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Project Final Report (PFR)

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Weight Analysis for Surveillance Pods (WASP)

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Table of Acronyms

Table 1: Table of Acronyms

Acronym	**Definition**
AES	Aerospace Engineering Sciences
BOTE	Back of the Envelope
CAD	Computer-Aided Design
CDD	Conceptual Design Document
CDR	Critical Design Review
CG	Center of Gravity
CONOPS	Concept of Operations
COTS	Consumer Off-The-Shelf
CPE	Critical Project Element
CU	University of Colorado (Boulder)
DAQ	Data Acquisition System
DR	Design Requirement
E&S	Electronics and Software
EM	Electro-Mechanical
FEA	Finite Element Analysis
FIFO	First In - First Out
FOS	Factor of Safety
FR	Functional Requirement
FSO	Full Span of Operation
GUI	Graphical User Interface
IAS	ISR, Aviation, & Security
ISR	Intelligence, Surveillance, & Reconnaissance
LCC	Load Cell Characterization
LMTT	Lug Mount Tensile Test
MAT	Measurement Accuracy Test
MIL-STD	Military Standard
MTS	Materials Test Systems
MSR	Manufacturing Status Review
NI	National Instruments
NIST	National Institute of Standards and Technology
PDD	Project Definition Document
PDR	Preliminary Design Review
PFR	Project Final Report
R2R	Return to Research
SAT	System Accreditation Test
SAWE	Society of Allied Weight Engineers
SEIT	Systems Engineering, Integration, and Test
SFR	Spring Final Review
SI	Sliding Interface
SIT	Structural Integrity Test
SNC	Sierra Nevada Corporation
TRR	Test Readiness Review
UI	User Interface
V&V	Verification & Validation
VBA	Visual Basic for Applications
WASP	Weight Analysis of Surveillance Pods

Notable Term Definitions

Table 2: Notable Term Definitions

Term	Definition
Frame	The physical truss structure of WASP.
Hard Stop	Physical restraint to ensure a constant tilt angle of WASP's testbed.
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.
Sliding Interface	Intermediate assembly that translates vertically along WASP's frame and connects to the testbed via the load cells.
Test	The execution of a full procedure which starts after set-up and concludes when weight and CG values are output.
Testbed	Comprised of the inner and outer testbeds, which connect to the pod via lugs and facilitate tilting.
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.

Definition of Symbols (Nomenclature)

Table 3: Nomenclature Definitions

Symbol	Definition
a	Area [in^2]
α	Tilt Angle [°]
F	Force [lbf]
I	Second Moment of Area [in^4]
L	Length [in]
M	Moment [lbf-in]
P	Applied Load [lbf]
R	Reaction Force [lbf]
σ	Normal stress [psi]
τ	Shear Stress [psi]
W	Weight [lbf]
ΔFSA	Length from Force Sensor Center-Axis to Axle along X-Direction [in]
ΔL	Length from Force Sensor to Center Hole of Lug Mount along X-Direction [in]
ΔX	Length between Forward and Aft Force Sensors along X-Direction [in]
ΔY	Length from Force Sensor to Y = 0 Axis in Y-Direction [in]

1 Project Purpose

Parker Simmons, *Matthew Zola*

1.1 Problem Statement

Within the defense industry, the need for intelligence has become increasingly prominent. One of the leaders in this field is the Sierra Nevada Corporation (SNC) and their ISR (Intelligence, Surveillance, and Reconnaissance), Aviation and Security (IAS) division. SNC has designed ISR pod products that have the ability to be mounted on many aircraft, enabling a broad range of surveillance operations. The weight and location of the X, Y, and Z center of gravity (CG) are vital to achieve the attachment tolerances of a given aircraft. These strict attachment tolerances are defined to ensure safe flight will be attained on the aircraft. Without meeting these tolerances, challenges with maneuverability and controls can increase the risks of failure. The current method of determining weight and CG of the pods at SNC is by hoisting them into the air with a forklift and load straps, performing force gauge measurements, and hand-processing this data. This process has been identified as both ineffective and a safety hazard to working engineers and the pod itself.

This project, Weight Analysis for Surveillance Pods (WASP), aims to streamline the process of finding the weight and CG of the pods to increase efficiency as well as protect the engineers and ISR pods themselves. To do this, the team looks to design and build a maneuverable structure that is capable of securely holding the pod, collecting necessary sensor measurements, and calculating the weight and CG within the accuracy required by SNC. To complete these objectives, in-depth design and analysis must be conducted to find the needed measurements with precision and accuracy. Additionally, the structural integrity of the system must also be verified to protect the pods from damage.

1.2 Mission Statement

Weight Analysis of Surveillance Pods (WASP) will provide SNC mass properties engineers with an upgraded apparatus and standardized method for determining the weight and center of gravity of various ISR pods.

1.3 Related Work

In the aerospace industry, there are two main categories of methods used to obtain the weight and balance of an object. The first and most common method is the static method. This method involves supporting the object at multiple points using force sensors [4] and performing moment calculations to determine the weight and axis-specific CG components. In order to calculate the CG of all three axes, the object or measuring tool must be rotated so that components of each axis can be aligned with the earth's gravity [5]. A project team at the University of Idaho used this method in the design and construction of a tool capable of measuring the CG of objects up to 75 lbs in weight [2]. Members of the Department of Industrial Engineering at the University of Bologna also developed a technique in which the object is statically suspended in two points and inclinometers are used to make angle measurements. Similar to the force measurements, the angle measurements can be used to back-calculate the CG components [6]. The second method is called the dynamical method, and it exploits the dynamical properties of the object itself to back-calculate the CG components. One example of this method is called the Trifilar Torsional Pendulum, which suspends the object by a cable at three separate points. The pendulum is then perturbed and the resulting period of oscillation about each cable can be used to calculate all three CG components, as well as the full moment of inertia tensor [7]. While this method can produce a great deal of information, many objects (including the ISR pods), are not suitable to being suspended by cables due to their size and weight. After reviewing past work in the experimental mass properties determination realm, it is evident that further work is needed for this project to scale up the size and weight capacity of previously developed devices.

2 Project Objectives and Functional Requirements

Samuel Felice, ***Ansh Jerath****, Emma Markovich*

2.1 Specific Objectives & Levels of Success

The specific objectives for WASP are outlined in Table 4 below. The levels are broken down into three categories: "Threshold", "Objective" and "Target". Level 1 objectives reflect the "Threshold" expectations for the capabilities of WASP. The project is deemed successful if, at minimum, Level 1 or "Threshold" objectives are met. Level 2 objectives reflect the "Objective" expectations of the capabilities while Level 3 reflect the "Target" expectations. The team designed to the "Target" objectives. These levels are applied to six key focus areas for the project which are Structural Integrity, Mounting and Interfacing, Measurement Accuracy, User Interface, Test Operation and Transportation. The criteria for each project element and success level can be observed in Table 4. For reference, Figure 1 depicts the pod-fixed coordinate frame, for which X, Y, and Z coordinate directions are defined.

