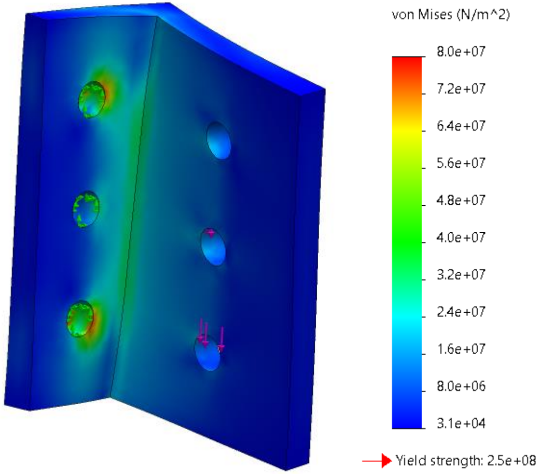
Leg Cleat - FEA



Max Displacement: 0.0008in

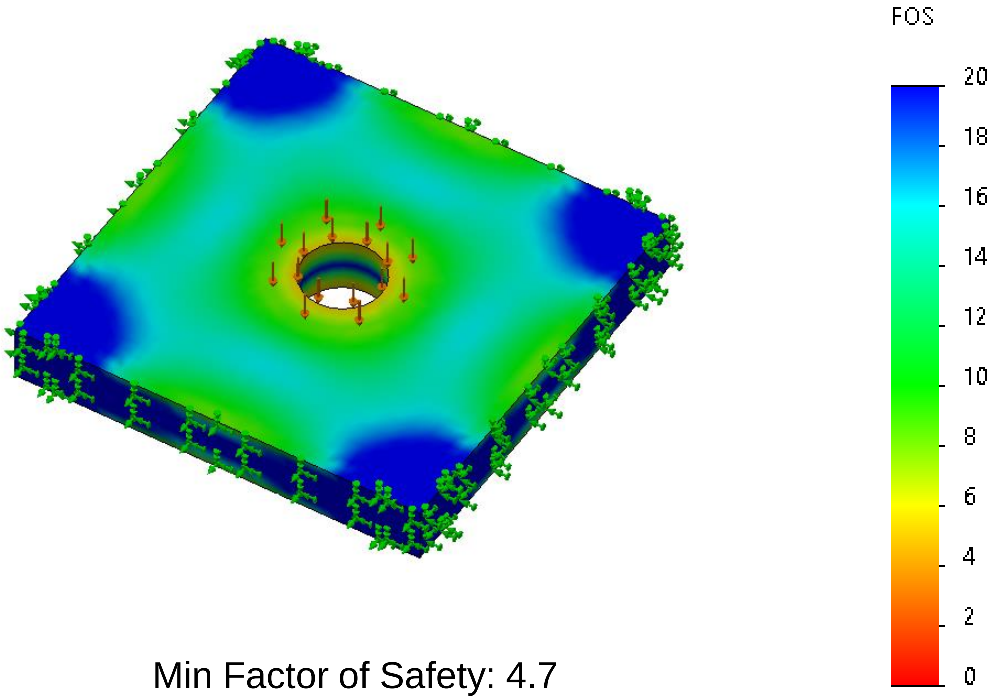


Min Factor of Safety: 3.1



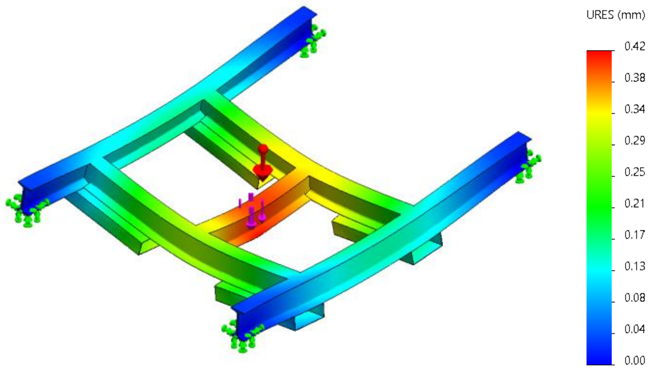
Max Stress: 11.6 ksi

Leveling Feet Mounting Plates

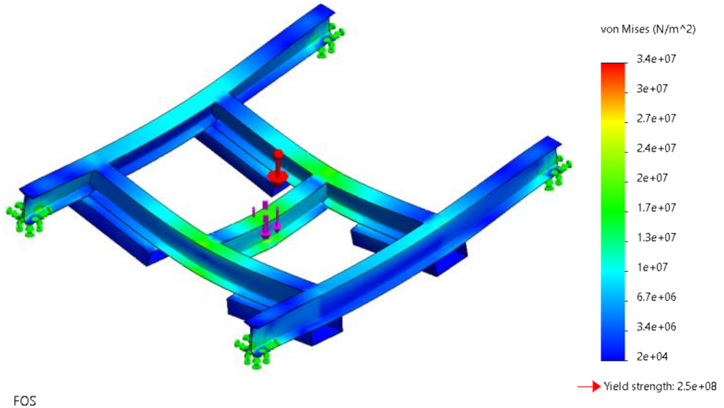


Min Factor of Safety: 4.7

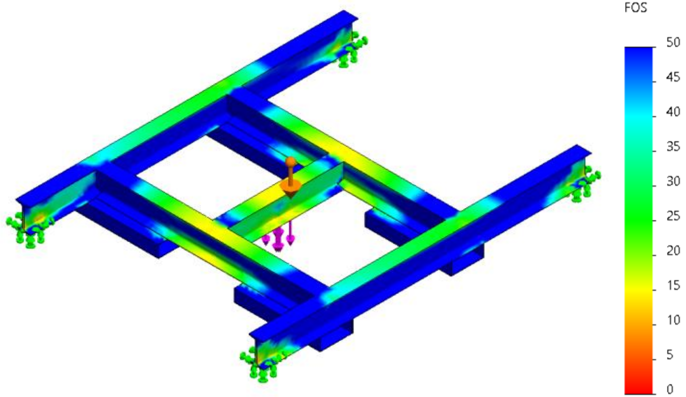
Top Frame - FEA



Max Displacement: 0.0165in



Max Stress: 4.93ksi



Min Factor of Safety: 7.4

Top Frame + Legs - Results

Analysis	Part with Max Stress (FEA only)	Maximum Stress (ksi)	Safety Factor
Leg - Compression	N/A	0.840	43
Leg - Buckling	N/A	N/A	63
Cleat Bolt Shear	N/A	12.4	7.0
FEA - Leg Cleat	Leg Bolt Holes	11.6	3.1
FEA - Leveling Feet Mounting Plates	Plate	7.7	4.7
FEA - Top Frame	Pin Holes	4.9	7.4

Structural Analysis - Sliding Interface

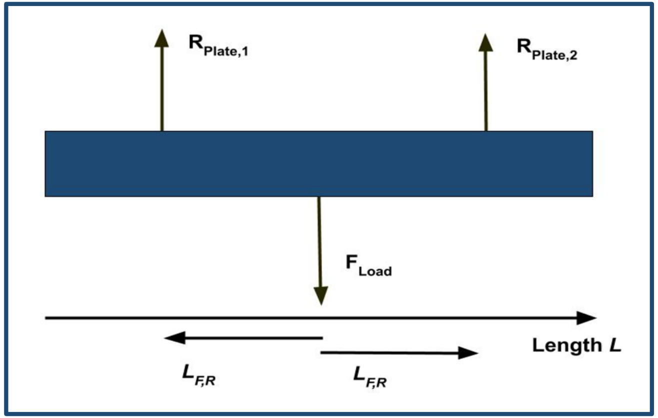
Analyses

- BOTE
  - Pin shear
  - Bending of pin plate
- FEA
  - Pin plate
  - Full sliding interface

Sliding Interface - BOTE

Sliding interface pin shear

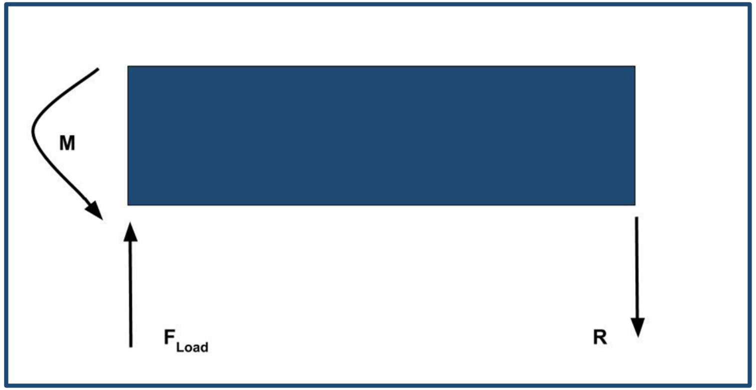
- Simple shear in pin due to load and plates
- Symmetric; Simple beam analysis with point loads
- 1144 Carbon Steel - 87000 psi yield strength
- Load on Pin = Max total load/4
  - Plates offer reaction forces (Reaction (each plate) = Load on Pin/2)
- Maximum stress = 5793 psi (bending/Flexure Formula)
- Maximum load = 700 lb
- Safety Factor = 15.52
- Diameter of Pin = 0.5 inches



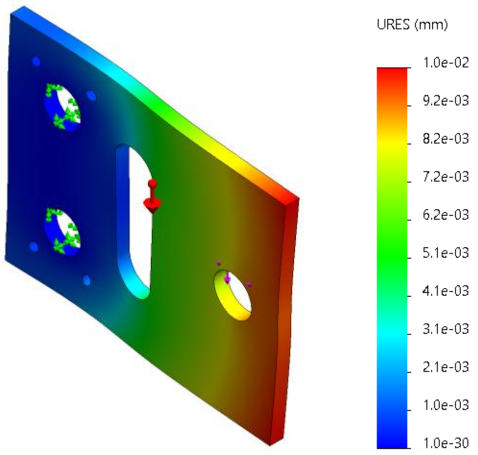
Sliding Interface - BOTE

Bending of pin plates

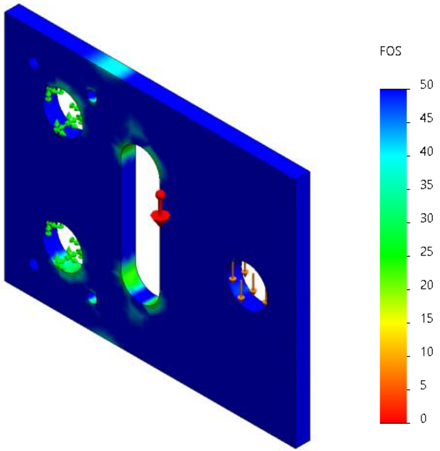
- Plates simplified to beam
  - Only looking at section of plate with applied and reaction forces/moments
- Maximum Load: 350 lb (½ of total load in pin)
- Maximum Stress: 1659.3 psi (bending)
- 1144 Carbon Steel - 87000 psi yield strength
- Safety Factor: 52.4



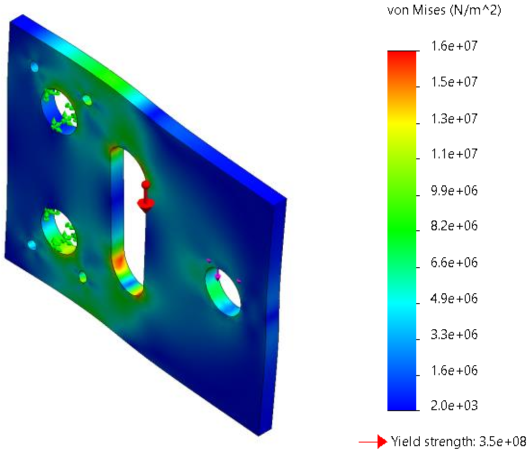
Sliding Interface Plate - FEA



Max Displacement: 0.00004in

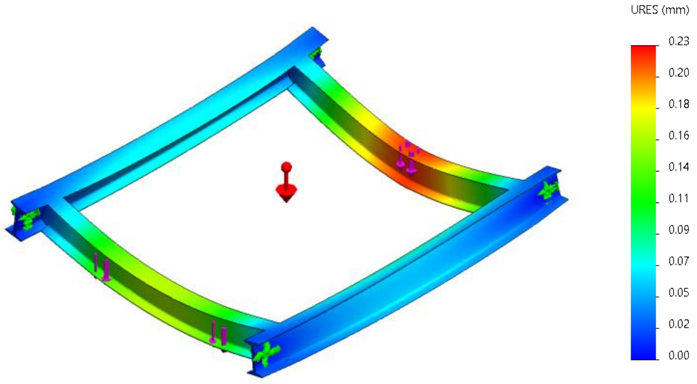


Min Factor of Safety: 21

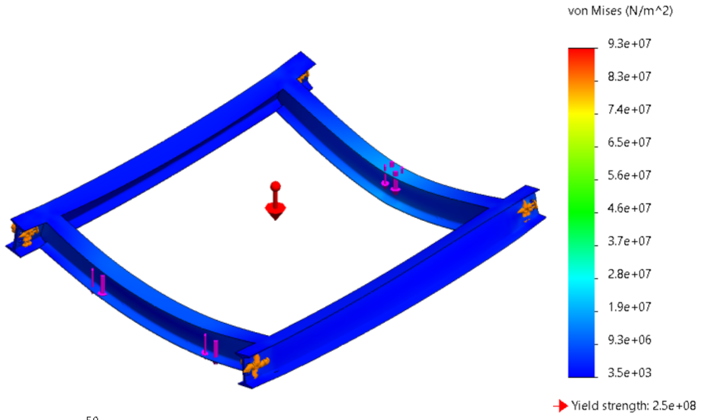


Max Stress: 2.32ksi

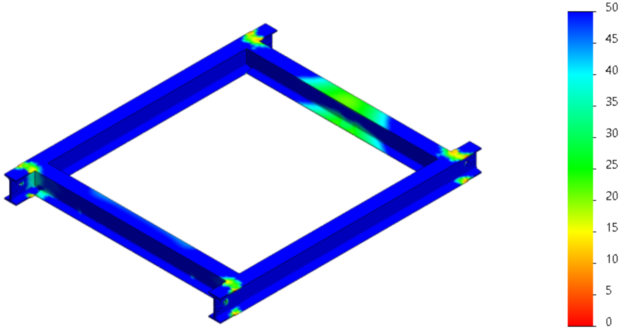
Sliding Interface - FEA



Max Displacement: 0.0091in



Max Stress: 13.5ksi
(Pin Holes)



Min Factor of Safety: 12
(Stress Concentration Ignored)

Sliding Interface - Results

Analysis	Part with Max Stress (FEA only)	Maximum Stress (ksi)	Safety Factor
Sliding Interface Pin Shear	N/A	5.79	15.5
Sliding Plate Bending	N/A	1.70	52
FEA - Sliding Plate	Middle Pinhole	2.3	21
FEA - Sliding Interface	Pinholes*	13.5	12 (4.3 Ignored by inaccurate stress concentration)

*This analysis did not model the welds on the sliding plate - it is very conservative

Structural Analysis - Testbed

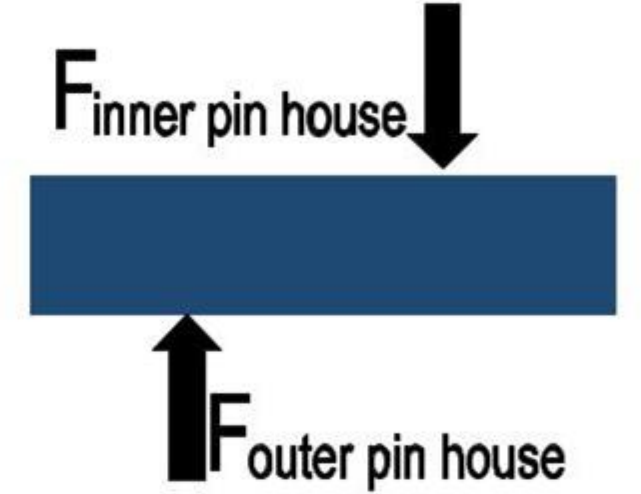
Analyses:

- BOTE
  - Level pin shear
  - Level pin bending
  - Hard stop rod axial loading
- FEA
  - Leveling pins and housings
  - Full testbed

Testbed - BOTE

Level pin shear

- Simple shear
- 1144 Carbon Steel
  - Normal yield stress of 87000 psi
- ¾” diameter pins: A_c = 0.442 in^2
- Maximum load: 735 lbs
- Maximum stress: 1.66 ksi
- Safety factor: 29.8



Testbed - BOTE

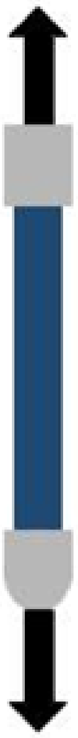
Level pin bending

- The space between the pin houses raises bending concerns
- Model as a cantilevered beam from the end of the outer pin house to the beginning of the inner pin house
- Force: 735 lbs
- Maximum bending stress: 1.25 ksi
- Safety Factor: 67

Testbed - BOTE

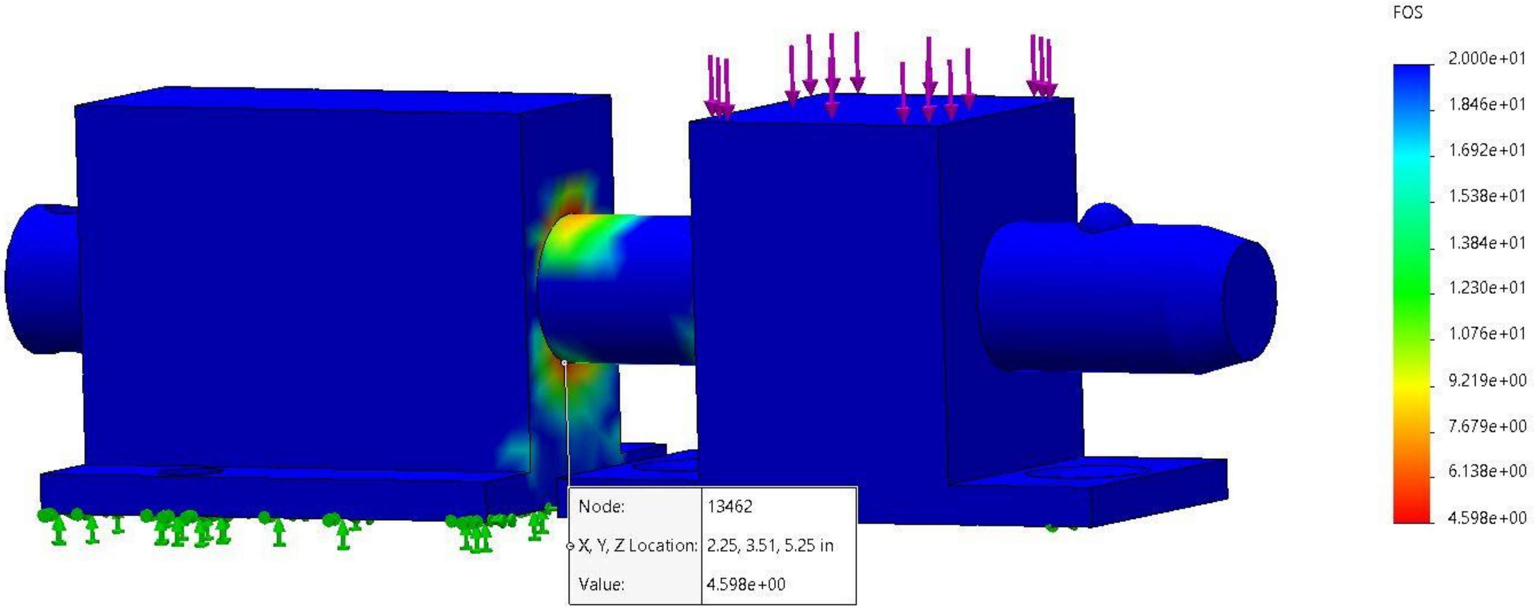
Hard stop rod: axially loaded

- Maximum load: 710 lbs
- Rod is Grade 8 Steel
  - Yield stress of 150000 psi
- ½” diameter, A_c = 0.196 in^2
- Maximum stress: 3.62 ksi
- Safety factor: 41.5