Table 4: WASP Specific Objectives [3]

Project Elements	**Level 1** Threshold	**Level 2** Objective	**Level 3** Target
Structural Integrity	The tool will support pod weight up to 1000 lbs in suspension with a safety factor of 2.0. [3]	The tool will support pod weight up to 2000 lbs in suspension with a safety factor of 2.0. [3]	
Mounting and Interfacing	The tool will connect to 14" and 30" pod lug configurations and mount to/detach from the pods with the support of the transportation cradle.		The tool will have modular capabilities to connect to future pod lug configurations and mount to/detach from the pods with the support of the transportation cradle.
Measurement Accuracy	The measurement method will deliver the weight of the pod within an accuracy of ±0.1% and X CG and Z CG locations with an accuracy of ±0.1".	The measurement method will deliver the weight of the pod within an accuracy of ±0.1% and X CG, Y CG, and Z CG locations with an accuracy of ±0.1".	
User Interface	The measurement tool will output data to be manually entered into the software tool to perform calculations.	The measurement tool will autonomously input data to the software tool to perform calculations.	The measurement tool will autonomously collect and analyze weight and CG location data and export results to an Excel-compatible file.
	The software tool will utilize an Excel workbook that will deliver the pod weight, X CG, and Z CG values averaged over at least 2 and up to 5 measurement sets.	The software tool will utilize an Excel workbook that will deliver the pod weight, X CG, Y CG, and Z CG predictions averaged over at least 2 and up to 5 measurement sets.	The software tool will utilize an Excel workbook that will deliver the pod weight, X CG, Y CG, and Z CG values averaged over more than 5 measurement sets.
Test Operation	Test will be completed by 3 engineers.	Test will be completed by 2 engineers.	
	Test will be completed in 1 hour.	Test wil be completed in 0.5 hours.	
Transportation	The tool will be maneuverable on the hangar floor by 3 team members.	The tool will be maneuverable on the hangar floor by 2 team members.	

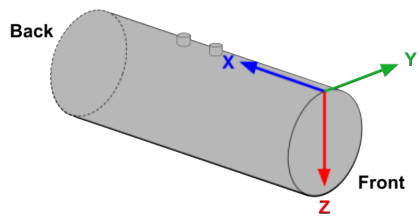

Figure 1: ISR Pod Coordinate Frame

2.2 Concept of Operations

A breakdown of the complete mission can be seen in Figure 2 as the Concept of Operations (CONOPS). The CONOPS demonstrates the breakdown of the mission objectives into chronological steps. WASP must be transported and unloaded from the SNC box truck. Then, WASP will be moved around within the hangar via rolling on the caster wheels. From there, the ISR pod will be mounted to WASP and lifted from the pod cradle. Next, WASP will weigh the pod and records measurements for at least three measurement sets, which each include load and angle data in a flat and tilted configuration. Recorded measurements will be transferred to a MATLAB User Interface (UI) which will calculate the average total weight and X, Y, and Z CG locations. Finally, the process is reversed to lower the pod back to its cradle, detach it from the mounting interface, and ultimately remove it from the hangar.

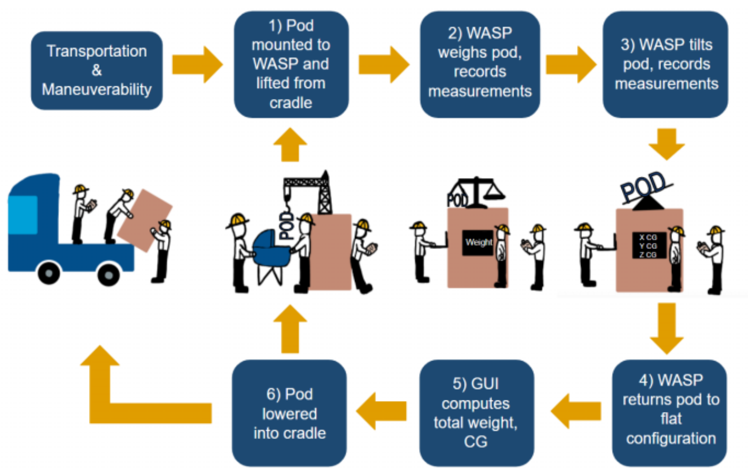

Figure 2: Concept of Operations

2.3 System-Level Functional Block Diagram

Figure 3 provides a high-level overview of the systems necessary for the WASP to perform the required tasks. Starting at the left, the ISR pod will be wheeled underneath the WASP frame via the ISR pod cradle. It will then be mounted to the inner testbed via the proper lug mounts. The inner testbed is connected to the outer testbed by a tilting axle, a cable-shackle apparatus, and two shear pins. The testbed serves the function of measuring the CG and weight, as it is connected to the sliding interface via a set of three tension load cells. The sliding interface, which is composed of structural I-beams and a sliding carriage, serves to keep the testbed secure as it is lifted into place by the chain hoist, which is connected to the outer frame. The frame serves to hold the entire structure at a sufficient height as to allow for tilting to a high enough angle to reach meet measurement accuracy requirements. The information from the load cells is recorded and interpreted by an electronics and software (E&S) suite, which is comprised of data acquisition (DAQ) devices, an SNC computer, and a UI that inputs data and output results on weight and CG.

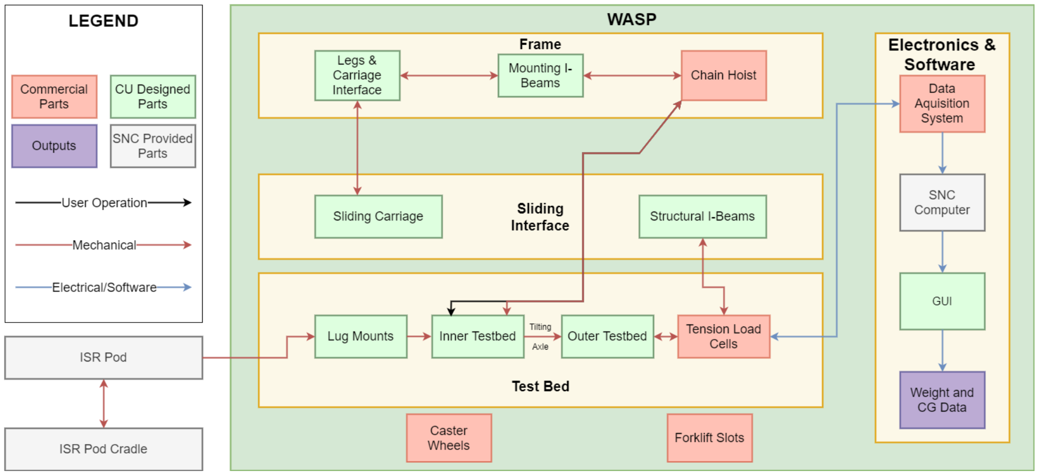

Figure 3: Functional Block Diagram for WASP

2.4 Project Deliverables

There are two sets of deliverables for this project: Customer and Course. Customer deliverables include a final product of a tool composed of a structural frame, measurement devices and data processing unit, a User Interface application, and a User Manual with operating and setup procedures as well as troubleshooting and maintenance information. Course deliverables include Project Definition Document (PDD), Conceptual Design Document (CDD), Preliminary Design Review (PDR), Conceptual Design Review (CDR), Manufacturing Status Review (MSR), Test Readiness Review (TRR), Professional Conference Paper, Spring Final Review (SFR) and Project Final Report (PFR).