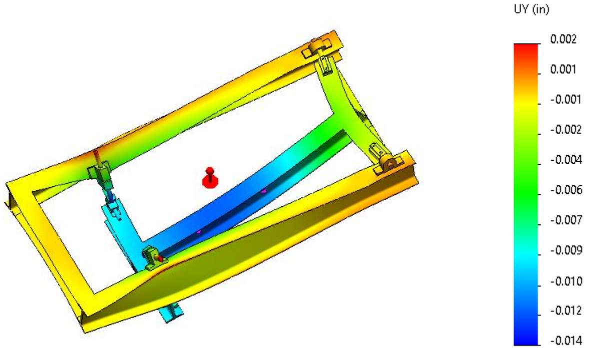
Testbed - FEA

Level pins and pin housing



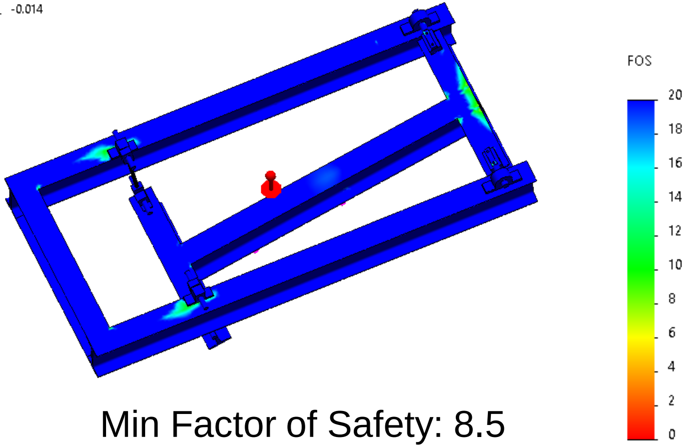
Min Factor of Safety: 4.6

Testbed - FEA



Max Displacement: 0.005 in

Max Stress: 4.2 ksi



Min Factor of Safety: 8.5

Testbed - Results

Analysis	Part with Max Stress (FEA only)	Maximum Stress (ksi)	Safety Factor
Level Pin Shear	N/A	1.6	31
Level Pin Bending	N/A	1.3	67
Hard Stop Rod Axial Loading	N/A	3.6	41.5
FEA - Pin and Pin Housing	Outer Testbed Pin House	11.6	4.6
FEA - Tilted Testbed (Pinned)	Outer Testbed	4.2	8.5
FEA - Tilted Testbed (Lifting)	Outer Testbed	5.5	5.0
FEA - Flat Testbed (Pinned)	Pins	10	6.0
FEA - Flat Testbed (Lifting)	Pins	0.86	10

Structural Analysis - Lug Mounts

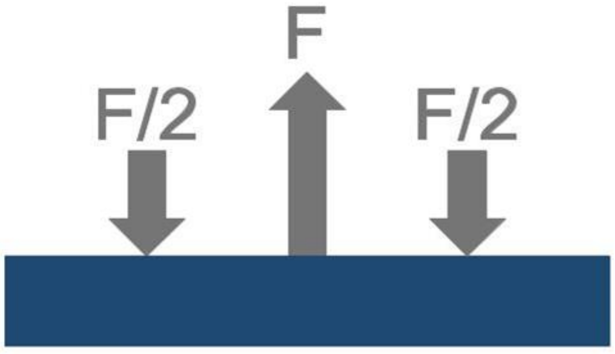
Analyses:

- BOTE
    - Bending of top plate
    - Bending of the lug pin (level)
    - Shear in the flange (level)
    - Axial load in flange sides (level)
    - Bending of the flange bottom (level)
    - Bending of the flange side (tilted)
        - Fixed-fixed (Best case)
        - Cantilevered (Worst case)
- FEA (level and tilted configurations)
    - Lug mount (flange and top plate)
    - Lug mount flange
    - Lug pins

Lug Mounts - BOTE

Lug Plate Bending

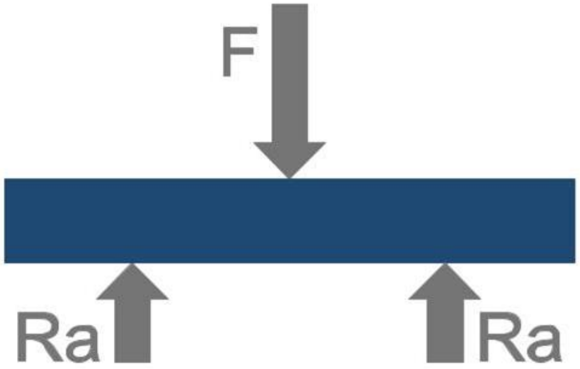
- ⅜” thick, 4” long, 3.5” wide
- Second-order bending analysis [6]
  - Assuming free ends and symmetry
- Maximum bending moment: -500 lb-in
- Maximum bending stress: 5.3 ksi
- Safety factor: 6.807



Lug Mounts - BOTE

Lug Pin Bending (Level Case)

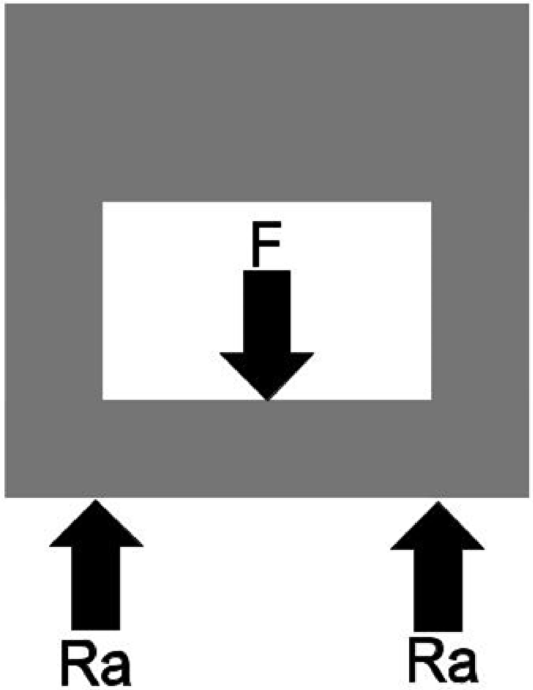
- Geometry depends on lug mount type (100lb, 1000lb, 2000lb class)
- F will be half the weight of the pod in the level case
- Second-order bending analysis, assuming pinned ends and symmetry
- Very low second area moments of inertia
  - $I_x = 0.01063$ in^4 for the 1000lb lug pin
- Maximum bending moment: -243.75lb-in
- Maximum bending stress: 6.88ksi
- Lowest safety factor: 5.28 (1000lb lug pins)



Lug Mounts - BOTE

Flange Shear (Level)

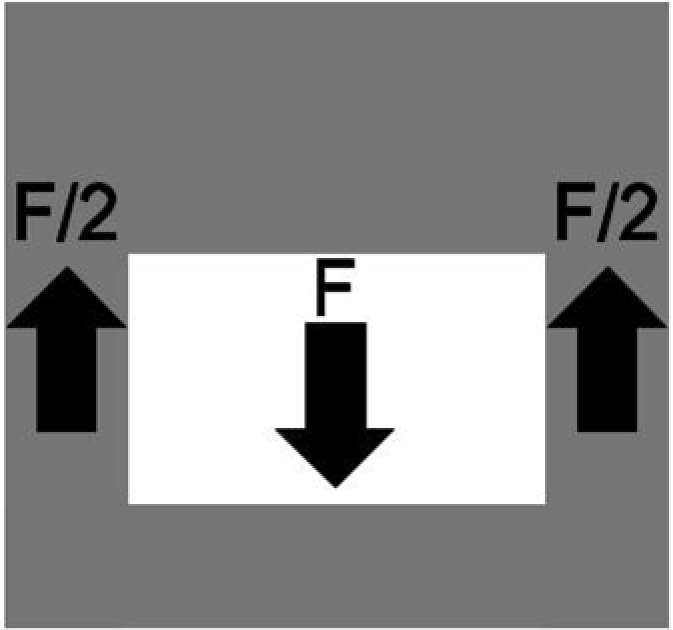
- Directly related to bending problem (2 slides ahead of this one)
- Double shear
- Cross Sectional Area is 0.249 in^2
- Shear Stress = 0.58 Normal Stress (Steel)
- Max shear force: 500lb
- Max shear stress: 2.01 ksi
- Safety factor: 10.48



Lug Mounts - BOTE

Flange Axial Load (Level)

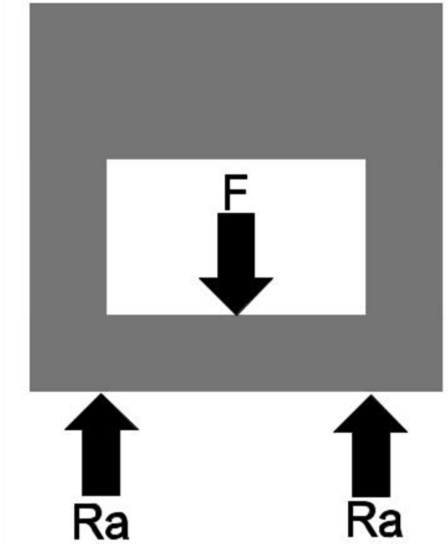
- Sides of flange are in tension
- Cross Sectional Area on each side is 0.51 in^2
- Maximum shear force per side: 500lb
- Maximum normal stress: 1.20 ksi
- Safety factor: 60.40

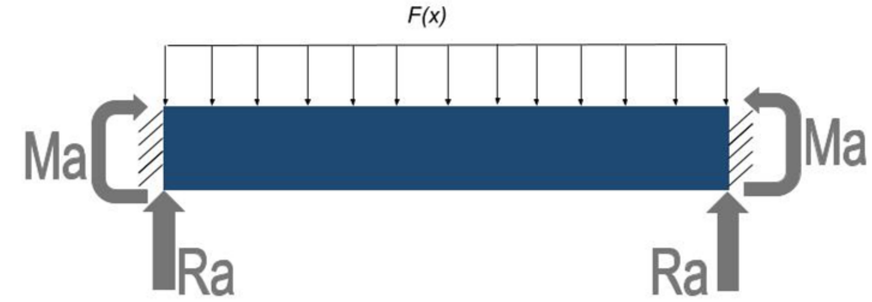


Lug Mounts - BOTE

Flange Bending (Level)

- Reaction force and moment on each side
- Second order bending problem: fixed-fixed
- Modeled with the load distributed across the bottom rather than being a single point at the center
- Maximum moment: -75 lb-in
- Maximum normal stress: 4.36 ksi
- Safety factor: 8.33

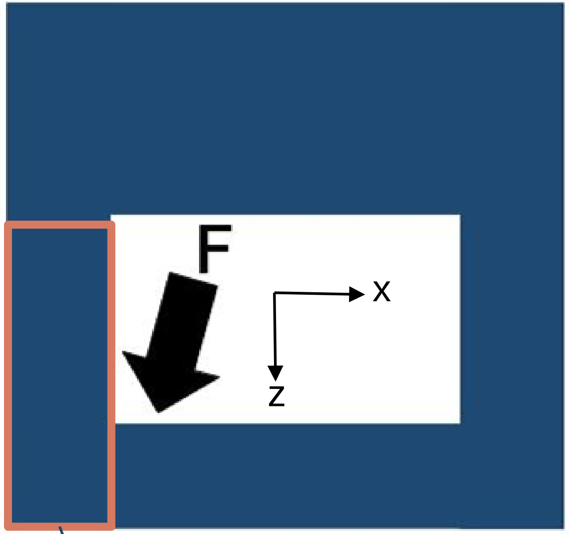


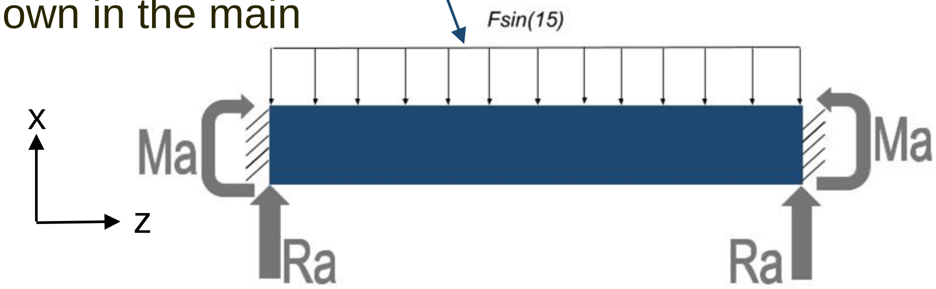


Lug Mounts - BOTE

Flange Bending (Tilted, Fixed-Fixed)

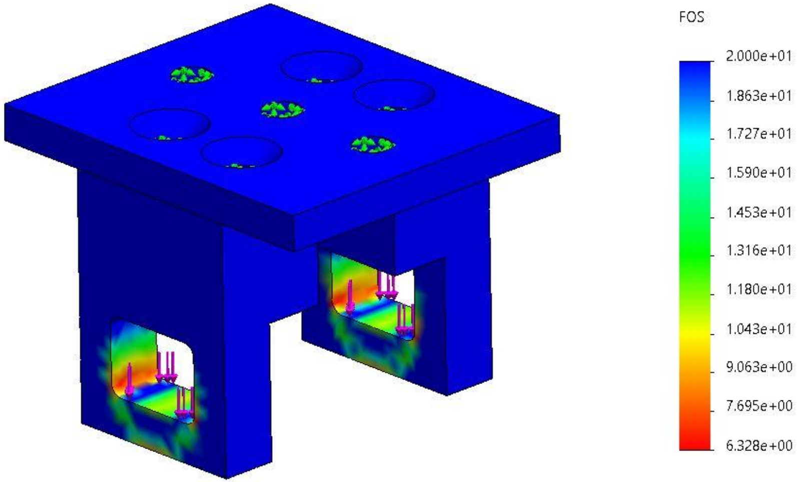
- Part of the force (sin(15)) acts in the y-direction
- Second order bending problem: fixed-fixed
- Modeled with the load distributed across the left slide
- Maximum moment: -18.59 lb-in
- Maximum normal stress: 1.03 ksi
- Safety factor: 35.19
- This is a favorable over-simplification
    - Stark contrast to the BOTE shown in the main slides





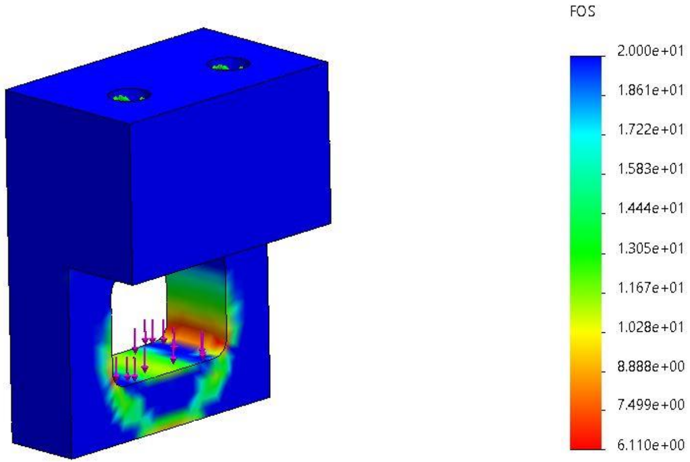
Lug Mounts - FEA (Level Case)

Lug Mount Assembly



Min Factor of Safety: 6.3

Isolated Flange

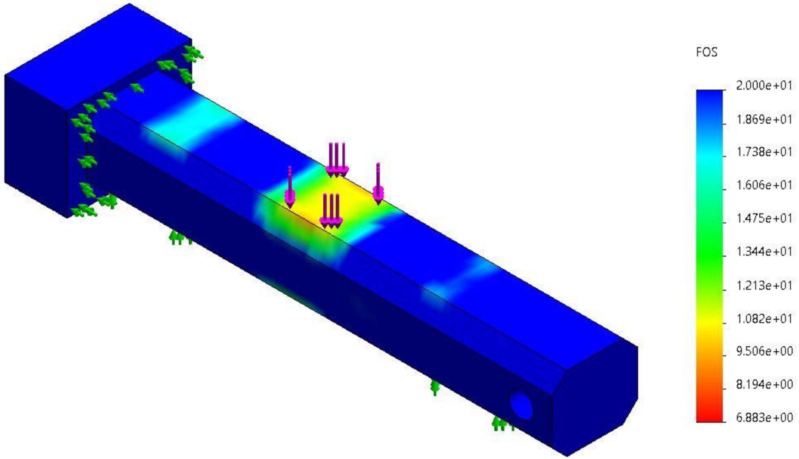


Min Factor of Safety: 6.1

Lug Mount FEA assumes 50% of the pod weight rests on each mount when level

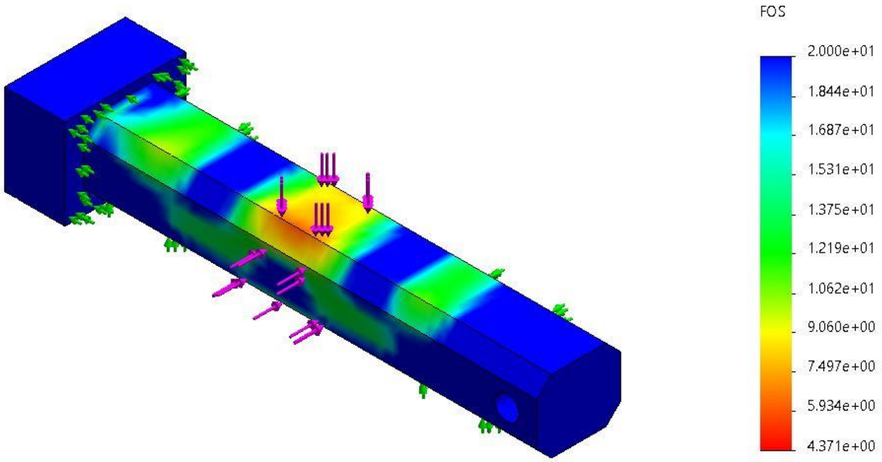
Lug Mounts - FEA

Lug Pin (Level Loading)



Min Factor of Safety: 6.9

Lug Pin (Tilted Loading)



Min Factor of Safety: 4.4

1000 lb lug pins shown here because they are the limiting case. Analyses on the 100 lb and 2000 lb pins were completed as well.