2.5 High-Level Functional Requirements

The high-level functional requirements (FR) for WASP were derived from customer requirements and project-critical methodology. The functional requirements are stated below in Table 5. Their motivations, flow-down design requirements, and Verification and Validation (V&V) methods are described in Section 3.1 Requirements Flowdown. Importantly, FR5 stated that the tool must fit inside of a box truck. This requirement was removed when the customer changed the transportation vehicle to a less restrictive flatbed truck.

Table 5: High Level Functional Requirements

Number	**Name**	**Requirement Description**
FR1	Weight Accuracy	WASP shall measure the weight of the ISR pod.
FR2	CG Accuracy	WASP shall measure the X, Y, and Z CG of the ISR pod.
FR3	Interface	WASP shall interface with all existing ISR pods.
FR4	Form-Factor	WASP shall be free standing, and shall be easily maneuvered around an aircraft hangar by engineers or technicians.
FR6	Operation	WASP shall have a test procedure to make consistent weight and CG measurements.
FR7	Maneuverability	WASP shall not maneuver the ISR pods in any manner that may cause damage to them.
FR8	Calculation	WASP shall include a computer based tool to aid in calculations.

3 Final Design

*Maddie Dube, **Adam Elsayed**, Ansh Jerath, Emma Markovich, Bailey Roker, Matthew Zola*

This section details the final design of WASP. It is important to note that this design includes many updates that were deemed necessary during manufacturing and testing - vital aspects of the engineering process. It was through various lessons learned, which will be discussed in this section, that the design was developed into its current form.

3.1 Requirements Flowdown

The final design must be framed in the context of project requirements to better explain specific design choices. The evolution of the WASP design from preliminary concepts to the finished product was driven by constraints with time, money, and the rest of the following requirements.

FR 1. WASP shall measure the weight of the ISR pod.

Motivation: Customer specified functional requirement.

V&V: Demonstration - WASP outputs weight value when a full test is performed.

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

Motivation: Customer specified accuracy requirement.

V&V: Inspection/Testing/Demonstration - Inspection of sensor specifications. Perform several tests and confirm that reported weight meets the accuracy requirement for at least two tests on a test pod of known weight.

DR 1.1.1. Sensors shall be of high enough resolution ($\leq$0.2 lbs) to meet weight tolerance requirement.

Motivation: Required resolution to achieve tolerance of lightest pod (200 lb).

V&V: Inspection/Demonstration - Inspection of sensor specifications and demonstration of sensor output resolution.

DR 1.1.2. Sensor shall be precise enough (repeatability $\leq$0.11 lb) to meet the weight accuracy requirements.

Motivation: Required precision to ensure desired measurement tolerance.

V&V: Inspection/Testing - Inspection of sensor specifications. Repeatability test that involves applying a load, recording multiple measurements in this configuration, then statistically evaluating variance in measurements.

DR 1.1.3. Sensors shall be calibrated such that measured values are accurate to within ±0.1% of the pods true total weight.

Motivation: Customer specified accuracy requirement.

V&V: Inspection/Testing - Inspection of sensor specifications as well as physical testing of linearity and accuracy using Instron material testing system (MTS) machine.

DR 1.1.4. Sensors shall be removable from the frame to minimize harmful vibrations due to transporting the device.

Motivation: Vibrations due to transportation and maneuvering methods can harm the sensor's functionality and accuracy, so such vibrations should be limited where possible.

V&V: Demonstration - A frame-sensor connection and disconnection cycle will verify the removable nature of this interface.

DR 1.2. Sensors will be recalibrated per sensor supplier-recommended method prior to each measurement set.

Motivation: Minimizing errors in sensor measurements due to drift, bias, hysteresis, etc.

V&V: Inspection - Operational guidelines and user manual will require sensor recalibration prior to each measurement set.

FR 2. WASP shall measure the X, Y, and Z CG of the ISR pod.

Motivation: Customer specified functional requirement.

V&V: Demonstration - WASP outputs CG location values when a full test is performed.

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

Motivation: Customer specified accuracy requirement.

V&V: Demonstration - Perform several tests and confirm CG location values are within specified accuracy for five tests of test article with known CG.

DR 2.1.1. Sensors shall have high enough resolution ($\leq$ 0.2 lbs) to meet the CG accuracy requirements.

Motivation: Sensor measurement resolution determines the precision of the predicted CG values.

V&V: Inspection - Confirm the resolution of measurements from the sensor satisfies the resolution tolerance specified.

DR 2.1.2. Sensors shall be precise enough (repeatability $\leq$0.11 lb) to meet the CG accuracy requirements

Motivation: Required precision to ensure desired measurement tolerance.

V&V: Inspection/Testing - Confirm the repeatability tolerance on the sensor data sheet. Perform a test that measures a known load several times and analyzes variation in measurement.

DR 2.1.3. Sensors shall be calibrated such that measured values are accurate to within ±0.1 in. of the pods true CG.

Motivation: Customer specified accuracy requirement.

V&V: Inspection/Testing - Inspection of sensor specifications as well as physical testing of llinearity and accuracy using Instron MTS machine.

DR 2.1.4. Sensors shall be removable from the frame to minimize harmful vibrations due to transporting the device.

Motivation: Vibrations due to transportation and maneuvering methods can harm the sensor's functionality and accuracy, so such vibrations should be limited where possible.

V&V: Demonstration - A frame-sensor connection and disconnection cycle will verify the removable nature of this interface.

DR 2.2. Sensors shall be recalibrated per sensor supplier-recommended method prior to each measurement set.

Motivation: Minimizing errors in sensor measurements due to drift, bias, hysteresis, etc.

V&V: Demonstration - Engineer recalibrates sensors per the appropriate method before each measurement set is obtained.

DR 2.3. WASP shall use at minimum three sensors to measure CG in three-dimensions.

Motivation: For 3-dimensional CG determination, measurements at three different locations are necessary.

V&V: Inspection - Visually confirm that at least three sensors are used when obtaining CG measurement sets.

FR 3. WASP shall interface with all existing ISR pods.

Motivation: Customer specified design requirement. SNC requires a single tool that can return useful measurements on all current pod designs.

V&V: Demonstration - WASP will mount to and lift all five existing pod types.

DR 3.1. WASP shall support pods of 2000 lbs with a safety factor of 2.0 to make safe and accurate measurements. This safety factor requirement does not apply to any E&S-related parts.

Motivation: WASP must have the ability to support the weight of the pods so as to not drop or damage them, all the while returning meaningful measurements.

V&V: Testing - Thorough structural analysis will be done on each physical component of WASP, and the final manufactured tool will be loaded with an arbitrary 2000-lb CG simulator.

DR 3.2. The WASP mounting interface(s) shall support all current pod mounting designs.

Motivation: WASP must have the ability to mount to different pod types or else the tool would be deemed a failure.

V&V: Testing - The WASP mounting interface(s) will be attached to each pod design.