Lug Mounts - Results

Analysis	Part with Max Stress (FEA only)	Maximum Stress (ksi)	Safety Factor
Bending of Top Plate	N/A	5.3	6.8
Bending of Lug Pin*	N/A	6.88	5.28
Shear in the Flange (Level)	N/A	2.0	11
Axial Load in the Flange (Level)	N/A	1.96	19
Bending in the Flange Bottom (Level)	N/A	4.4	8.3
Bending in the Flange Side (Tilted) - Fixed-fixed	N/A	1.03	35
Bending in the Flange Side (Tilted) - Cantilevered	N/A	11.9	3.1
FEA - Level Lug Mount Assembly	Flange (2000 lb)	5.76	6.3
FEA - Tilted Lug Mount Assembly	Flange (2000 lb)	9.08	4.0
FEA - Level Lug Mount Isolated Flange	Flange (2000 lb)	5.95	6.1
FEA - Tilted Lug Mount Isolated Flange	Flange (2000 lb)	8.64	4.2
FEA - Lug Pin in Level Configuration	Lug Pin (1000 lb)	5.26	6.9
FEA - Lug Pin in Tilted Configuration	Lug Pin (1000 lb)	8.25	4.4

*For the lug pin, the 1000lb pin had the lowest safety factor. For all other analyses, the 2000lb mount had the worst safety factors. The analyses shown here are for the worst case (i.e. FEA of 2000 lb lug pin is not shown because it was safer than the 1000 lb lug pin)

Structural Integrity - Summary

DR 3.1: WASP shall support pods of 2000 lbs with a FOS of 2.0 to make safe and accurate measurements

Assembly	Minimum FOS	Part(s)	Function
Frame	3.1	Beam-Leg Cleats	Connect top frame beams to legs
Sliding Interface	4.3	I-Beam #6	Houses sliding interface pins and plates
Testbed	5.0	Outer Testbed	Connects testbed to sliding interface via load cells
Lug Mounts	3.0	2000 lb Lug Mount Flange	Hold lug pins in place

Structural Analysis - Bolt Engagement

Analyses:

- Axial loading safety factor
- Minimum length required for bolt to break before threads tear (Ke)
- Relevant equations shown here. See [2] for more details.

$$A_t = \pi\left(\frac{d_{bmp}}{2} - \frac{0.16238}{n}\right)^2$$

$$L_e = \frac{2A_t}{\pi d_{mt}[0.5 + n(d_{bmp} - d_{mt})\tan(30^\circ)]}$$

$$A_s = \pi L_e d_{mt}\left(0.5 + n(d_{bmp} - d_{mt})\tan(30^\circ)\right)$$

$$J = \frac{A_s S_{y,ET}}{A_n S_{u,IT}}$$

$$\boxed{K_e = J L_e}$$

$$A_n = \pi L_e d_{bmm}\left(0.5 + n\tan(30^\circ)(d_{bmm} - d_t)\right)$$

Bolt Engagement - Results

Bolt Connection	Bolt Diameter (in)	N (Threads per inch)	Current Engagement Length (in)	Ke (Min required engagement length for bolt to fail before thread tears) (in)	FOS against Bolt Failure (Axial Loading)	Pass/Fail	Notes
Lug mount plate to beam 9	3/8	16	0.7	0.6334	16.0231	Pass	Fine as is.
lug mount flange to lug mount plate	7/16	14	0.625	0.7614	29	FAIL (See alternatives)	Change to 3/8"-16 bolts for more threads per inch. Safety factor will drop slightly, but it will still be over 20.
Outer pin house to beam 7	5/16	18	0.7	0.517	19.37	Pass	Fine as is.
Inner pin house to beam 10	5/16	18	0.7	0.517	19.37	Pass	Fine as is.
Chain Hoist attachment to beam 9	1/2	13	0.55	0.8654	15	FAIL	Since safety factor is so high against the bolt breaking (FS=15), it isn't terribly concerning that the threads would tear before the bolt breaks. That being said, we will weld the hoist ring to beam 9 to provide additional support without having to redesign or mess with this off-the-shelf component.
Upper force sensor attachment blocks to beams 4/5	3/8	16	0.7	0.6387	7	Pass	Fine as is.
Axle bearing to beam 7	3/8	16	0.7	0.6334	28.485	Pass	Fine as is.
Axle block to beam 10	5/16	18	0.7	0.517	19.37	Pass	Fine as is.
Alternatives:							
Lug mount flange to lug mount plate (revision 2)	3/8	16	0.7	0.6387	21	Pass	With redesign, this is now fine.

Electronics Hardware

Omega LC103B Load Cells [8]

Specifications:

Accuracy (>25lb): class C3

Approvals(>25lb): OIML R60

Output sensitivity (mV/V): 3.0±0.008 *(≤25lb 2.0±0.006)*

Maximum number of load cell intervals (nLC): 3000

Ratio of minimum LC verification interval (Y=Emax/vmin): 10000

Combined error (%FS): ±0.020

Minimum dead load: 0

Safe overload (%FS): 150%

Ultimate overload (%FS): 300%

Zero balance (%FS): ±1.0%

Excitation, recommended voltage (V): 5 to 12(DC)

Excitation maximum (V): 18(DC)

Input resistance (Ω): 430 ± 50

Output resistance (Ω): 351 ± 2

Insulation resistance (MΩ): ≥ 5000 (50VDC)

Compensated temperature (°C): -10 to 40

Operating temperature (°C): -35 to 65

Storage temperature (°C): -40 to 70

Element material: Stainless steel

Ingress protection (according to EN 60529): IP67

Recommended torque on fixation (Thread:lbf.ft):1/4"UNF:18 1/2"UNF:55 3/4"UNF:330 1"UNF:550 1 1/8"UNF:1070

Recommended torque on fixation (Thread:Nm):M8:25 M12:75 M20:450 M24:750 M30:1450

Wyler AG Clinotronic Plus [10]

Measuring range Messbereich		± 10 Arcdeg	± 30 Arcdeg	± 45 Arcdeg ± 60 Arcdeg
Calibration / Kalibrierung	Last values at: / letzte Werte bei:	± 10 Arcdeg	± 30 Arcdeg	± 50 Arcdeg resp. ± 60 Arcdeg
Limits of Error / Fehlergrenze		< 1 Arcmin + 1 Digit	< 1.5 Arcmin + 1 Digit	< 2 Arcmin + 1 Digit
Settle time / Messzeit	Value available after / Anzeige nach:	< 2 Secs.		
Resolution / Auflösung	Dep. on units set / abhängig von Einstellung	> 5 Arcsec (0.025 mm/m)		
Temp. Coeff. / Temperatur-Koeff.	Zero and scale / Null und Skala	< 0.01 Arcdeg./°C		
Data connection / Anschluss		RS485 / asynchron / 7 Bit / 2 Stop Bit / no parity / 9600 Baud		
Battery / Batterie		1 x Size AA 1.5V Alkaline		

NI 9237 Bridge Module [14]

DATASHEET

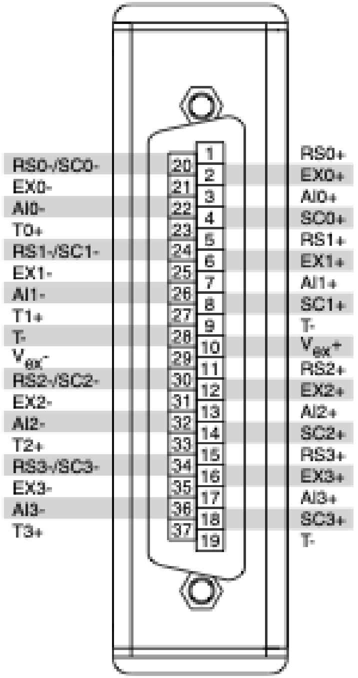
NI 9237

4 AI, ±25 mV/V, 24 Bit, 50 kS/s/ch Simultaneous, Bridge Completion

- 4 channels, 50 kS/s per channel simultaneous AI
- ±25 mV/V input range, 24-bit resolution
- Programmable half- and full-bridge completion with up to 10 V internal excitation
- 60 VDC, Category I bank isolation
- RJ50 or D-SUB connectivity options
- -40 °C to 70 °C operating range, 5 g vibration, 50 g shock

http://www.ni.com/pdf/manuals/374186a_02.pdf

NI 9237 Pinout/ Signal Descriptions [14]



Signal Descriptions

Table 1. NI 9237 Signal Descriptions

Signal Name	Description
AI+	Positive analog input signal connection
AI-	Negative analog input signal connection
RS+	Positive remote sensing connection
RS-	Negative remote sensing connection
EX+	Positive sensor excitation connection
EX-	Negative sensor excitation connection
T+	TEDS data connection
T-	TEDS return connection
SC	Shunt calibration connection

NI cDAQ-9171 Compact DAQ [15]

DEVICE SPECIFICATIONS

NI cDAQ™-9171

NI CompactDAQ One-Slot Bus-Powered USB Chassis

These specifications are for the NI cDAQ-9171 chassis only. These specifications are typical at 25 °C unless otherwise noted. For the C Series module specifications, refer to the documentation for the C Series module you are using.

Analog Input

Input FIFO size	127 samples
Maximum sample rate[1]	Determined by the C Series module
Timing accuracy[2]	50 ppm of sample rate
Timing resolution[2]	12.5 ns
Number of channels supported	Determined by the C Series module

https://www.ni.com/pdf/manuals/374037b.pdf

Analog Output

Number of channels supported	
Hardware-timed task	
Onboard regeneration	16
Non-regeneration	Determined by the C Series module
Non-hardware-timed task	Determined by the C Series module
Maximum update rate	
Onboard regeneration	1.6 MS/s (multi-channel, aggregate)
Non-regeneration	Determined by the C Series module
Timing accuracy	50 ppm of sample rate
Timing resolution	12.5 ns
Output FIFO size	
Onboard regeneration	8,191 samples shared among channels used
Non-regeneration	127 samples
AO waveform modes	Non-periodic waveform, periodic waveform regeneration mode from onboard memory, periodic waveform regeneration from host buffer including dynamic update

Risk Analysis

Risk Table

Risk	*Description*	*Effect*	*Mitigation*
MAN-LCP: Load Cell Placement *(Manufacturing)*	If sensors are placed poorly, then undesired non-axial forces may be applied to sensors	Load cell failure, inaccurate measurements	Having precise manufacturing plans and confirming load cell measurements with various measurement techniques
MAN-W: Misalignment from Welding *(Manufacturing)*	If welding leads to are misalignment of frame and/or legs, then accuracy in CG location may not be within desired threshold; structure could fail	Structural failure, inaccurate measurements	Careful manufacturing of the welds, following detailed manufacturing procedures, measurement techniques to improve CG accuracy
STR-CF: Structural Component Failure *(Structures)*	Any failure to components to WASP (alignment errors, deformation, etc.)	Can cause WASP to fail requirements (accuracy) if failure is severe; safety concerns	Careful modelling, testing components and structural integrity as well as detailed manufacturing instructions
POD-INT: Structural Interface with Pods *(Structures)*	Any inabilities that cause WASP to not attach to the lug mounts (misalignment, sizing errors, etc.)	If not attached property, it can cause functional failure	Careful design of lug mounts, testing/verification of lug connections
HUM-ERR: Human User Error *(Safety)*	Any human-induced error which can cause WASP to fail (incorrect attachment of lug mounts, pins are not inserted properly, etc.)	Functional failure of WASP as well as possible human injury	Implementation of detailed user manual, safety indicators on parts of WASP
COST: Budget Exceeds $5000 *(Finance)*	The maximum expenditures for the project cannot exceed the $5000	Failure to complete project; functional requirements failed	Extra precautions will be taken during manufacturing of structural components; precise inventory will be done and implementation of management reserves

Risks - Electronics & Software

Risk	***Description***	***Effect***	***Mitigation***
LC-Err: Load Cell Error Greater than Reported on Data Sheet	Combined error is reported; error isn't broken down (creep, repeatability). This may overestimate error values	WASP could fail weight and CG accuracy requirements	Testing load cell(s) accuracy to provide confidence in error
Inc-Err: Inclinometer Error Greater than Reported on Data Sheet	Data sheet may overestimate error values when measuring angle between testbed and floor angle	WASP could fail CG accuracy requirements	Geometry method to determine test bed angle
ES-COMMS: Electronics and Software System Communication Interruption	Communications within the E&S system can be interrupted by many sources	Data will not arrive to post-processing tool correctly	Detailed instructions for hardware set-up as well as E&S functionality tests
DMG-DAS: Damage to Data Acquisition System	Any forms of damage to the DAS (dropping, incorrect pin placement, ect.)	Data processing will not be possible	DAS is set-up in a safe location and detailed instructions for set-up and transport is provided

Risk Matrices - Electronics & Software

Pre-Mitigation

		Impact Level			
		Low	*Mild*	*Medium*	*High*
Likelihood Level	*High*				
	Medium			Inc-Err LC-Err	ES-COMMS DMG-DAS
	Low				

Post-Mitigation

		Impact Level			
		Low	*Mild*	*Medium*	*High*
Likelihood Level	*High*				
	Medium				
	Low			Inc-Err LC-Err	ES-COMMS DMG-DAS

Risks - Structures

Risk	*Description*	*Effect*	*Mitigation*
STR-CF: Structural Component Failure	Any failure to components to WASP (alignment errors, deformation, ect.)	Can cause WASP to fail requirements (accuracy) if failure is severe; safety concerns	Careful modelling, testing components and structural integrity as well as detailed manufacturing instructions
POD-INT: Structural Interface with Pods	Any inability for WASP to rigidly attach to the lug mount (misalignment, sizing errors, ect.)	If not attached property, it can cause functional failure	Careful design of lug mounts, testing/verification of lug connections
STR-FAT: Structural Fatigue	Failure due to WASP bearing loads up to 2000 lbs for many cycles	Can cause structural damage and pose safety concerns; functional failure	Design so FOS is very high and validate by testing; limit amount of tests per year

Risk Matrices - Structures

Pre-Mitigation

Likelihood Level \ Impact Level	Low	Mild	Medium	High
High				
Medium				STR-CF POD-INT
Low				STR-FAT

Post-Mitigation

Likelihood Level \ Impact Level	Low	Mild	Medium	High
High				
Medium				
Low				STR-FAT STR-CF POD-INT

Risks - SEIT/Miscellaneous

Risk	*Description*	*Effect*	*Mitigation*
DMG-P: Damage to SNC Pod during operation	Any internal or external damage to SNC pods	Any damage is categorized as functional failure	Operators must follow manual; make sure pod in mounted correctly
COST: Budget exceeds 5000 dollars	The maximum expenditures for the project cannot exceed the $5000	Failure to complete project; functional requirements failed	Extra precautions will be taken during manufacturing of structural components; precise inventory will be done; implementation of management reserves
COST-B: I-beam manufacturing error	Any damage done to any I-beam that prohibits use of them	If significant damage is done, new beams must be purchases	Extra precautions will be taken during manufacturing of I-beams; implementation of management reserves

Risk Matrices - SEIT/Miscellaneous

Pre-Mitigation

Likelihood Level \ Impact Level	Low	Mild	Medium	High
High				
Medium				COST COST-B
Low				DMG-P

Post-Mitigation

Likelihood Level \ Impact Level	Low	Mild	Medium	High
High				
Medium			COST COST-B	
Low				DMG-P

Risks - Safety

Risk	*Description*	*Effect*	*Mitigation*
HUM-SAF: Human User Safety	Injury to the operators or engineers using WASP.	Harm the user ranging from minor injuries to catastrophic injuries. Although larger injuries are less likely as minor injuries.	Safety aspects including an intensive user safety manual, safety gear, and safety measures are taken into consideration.
HUM-ERR: Human User Error	The possibility of the user making a mistake while dealing with WASP. Human errors can occur while completely tests as transporting WASP.	Can render the structure of WASP useless if the user makes an error that breaks a component. Human error can also harm the user.	Mitigation includes implementing a user manual that is easy to understand and safety measures aboard WASP like warning labels to ensure the user knows to be careful.

Risk Matrices - Safety

Pre-Mitigation

Likelihood Level	Impact Level: Low	Mild	Medium	High
High				
Medium			HUM-SAF	HUM-ERR
Low				

Likelihood Level	Impact Level: Low	Mild	Medium	High
High				
Medium				
Low		HUM-SAF		HUM-ERR

Post-Mitigation

Risks - Manufacturing

Risk	*Description*	*Effect*	*Mitigation*
MAN-LCP: Load Cell Placement	If sensors are placed poorly, then undesired non-axial forces may be applied to sensors	Load cell failure, inaccurate measurements	Having precise manufacturing plans and confirming load cell measurements with various measurement techniques
MAN-W: Misalignment from Welding	If welds are misaligned, then accuracy in CG location may not be within desired threshold; structure could fail	Structural failure, inaccurate measurements	Careful manufacturing of the welds; following detailed manufacturing procedures; measurement techniques to improve CG accuracy
MAN-BB: Beam-Beam Connections	If beam-beam connections are poorly welding, then connection integrity can be decreased	Structural failure, inaccurate measurements	Weld analysis; detailed manufacturing plan;
MAN-SCH: Schedule	Manufacturing is expected to take a long time which may cause the construction of WASP to not be completed on time	Incompletion of project	Manufacturing plan with timeline and planning with Prof. Rhode

Risk Matrices - Manufacturing

Pre-Mitigation

Likelihood Level \ Impact Level	Low	Mild	Medium	High
High			MAN-W	MAN-LCP
Medium			MAN-BB	MAN-SCH
Low				

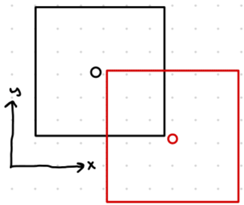
Post-Mitigation

Likelihood Level \ Impact Level	Low	Mild	Medium	High
High				
Medium		MAN-SIP MAN-W		
Low			MAN-BB MAN-SCH	

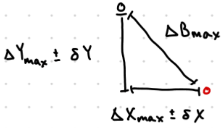
Load Cell Placement Error Sensitivity

Load Cell Misalignment Error

11-19-20



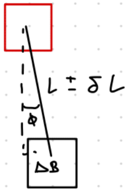
$\Rightarrow$



$$\Delta B_{max} \pm \delta B = \sqrt{\Delta Y_{max}^2 + \Delta X_{max}^2} \pm \delta B$$

$$\delta B = \sqrt{\left(\frac{\Delta X_{max}\, \delta X}{\sqrt{\Delta Y_{max}^2 + \Delta X_{max}^2}}\right)^2 + \left(\frac{\Delta Y_{max}\, \delta Y}{\sqrt{\Delta Y_{max}^2 + \Delta X_{max}^2}}\right)^2}$$

$$\delta B = \sqrt{\frac{\Delta X_{max}^2\, \delta X^2 + \Delta Y_{max}^2\, \delta Y^2}{\Delta X_{max}^2 + \Delta Y_{max}^2}}$$



$$\phi = \sin^{-1}\left(\frac{\Delta B}{L}\right) \pm \delta \phi$$

$$\delta \phi = \sqrt{\left(\frac{1}{\sqrt{1-\left(\frac{\Delta B}{L}\right)^2}}\,\frac{1}{L}\,\delta B\right)^2 + \left(\frac{1}{\sqrt{1-\left(\frac{\Delta B}{L}\right)^2}}\left(-\frac{\Delta B}{L^2}\right)\delta L\right)^2}$$

Summary

inputs: $\Delta Y, \Delta X$ = offset in Y, X-direction ≈ 0.02 in

$\delta Y, \delta X$ = error in Y-direction, X-direction offset measurement ≈ 0.02 in

L = length of load cell axle ≈ 8.75 in

δL = error in L measurement ≈ 0.02 in

$\Delta B = 0.02828$ in
$\delta B = 0.003564$ in
$\phi = 0.1852$ deg
$\delta \phi = 3.844836^{-4}$ in

Outputs:

$$\Delta B = \sqrt{\Delta Y^2 + \Delta X^2} \qquad \delta B = \sqrt{\frac{\Delta X_{max}^2\, \delta X^2 + \Delta Y_{max}^2\, \delta Y^2}{\Delta X_{max}^2 + \Delta Y_{max}^2}}$$

$$\phi = \sin^{-1}\left(\frac{\Delta B}{L}\right) \qquad \delta \phi = \sqrt{\left(\frac{1}{\sqrt{1-\left(\frac{\Delta B}{L}\right)^2}}\cdot\frac{1}{L}\cdot\delta B\right)^2 + \left(\frac{1}{\sqrt{1-\left(\frac{\Delta B}{L}\right)^2}}\cdot\frac{\Delta B}{L^2}\cdot\delta L\right)^2}$$