DR 3.2.1. WASP shall interface with both 14" and 30" lug spacing.

Motivation: Most pods are designed with the standard lug spacings given in MIL-STD 8591 [8].

V&V: Inspection - The mounting interface(s) will have lug slots 14" and 30" apart.

DR 3.2.2. WASP shall interface with any additional lug designs currently used by SNC IAS.

Motivation: Certain pods have additional complexities associated with the mounting interface and must be considered to ensure project success.

V&V: Demonstration - Pods with abnormal mounting interfaces will be connected to the mounting device.

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

Motivation: The pods can only be accurately analyzed when suspended from the lugs. Thus, WASP must lift pods in order to gather accurate measurements.

V&V: Testing - WASP Finite Element Analysis (FEA) model will apply 2000+ lb force (adjusted for maximum acceleration from the chain hoist) and show the factor of safety (FOS) is above the minimum allowed.

DR 3.4. WASP shall be designed such that it can support pods with an X CG within the confines of the lugs ± 3".

Motivation: The frame absolutely cannot tilt or rotate because of moments caused by different X CG locations for different pods. Note that the a given pods X CG should always be between the lugs ± 3" [8].

V&V: Testing - WASP FEA model will apply maximum weight at extreme potential X CG location to show FOS is above the minimum allowed.

FR 4. WASP shall be free standing, and it shall be maneuvered around an aircraft hangar by engineers or technicians.

Motivation: Customer specified design requirement. WASP should be easily maneuvered around an aircraft hangar.

V&V: Demonstration - WASP will be moved around an SNC IAS aircraft hangar.

DR 4.1. WASP shall have a transportation mechanism.

Motivation: There must be a convenient way to move WASP across a hangar floor. At the threshold, a forklift must be able to move WASP.

V&V: Inspection/Demonstration - An in-hangar transportation mechanism will be included in the final design. Instructions on how to connect mechanism to transportation correctly will be shown.

DR 4.1.1. WASP shall be locked in place during testing.

Motivation: WASP must not move during testing. When loaded with heavy objects, WASP should remain completely static for safety as well as measurement accuracy.

V&V: Demonstration - WASP will include a locking or removal mechanism that can be activated during testing. In order to ensure it functions properly, a practice measurement test will be performed with a 2000 lb test item while the maneuvering mechanism is locked/removed.

DR 4.2. WASP shall be moved by no more than 2 engineers/technicians.

Motivation: Customer specified design requirement. Pod weight and balance testing should utilize as little human physical exertion as possible.

V&V: Demonstration - Two team members from CU will move the unloaded WASP around an open space.

DR 4.2.1. WASP shall be maneuverable with less than 45 lbs of push/pull force per engineer/technician.

Motivation: MIL-STD 1472F Table XVIII [9] states that for a medium-traction environment (hangar floor and no-slip shoes), one individual should be able to push/pull a maximum of 45 lbs.

V&V: Analysis - If WASP has wheels, a dynamics-rooted derivation of the applied force needed from each engineer will be determined, using limits on allowable motion (speed, acceleration distance, etc.).

FR 5. WASP shall fit into an SNC IAS box truck.

This requirement is no longer applicable, as the frame can instead fit on an SNC flatbed truck.

FR 6. WASP shall have a test procedure to make consistent weight and CG measurements.

Motivation: WASP is being designed to complete weight and CG measurements. If a tool is delivered to SNC without a well-formed testing procedure, mission failure is far more likely.

V&V: Demonstration - Tests will be conducted by engineers who did not design WASP under team supervision to ensure the testing procedure is effective.

DR 6.1. 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.

Motivation: Customer specified requirement. The tool must support reasonable operation times to be a feasible replacement to the current method.

V&V: Demonstration - WASP team members must complete a test within the time constraints.

DR 6.1.1. WASP shall make one complete set of measurements and calculations in no more than ten minutes.

Motivation: Derived. A minimum of three measurement sets must be take during one test for redundancy as specified by the customer.

V&V: Demonstration - One set of measurements/calculations will be completed in less than ten minutes. This will also include the time it takes to disconnect and re-attach the pod to the mounting interface (not initial mount or final demount).

DR 6.2. WASP shall require no more than two engineers/technicians to complete one test.

Motivation: Customer specified requirement. The device should not require too much manpower to operate.

V&V: Demonstration - Two WASP team members will accurately and safely complete one pod weight and balance test.

DR 6.3. WASP shall have a physical user manual or procedure.

Motivation: The device will be operated by engineers/technicians that did not design or build WASP. They will need a set of instructions to safely and effectively operate and troubleshoot the device.

V&V: Inspection - The final deliverable will include a user manual.

FR 7. WASP shall not maneuver the ISR pods in any manner that may cause damage to them.

Motivation: The pods are expensive products, and if a pod is damaged as a result of the weight and balance tests, this project will fail.

V&V: Demonstration - An engineer or technician will make note of all the ways a pod/test article is maneuvered during a test.

DR 7.1. WASP shall not rotate the pod about the X-axis.

Motivation: Customer specified design requirement. Rotation about the X-axis is unnecessary for measuring CG and may lead to internal pod damage.

V&V: Demonstration - During a weight and balance test, WASP will not rotate the pod about the X-axis.

DR 7.2. The WASP lifting/tilting device(s) shall remain static when not lifting or rotating the pod.

Motivation: Movement during data acquisition would lead to inaccuracies and may introduce additional risk of damage to the pods.

V&V: Demonstration - When acquiring data during pod weight and balance tests, a team member will watch to ensure WASP remains completely static.

DR 7.2.1. The WASP loading and tilting mechanism(s) shall have (a) locking mechanism(s).

Motivation: The locking mechanism(s) ensure(s) that risks of damage to pods due to structural failure are minimized.

V&V: Inspection - Each moving part of WASP shall have at least one movement-restricting (locking) mechanism.

FR 8. WASP shall include a computer based tool to aid in calculations.

Motivation: Customer specified functional requirement.

V&V: Inspection - WASP will include the specified computer based tool.

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

Motivation: Allows for weight and CG data transfer from sensors to computers.

V&V: Inspection/Demonstration - WASP will interface with the computers through the computer based tool.

DR 8.1.1. Connections to sensors shall be detachable.

Motivation: Gives ability for separate storage of hardware and testbed structure. Harnesses will be protected from environmental conditions as well.

V&V: Inspection/Demonstration - WASP will show detachable connection to sensors during integration and testing.

DR 8.1.2. The computer based tool shall reboot connection with sensors after each measurement.

Motivation: Verifying successful data transmission will reduce risk of data errors through faulty connection.

V&V: Demonstration - WASP will reset connection to sensors during integration and testing to confirm connection.

DR 8.2. WASP shall have a supporting User Interface (UI) that processes and analyzes sensor data.

Motivation: Customer specified interface requirement. Efficient transfer of measurements to the user will give the opportunity to complete multiple measurement sets in a shorter amount of time.

V&V: Demonstration - WASP includes a UI that reads sensor measurement data and runs necessary calculations.

DR 8.2.1. UI shall function autonomously.

Motivation: Ease of use for users, so more measurements can be completed in a shorter amount of time.

V&V: Demonstration - WASP will perform measurements and interfacing to users autonomously during testing and integration.

DR 8.2.2. UI shall have alternative functioning methods as a back-up to the autonomous system.

Motivation: Redundancy is needed if autonomous measurements from WASP fail to perform correctly.

V&V: Demonstration - WASP will provide options for types of measurements and interfacing to users during testing and integration.

DR 8.3. WASP shall save results for weight and CG values in an Excel-compatible file type.

Motivation: Customer specified requirement that will ensure the output of the tool is usable and understandable by SNC engineers.

V&V: Demonstration - Verify that final saved results are stored in a file that can be viewed as Excel Workbook.

3.2 Final Design Overview

With the requirements now presented and the rationale behind each of them explained, the final solution can be addressed. The functional and design requirements identify six critical project elements (CPE) that influenced major design choices. Each element relates to a project focus area and the associated specific objectives. Figure 4 summarizes the CPEs.

CPE Number	CPE Title	CPE Description
E1	Frame Design (Logistical, Technical)	All static and dynamic loading associated with attaching, loading, suspending, and tilting pods must be handled by the frame. The design must also be portable and support a minimum of 1000 lbs. Acquiring adequate testing space and equipment may pose a logistical challenge, and if the frame fails, a redesign may not be feasible with the remaining time and budget
E2	Mounting Interface (Technical, Logistical)	Obtaining blueprints to all lug interfaces during the early design phase is critical to create a capable and useful tool. Otherwise, WASP may not be capable of accommodating all current and future pod types
E3	Accuracy (Technical)	The device must be capable of weight measurements within ±0.1% of the true value, and CG measurements within ±0.1" of the true value. If these minimum accuracy thresholds are not achieved, WASP will not be useful for SNC. Furthermore, this accuracy will need to be demonstrated through measurement of pods with precisely known weights and CG values. Obtaining multiple test articles with these precisely known values will be a logistical challenge.
E4	Ease of Use (Logistical)	The weight and CG testing procedures must be extremely well-developed and detailed to ensure the safe and efficient use of WASP. Otherwise, SNC engineers may not be able to correctly operate WASP, which may result in injuries, damage to the pods, and faulty data
E5	Safety (Technical, Budgetary, Logistical)	Considering the loads involved, the safety of both the users and the pods will be a concern during the validation process. If proper safety procedures are not employed, the multi-million dollar pods may be damaged and users may be seriously injured

Figure 4: Critical Project Elements

The final solution includes equation development, structural design, electronics, and software. Each of these subsystems are discussed in detail below.

3.2.1 Weight and CG Equation Development

To facilitate achievement of the primary goal of this project, equations for pod weight and CG were derived from principles of static equilibrium and moment balance. The equations utilize forces sensed by load cells and various absolute and relative angle measurements.

Figure 5 details the load cell configuration on the testbed structure. Three load cells are used, and the force experienced by each sensor is denoted by F1, F2, and F3, respectively. In the tilted configuration, these forces are denoted with a prime. Weight is calculated by summing the force measurement from each of three sensors (Equation 1).

$$W = \sum_{i=1}^{3} F_i \tag{1}$$

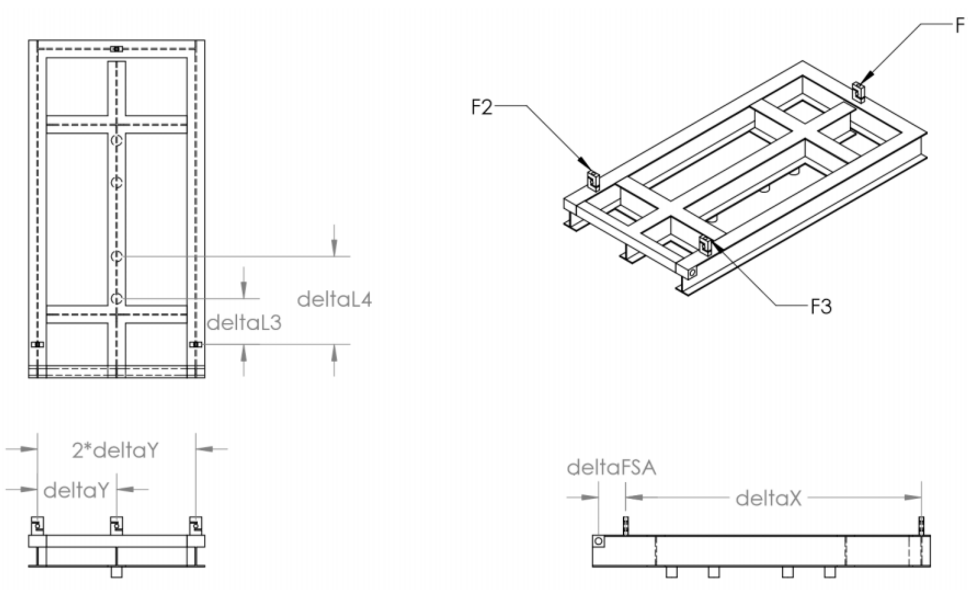

Figure 5: Load Cell Setup on Testbed

$$\Delta XF = \frac{(F_1)\Delta X}{W} \tag{2}$$

$$XCG = \Delta XF - \Delta L \tag{3}$$

$$YCG = \frac{(F_3 - F_2)\Delta Y}{W} \tag{4}$$

To calculate the X CG location, a moment balance is performed about the forward set of force sensors (F2 and F3) to determine the X-distance from the forward lug at which the weight force acts (X CG), since the magnitude of this force is known. A similar process is carried out for the Y CG, carrying out a moment balance about the aft force sensor (F1). The resulted equations for X CG and Y CG can be seen above in Equations 3 and 4.

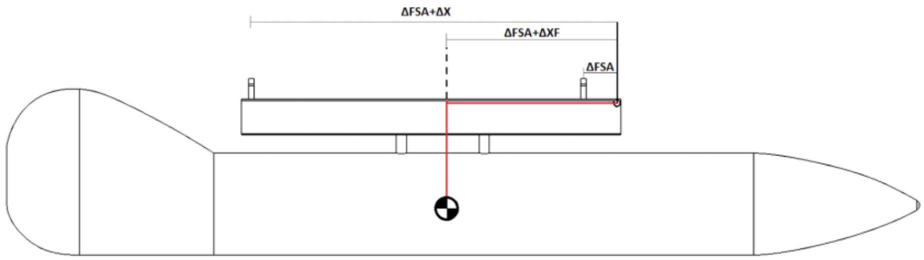

Figure 6: Pod in Flat Configuration (for Equation Derivation)

In order to calculate the Z CG location, the pod is tilted through some angle, denoted in Figure 7 as α. This moves the CG of the pod forward by some amount proportional to the Z CG (the further down the Z CG, the further forward the CG moves). By analyzing a new moment balance around the forward set of force sensors, the change in CG location can be accurately measured. The Z CG is then calculated by exploiting this change in CG location as seen in Equation 6. Figure 7 illustrates this change in CG location and the associated changes in length based on the tilt angle α.