Verification & Validation

Sensor Characterization Test Details

- Materials
  - E&S
    - NI 9237 DAQ bridge module (on loan from AES)
    - NI 9171 cDAQ (on loan from AES)
    - 3 x 500 lbs FSO Omega LC103B tensile load cell (SNC Purchase)
    - 3 x 1000 lbs FSO Omega LC103B tensile load cell (SNC Purchase)
    - Computer to run GUI (internal)
  - External Hardware
    - Instron MTS tensile testing machine (Pilot Lab)
  - Safety Equipment
    - Eye protection

Sensor Characterization Procedure

1	Connect one of the 500 lbs FSO sensors to the NI 9237 bridge module.
2	Connect NI 9237 bridge module to cDAQ, connect cDAQ to computer. Open WASP GUI
3	Insert load cell into Instron MTS machine using appropriate grips.
4	Zero load cell readings in WASP software. Verify GUI is reading load cell data.
5	Apply 100 lbs to the load cell using the MTS machine software.
6	Calibrate sampling in WASP software until measured output fits within 100 lbs ± 0.1 lbs
7	Unload the load cell using the MTS machine software.
8	Incrementally load the load cell in 10 evenly spaced increments up to the FSO. At each load, wait 5 seconds and record the measured load cell data in the WASP GUI. Also record the MTS machine data using the MTS machine software.
9	Unload the load cell. Unclamp the load cell and remove from the MTS machine. Disconnect the load cell from the NI 9237 bridge module.
10	Repeat steps 1 through 3 and 8 with each of the other 500 lbs FSO load cells.
11	Repeat steps 1 through 9 with the 1000 lbs load cells.
12	Save and upload all data to WASP drive in Analysis folder. Disconnect the NI 9237 and cDAQ from the computer. Store all WASP E&S materials in WASP storage locker.

E&S Functionality Test Details

- Materials
  - NI 9237 DAQ bridge module (on loan from AES)
  - NI 9171 cDAQ (on loan from AES)
  - 1 x 100 lbs FSO compression load cell (electronics shop)
  - Computer to run GUI (internal)
  - D-sub connecting wires (soldered) (electronics shop)

E&S Functionality Test Procedure

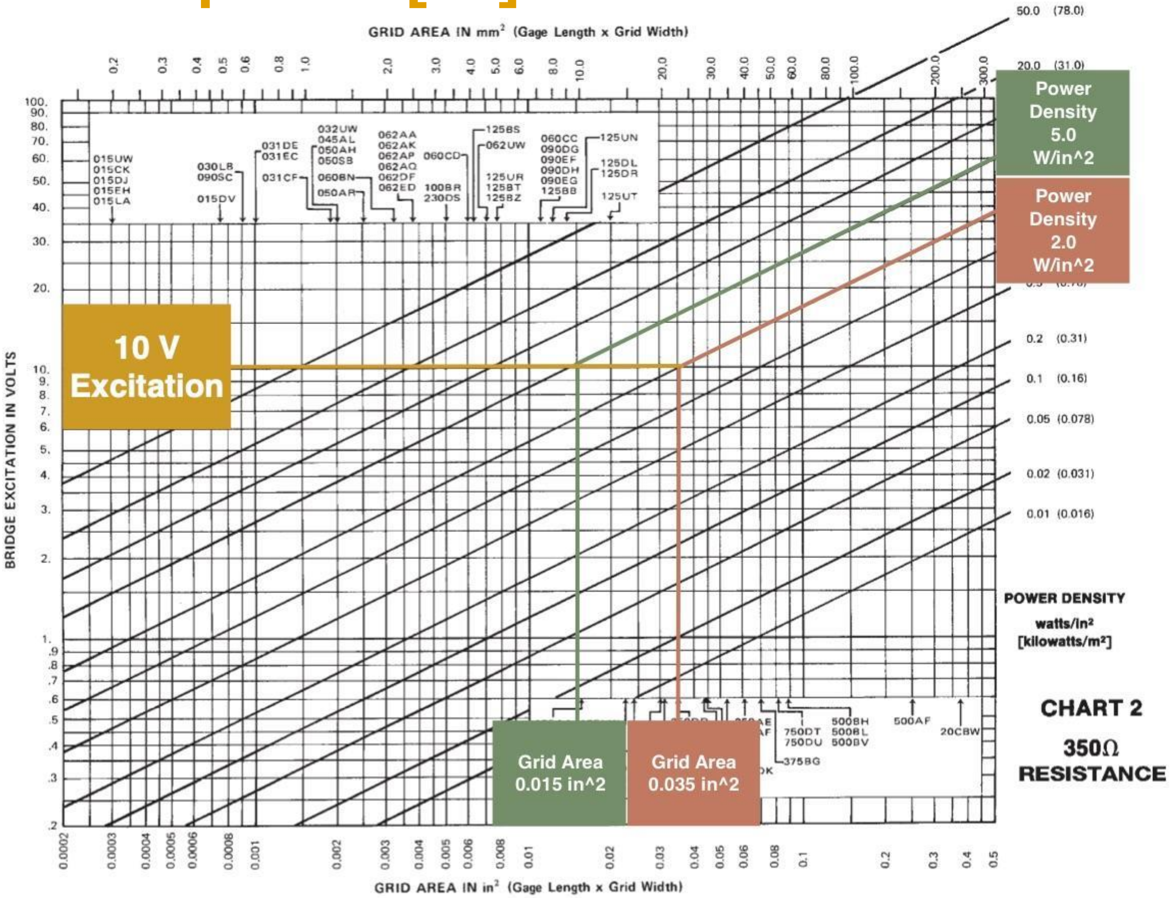
1	Connect cDAQ to computer. Open UI.
2	Connect NI 9237 bridge module to DAQ.
3	Connect load cell to NI 9237 bridge module using the D-sub connectors.
4	Check load cell connection to the computer.
5	Extract signal data from the load cell.
6	Calibrate NI 9237 bridge module to load cell voltage outputs.
7	Verify that the load cell measurements correspond to expected behavior as the load cell is loaded/unloaded with test articles using the UI. Ensure the maximum load of the load cell (100 lbs.) is not met or exceeded.
8	Close UI. Safely eject the cDAQ from the OS on the computer. Disconnect load cell, DAQ/cDAQ, NI 9237 bridge module.
9	Return load cell to electronics shop.

Structural Test Details

- Materials
  - Strain Gauges
    - 2 Half-bridge, 1 quarter-bridge with CEA-06-250UW-350 linear gauges (purchase)
    - 7 x 350 ohm resistors (electronics shop)
    - M-Bond 200 Installation kit (electronics shop)
    - Soldering materials (electronics shop)
  - E&S
    - NI 9237 DAQ bridge module (on loan from AES)
    - NI 9171 cDAQ (on loan from AES)
    - 1 x 1000 lbs FSO tensile load cell (electronics shop)
    - Computer to run GUI and LabView (internal/on loan from AES)
  - External Hardware
    - Forklift (machine shop)
    - 1000 lbs Pulleys (machine shop)
  - Safety Equipment
    - Hardhats, eye protection

Strain Gauge Power Dissipation [12]

- **350Ω Resistance**
  - Same as LC103B
- **10V Excitation**
- **Moderate Accuracy**
  - Static conditions
  - 2 - 5 W/in^2
- **Grid Area Range**
  - 0.015 - 0.035 in^2
- **5 x EA-06-250UW-350-L**
  - 2 half-bridges
  - 1 quarter-bridge



Structural Test Procedure

1	Place WASP on level ground with the forklift. Verify that the inclinometer measures an angle of ±0.025 deg. from the horizontal.
2	Verify that the attached load cells are rated for 1000 lbs.
3	Verify that all strain gauges are correctly adhered to the critical points on WASP's frame. Verify that the strain gauges are correctly connected to the NI 9237 and that the UI is receiving data from the sensors.
4	Lower the sliding interface to the loading configuration using the chain hoist by standing at minimum 4 ft. from the WASP structure. Ensure additional team member can see the entire structure and chain hoist operator (look for potential hazards).
5	Verify the lug connection point of interest is centered directly over the pulley/anchor (move forklift if necessary).
6	Attach load cell to the lug point of interest.
7	Attach forklift chain/strap to load cell while additional team member watches for hazards from 4 ft. away.
8	Run chain/strap through pulleys and connect to forklift.
9	Zero strain gauge and load cell readings in LabView/Matlab. Verify that the load cell reacts as expected to applied force (apply force by hand).
10	Increase load on system in 100 lbs. increments up to 1000 lbs., each time saving strain gauge and load cell data in LabView/Matlab. Wait 5 seconds until load cell reading stabilizes before saving data. After 1000 lbs. of applied load, export data to an Excel file. All team members must be at minimum 4 ft. from the WASP structure during this part of the test.
11	Remove all applied load on the structure.
12	Disconnect the chain/strap/come-along from the load cell. Remove the load cell.

Structural Test Procedure

13	Raise the sliding interface to the measurement configuration using the chain hoist from 4 ft. away.
14	Insert the sliding interface shear pins. Verify a rigid connection by slackening the chain hoist. Disconnect the chain hoist from the inner testbed.
15	Repeat steps 6 through 8.
16	Repeat steps 10 through 13.
17	Reattach the chain hoist to the inner testbed, and pull until there is no slack in the chain from 4 ft. away.
18	Remove the testbed shear pins. Lower the inner testbed to the desired angle using the chain hoist from 4 ft. away.
19	Pin the hard-stop members to the inner and outer testbeds to prevent the testbed from tilting further.
20	Once both hard-stops are in place, verify a solid connection by slackening the chain hoist. Then detach the chain hoist from the inner testbed.
21	Repeat steps 6 through 8.
22	Repeat steps 10 through 13.
23	Reattach the chain hoist to the inner testbed, and pull until there is no slack in the chain from 4 ft. away.
24	Remove the pins and the hard-stop members from WASP.
25	Use the chain hoist to pull the inner testbed back to level, and re-insert the testbed shear pins.
26	Remove the sliding interface shear pins. Lower the sliding interface to the loading configuration using the chain hoist from 4 ft. away.
27	Save and export any last data. Cut power to load cell and strain gauges. Disconnect all wired connections. Remove strain gauges from WASP (unless another test is to be conducted).