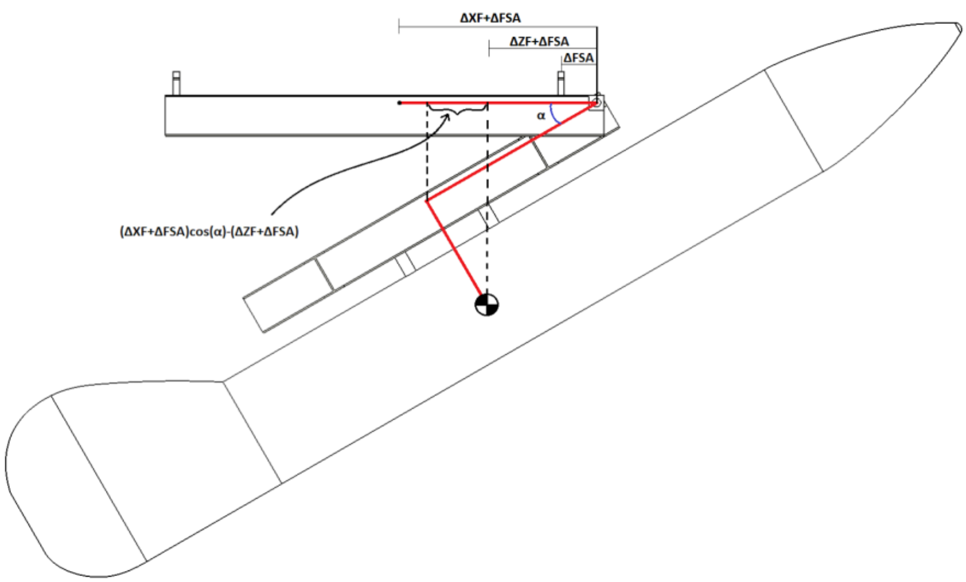

Figure 7: Pod in Tilted Configuration (for Equation Derivation)

$$\Delta ZF = \frac{(F_1')\Delta X}{W'} \tag{5}$$

$$-ZCG = \frac{(\Delta XF + \Delta FSA)\cos(\alpha) - (\Delta ZF + \Delta FSA)}{\sin(\alpha)} \tag{6}$$

It is expected that the surface upon which the tool is placed for testing is not perfectly level. In this case, it is important that any angular offset of the tool about the X and Y axes is accounted for during calculations. To do such, a direction cosine matrix that represents the rotational transformation between the assumed perfectly level coordinate system and the true rotated coordinate system is generated. The CG location calculated per the above equations is then multiplied by this matrix in order to determine the true CG location of the store, expressed in the body-fixed coordinate system of the store (Figure **??**).

3.2.2 Equation Updates Post-Manufacturing

At the completion of manufacturing, the team noticed that there were significant discrepancies between the assumed load cell alignment and their actual positions. As one example, the original equations assumed that load cell force F1 was located on the x-axis ($y = 0$) and that the forces F2 and F3 were equidistant from the x-axis. In reality, neither of these geometries hold, requiring the moment balance equations to be recalculated based on the misalignments. Figure 9 identifies each load cell's y-position independently, and the corrected version of the Y CG equation is found in Equation 9. The load cells were also misaligned along the X-axis, as the original equations assumed that F2 and F3 were attached at equivalent distances from F1. Figure 8 illustrates the independence of these dimensions, and Equation 8 is the corrected equation for the X CG. The Z CG equation was impacted in the same way as the X CG equation regarding corrections for misalignment. Importantly, the Z CG equation also underwent a revision to report the Z CG from a more meaningful location on WASP, since the original equations report the Z CG as a distance from the center of the axle. For this reason, a Z-offset parameter was introduced to account for the distance from the center of the axle to the bottom of the inner testbed beam at the lug mount location (Figure 10). The corrected Z CG equation is given in Equation 11.

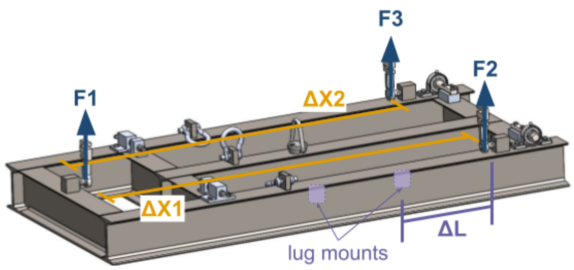

Figure 8: Load Cell Alignment Geometry - X

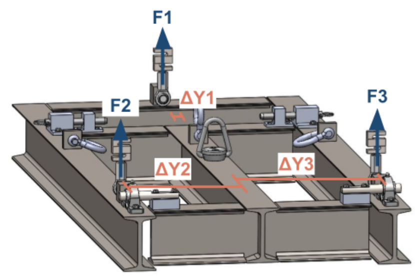

Figure 9: Load Cell Alignment Geometry - Y

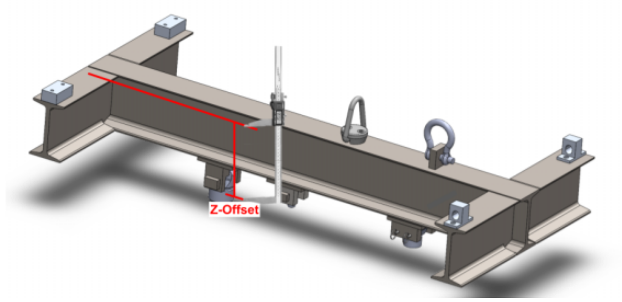

Figure 10: Z-Offset Parameter

$$\Delta \mathrm{XF} = \frac{\Delta \mathrm{X}_1(\mathrm{F}_1) + (\Delta \mathrm{X}_1 - \Delta \mathrm{X}_2)\mathrm{F}_3}{\mathrm{W}} \tag{7}$$

$$\mathrm{X\ CG} = \frac{\Delta \mathrm{X}_1(\mathrm{F}_1) + (\Delta \mathrm{X}_1 - \Delta \mathrm{X}_2)\mathrm{F}_3}{\mathrm{W}} - \Delta \mathrm{L} \tag{8}$$

$$\mathrm{Y\ CG} = \frac{\Delta \mathrm{Y}_1(\mathrm{F}_1) - \Delta \mathrm{Y}_2(\mathrm{F}_2) + \Delta \mathrm{Y}_3(\mathrm{F}_3)}{\mathrm{W}} \tag{9}$$

$$\Delta \mathrm{ZF} = \frac{\Delta \mathrm{X}_1(\mathrm{F}_1{'}) + (\Delta \mathrm{X}_1 - \Delta \mathrm{X}_2)\mathrm{F}_3{'}}{\mathrm{W}'} \tag{10}$$

$$\mathrm{Z\ CG} = \frac{\Delta \mathrm{XF} + \Delta \mathrm{FSA}}{\tan(\alpha)} - \frac{\Delta \mathrm{ZF} + \Delta \mathrm{FSA}}{\sin \alpha} - (\text{Z-offset}) \tag{11}$$

3.2.3 Structures and Mechanical Design

An isometric of the entire structure is given in Figure 11. The following sections detail the most important parts of the structural design and its operation.

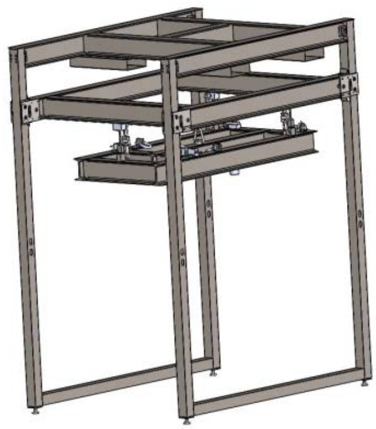

Figure 11: Isometric View of the WASP Structure as of SFR

Lug Mounts

One of the most crucial aspects of the structural design is the lug mounts. These directly affect the majority of the CPEs, namely E1, E2, E3 and E5. Not only do the mounts address the structural integrity and interfacing concerns, but the deflection of these components can lead to bias in the CG calculation. Multiple design iterations and analyses were completed on these mounts to ensure that they contribute to, rather than interfere with, the success of this project.

Each lug mount assembly consists of four parts: a top plate, which is bolted into the testbed, two flanges, which are bolted to the top plate, and a pin, which slides through holes in the flanges and the lug itself to secure the pod during testing.

There are four types of lug mounts, each capable of interfacing with a different kind of lug that WASP is required to be compatible with. Three of these mounts are designed around standard military lugs detailed in MIL-STD 8591 [8]. The final mount was designed around a third party (TP) lug. Each mount is shown attached to the testbed in Figure 12. One thing to note is that these mounts are modular. They can be attached and detached as needed to interface with different pods of interest at any time.

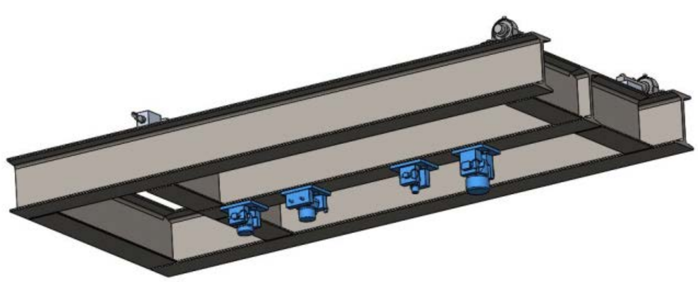

Figure 12: Lug Mounts Attached to the Testbed

The four mounts, with their respective pins and lugs, are shown in Figures 13, 14, 15 and 16.

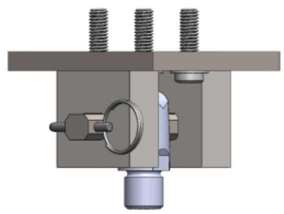

Figure 13: 100lb-Class Lug Mount with Lug Pinned

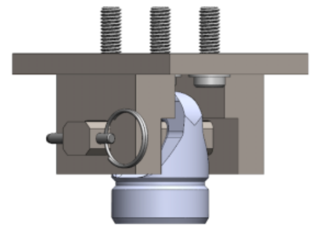

Figure 14: 1000lb-Class Lug Mount with Lug Pinned

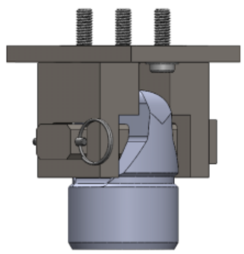

Figure 15: 2000lb-Class Lug Mount with Lug

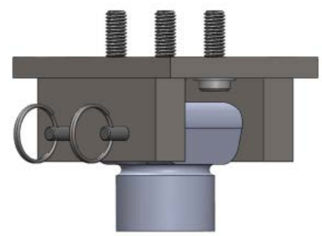

Figure 16: TP Lug Mount with Lug Pinned

Analysis of the lug mounts was critical to project success, as structural failure of a mount would be catastrophic; it would cripple WASP and potentially harm the pods and any nearby personnel. Both back-of-the-envelope and finite element analyses were completed to ensure that this would not be an issue. Since the four lug mount types all have similar geometry, the mount that comes closest to failure is the 2000lb-class version since it has the highest potential loading scenarios. The results of all lug mount analyses are presented in ST-53 in the project archive associated with this report.

Chain Hoist, Trolley, and Top of the Frame

Another important aspect of the design is the method by which lifting and tilting is completed. This action directly affects E1 and E5. Actuation is handled by a chain hoist, which is attached to a hoist trolley on the top of the frame above and a hoist ring on the testbed below. The testbed and sliding interface can be raised and lowered via the chain hoist while the inner and outer testbeds are pinned in their level configuration. To quasi-rigidly attach the sliding interface and testbed during chain hoist lifitng maneuvers, extendable and retractable aluminum block "bumpers" and employed (discussed further in a later section). The sliding interface then moves up and down with the testbed. When the sliding interface is pinned, chain hoist can lift the inner testbed such that the testbed leveling pins are not bearing load and can be removed, and then the inner testbed can be lowered by the chain hoist to its tilted configuration. A steel cable attached to both the inner and outer testbeds becomes taut in the tilted configuration, at which point the chain hoist can be detached for measurement. Each of the components mentioned here are discussed in further detail in the coming sections. Note that an alternative design known as "hard stop" bars can be inserted to keep the testbed at a constant tilted angle for more testing accuracy. This design was developed but never manufactured due to potential pinching hazards.

The chain hoist selected for this project is the CM Hurricane 360 chain hoist (Figure 17) with a 4000lb load capacity [10]. This chain hoist is ideal for WASP because the pull chain, which is manually operated, can be pulled at any angle. This prevents the pull chain from interfering with the pod and also allows the operator to maintain a safe distance during lifting and tilting. The hoist requires 75lbs of pull force to operate *at full capacity.* Since the maximum load that could ever be experienced is less than 3000lbs, the maximum expected human exertion is lower than 75lbs, which adheres to the human factors requirements set forth by Military Standard 1472F [9].

Figure 17: CM 360 Hurricane Chain Hoist

Figure 18: CM Hoist Trolley

The hoist trolley (Figure 18) was added to prevent the lift chain from operating at an angle during tilting. Chain hoists are not meant to be loaded at an angle, mainly to prevent heavy objects from swinging. While this is not a concern for WASP, there is still a chance that loading the hoist at an angle could result in the chain hoist internal mechanisms being damaged or failing. The trolley can slide back and forth in the x direction, so that when the hoist ring on the testbed moves as the inner testbed is tilted and the lift chain develops a small angle, the trolley can move to correct this angle and ensure the chain is loaded vertically. The trolley also has a capacity of 4000lbs.

The top of the frame (see Figure 11) was designed to support the load placed on the structure by the chain hoist. This includes the weights of the pod, the testbed, and the sliding interface, as well as the additional force required to accelerate these components upward during lifting. There is a single centerbeam on which the hoist trolley will reside. The remaining beams are there to support this beam and connect it to the legs of the structure. Note that the crossbeams are not centered. This is due to the fact that the hoist ring on the testbed is not centered, and thus the centerbeam had to be shifted to allow the trolly adequate movement during tilting. Multiple analyses, in ST-50 of the project archive, were completed to ensure the frame was safe.