Analysis Test Details

- Materials
  - WASP
    - E&S
      - NI 9237 DAQ bridge module (on loan from AES)
      - NI 9171 cDAQ (on loan from AES)
      - 3 x 500 lbs FSO Omega LC103B tensile load cell (SNC Purchase)
      - Computer to run GUI (internal)
    - Structure
  - External Hardware
    - Forklift (machine shop)
    - Bertha (SNC test article)
    - Hand truck for Bertha (machine shop)
  - Safety Equipment
    - Hardhats
    - Eye protection

Analysis Test Procedure

1	Place WASP on level ground with the forklift. Verify that the inclinometer measures an angle of ±0.025 deg. from the horizontal.
2	Install appropriate set of load cells.
3	Lower the sliding interface to the loading configuration using the chain hoist by standing at minimum 4 ft. from the WASP structure. Ensure additional team member can see the entire structure and chain hoist operator (look for potential hazards).
4	Wheel the test article directly under the inner testbed using a hand flatbed truck. Mount test article to the inner testbed using provided lugs (14" TP lug type), which requires a total of four pins (and the corresponding sub-pins) to be inserted between the lugs and the lug mounts.
5	Lift sliding interface to the measuring configuration using the chain hoist (standing at minimum 4 ft. from the WASP structure and and having additional team member watching for hazards). insert sliding interface shear pins.
6	Slacken the chain hoist (2 full arm-length tugs on chain) and detach the chain hoist from the inner testbed. Verify additional team member is watching for hazards while detaching the chain hoist.
7	Use GUI to record measurements from WASP's three load cells.
8	Reattach the chain hoist to the inner testbed, and pull until there is no slack in the chain from 4 ft. away. Verify additional team member is watching for hazards while attaching the chain hoist.
9	Remove the shear pins from the inner testbed, and lower the test article to the desired tilt angle using the chain hoist while standing 4 ft. away and an additional team member is actively watching for hazards.
10	Pin both hard-stop members at both ends (4 pins total) to the inner and outer testbeds to prevent the testbed from tilting further.

Analysis Test Procedure

11	Once both hard-stops are in place, slacken the chain hoist with 2 full arm-length tugs on the chain and detach the chain hoist from the inner testbed. Ensure additional team member is looking for hazards while detaching the chain hoist.
12	Use GUI to record measurements from WASP's three load cells.
13	Reattach the chain hoist to the inner testbed, and pull until there is no slack in the chain.
14	Remove the pins and the hard-stop members from WASP. Ensure additional team member is watching for potential hazards while the hard stops are being removed. Ensure the chain from the chain hoist cannot come in contact with the engineer working in WASP at this time.
15	Use the chain hoist to pull the inner testbed back to level from 4 ft. away, and re-insert the testbed shear pins.
16	Export computed weight and CG values to Excel file.
17	Repeat steps 6 through 16 four more times for a total of five measurement sets.
18	Maneuver the hand truck directly under the testbed. Remove the sliding interface pins and lower the sliding interface until the test article rests on the hand truck surface using chain hoist from 4 ft. away.
19	Remove all four lug pins (including each associated sub-pin) attaching the test article to the inner testbed. Remove the test article by wheeling the hand truck away from WASP.

Timing Breakdown (FR5)

- Chain Hoist Lift/Lower Time:
  - Time it takes to raise/lower testbed; 3 ft distance
  - 3 ft/min raise/lower time [13]
  - Raise and lower twice per measurement set (4 min)
  - 3 measurement sets (***12 total min***)
- Pin Insertion and Removal Time:
  - Pins - Sliding Interface (12), Tilting (4) = 16 total
  - Number of measurement sets = 3
  - (3 measurement sets) x (16 total pins) = 48 insertions/removals
  - 10 seconds per insertion/removal → 48 x 10s = 480 seconds = 8 minutes
  - Insert/remove hard-stops = 2 minutes
  - ***10 minutes total***
- User Interface & Computation Time:
  - Includes all operator interaction with the User Interface
  - Estimated 1 minute for operator interaction + 1 minute run time ***(2 minutes total)***
- Pod Mount/Demount Time:
  - This time will most likely be all allocated to pod mounting and unmounting ***(6 minutes total)***
    - Mounting/Demounting time does *not* include first mount and last demount

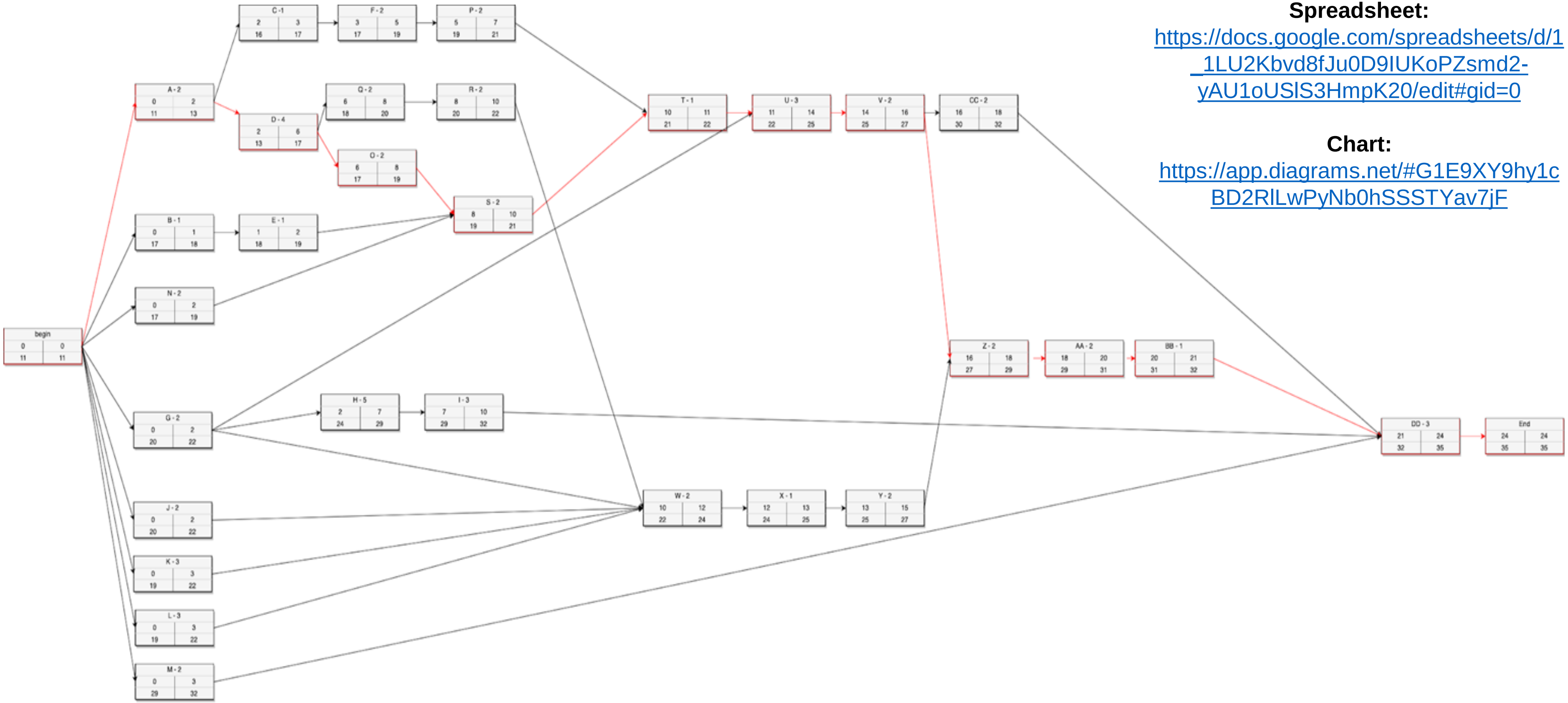
30 min total for all activities

Manufacturing

Manufacturing Task List

A	Cutting the I beams down to size		I	creating/milling lug mount pins		Q	Building outer testbed		Y	Add chainhoist attachment: Bolt and then weld
B	Cutting square tubes (legs and support bars) down to size		J	building sensor attachments		R	building inner testbed		Z	align load cell mounts on test bed and tack them
C	Cutting beam 3's for beam-leg connection		K	building axle and attachments		S	adding interface attachments to sliding interface and sliding interface plates		AA	Epoxy/bolt bumper bars to upper load cell mounts
D	Cutting I beams for beam-beam connection		L	building pin housings		T	loosly bolt H frame to legs and insert sliding interface		BB	bolt load cells mounts to sliding interface
E	Milling holes into legs		M	building tilting hardstops		U	spot welding support bars and doing minimal adjusting between H frame connection and support connections all while testing that the sliding interface slides up and down without issue		CC	make measurements and ajust or confirm, then complete the welding
F	Drilling/Milling holes into beams		N	Building the plastic interface attachments		V	Determine where load cell interface tapped holes will be added to the sliding interface using tack/pin method		DD	Cut and attach forklift slots
G	Creating/milling lug mount plates, sliding interface pin plates, and caster wheel attachments		O	Building sliding interface		W	Drill/mill holes in inner testbed, outer testbed and sliding interface		EE	End
H	creating/milling lug mount flanges		P	building H frame		X	Connecting inner testbed to outer testbed			

Manufacturing Precedence Diagram



Spreadsheet:
https://docs.google.com/spreadsheets/d/1_1LU2Kbvd8fJu0D9IUKoPZsmd2-yAU1oUSlS3HmpK20/edit#gid=0

Chart:
https://app.diagrams.net/#G1E9XY9hy1cBD2RlLwPyNb0hSSSTYav7jF