Sliding Interface, Sliding Plates, and Positioning Lasers

In order to produce accurate and repeatable mass properties data (E3), it is critical that the load cells be axially loaded and completely static during measurements. The sliding interface is incorporated into the design for just that purpose. Its main function is to prevent the testbed from rotating during lifting and tilting. It also serves as the point of connection to the frame for the load cells, and is pinned in place during measurements so that the entire pod and testbed weight is supported exclusively by the load cells. The entire sliding interface assembly is pictured in Figure 19.

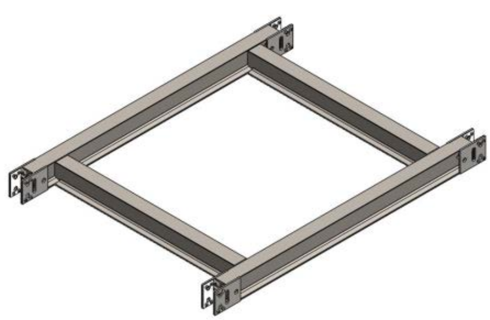

Figure 19: Sliding Interface Assembly

The interface works to prevent rotation of the load cells relative to the frame by having direct contact with the legs of WASP. If there were any moment imparted on the testbed by the chain hoist or the pod weight during lifting or tilting, the steel plates that are both welded and pinned to the SI beams would impart counter-moments and keep the sliding interface, outer testbed, and load cells in a level orientation. The direct contact between the plates and legs solved one problem but raised another concern: friction. If the friction between these components is too great, the sliding interface could potentially seize up and prevent actuation. After multiple design iterations, including linear bearings with a shaft and Al-8020 extrusion rails, this was simply solved by adding plates made out of a low-friction plastic between the legs and interface plates. These additional plates are showcased in white in Figure 20. A ballast weight was also added to the sliding interface to offset moments caused by the sliding interface itself, thus decreasing the maximum potential loading to which these plates are subjected.

The sliding interface steel plates serve as the means by which the subassembly is pinned to the legs during testing, as shown in Figure 21. There are two of these plates at each leg. The inner plate is welded in place, while the outer plate is secured with a bracket so that it can be removed to perform necessary maintenance on plastic plates.

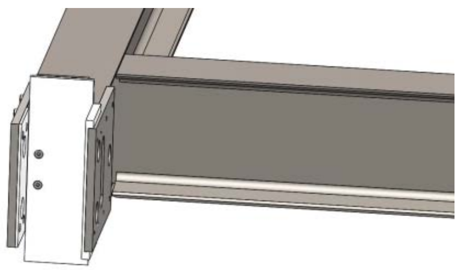

Figure 20: Plastic Plates used for Smooth Lifting

Figure 21: Sliding Interface Pinned to the Frame

During the testing phase, it was observed that the ball and socket joint linkages that connect the sliding interface to the testbed below can rest in multiple positions due to high friction. This poses an issue, as the load cells may measure a weight distribution with the testbed in one position during one measurement, and another weight distribution with the testbed in a slightly different position in the next measurement. This led to high amounts of random error in measurements, preventing repeatable CG output results. This issue was rectified by fixing lasers to the testbed structure. Before measurements, the testbed alignment can be marked by marking dots on the sliding interface where the laser beams come in contact with it. Then, before each measurement and tare, the testbed is to be realigned to this position. This solution significantly reduced the random error associated with CG values.

Testbed, Axles, and Tilt-Limiting Method

As discussed previously, WASP must be able to tilt the pod to measure the Z CG without tilting the load cells. This derived requirement primarily drives the detailed design of the testbed structure, which includes a pivoting axle. The performance of the testbed structure directly affects measurement accuracy as well as structural integrity, and thus plays a major role in satisfying CPEs E1 and E3. Any displacement of the load cells or structural components during loading cannot be accounted for in the CG calculations, and was therefore minimized (see discussion of lasers in the section above).

The testbed structure is comprised of the inner and outer testbeds, as shown in Figure 22. The outer testbed is connected to the rest of WASP via three tension load cells and is designed to remain parallel with the ground during all measurements. The inner testbed is connected to the outer testbed via an axle, and is designed to rotate downward for a "tilted" measurement. This design ensures that when the inner testbed and the pod are tilted, the load cells remain in line with gravity, which is essential to making accurate weight and CG calculations. The inner testbed is pinned at the end opposite the axle for level-measurement and transient states. For tilted measurements, a steel cable becomes taut in a specific configuration under the weight of the inner testbed and pod (seen in Figure 23). On the top of the inner testbed is a hoist ring, which serves as a connection point for the chain hoist to be attached to during lifting and tilting operations.

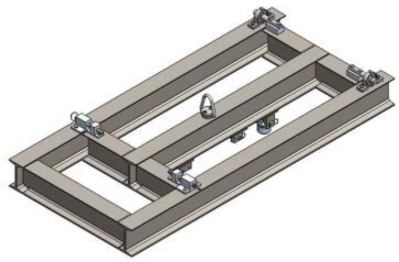

Figure 22: Testbed Structure - Level

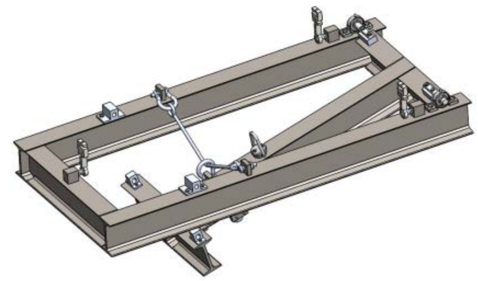

Figure 23: Testbed Structure - Tilted

Early concepts of the testbed design featured an axle that spanned the full width of the outer testbed. However, preliminary back-of-the-envelope (BOTE) calculations revealed that the long axle would be susceptible to bending under high loads. To counteract this effect, the axle was split into two much shorter pieces at each connection point, which is reflected in the final design. The tradeoff to this design change was the risk of misaligning the axles during manufacturing. To mitigate this risk, the bearings within which the axles sit were selected to have slotted bolt holes to allow for small adjustments to be made in the axle alignment. Another concern with the design was the bending stress applied to the pins connecting the inner and outer testbeds in the level configuration, especially because of their hardened/brittle nature. Careful analysis on the pins was completed to ensure a safe connection.

As with the rest of the design, the testbed assembly was modeled using both SolidWorks FEA and BOTE hand-calculations to ensure structural failure was not a concern. These results are given in ST-52

Load Cell Attachments and Bumpers

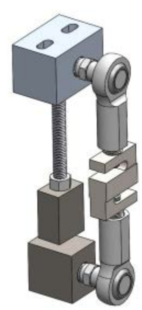

Figure 24: Force Sensor Attachment Assembly

Figure 24 shows the force sensor attachment assembly block. In order to prevent any moments from being applied to the sensors, and in order to ensure that they remain as vertical as possible during testing, the force sensors cannot be mounted directly into the testbed or sliding interface (as previously discussed). Instead, they are mounted to separate attachment 'blocks' using a pair of ball joint linkages, which are inserted into the blocks as shown in the figure above. Each assembly has two ball joint linkages and two blocks. While the blocks on the testbed are welded in place, those attached to the sliding interface (grey) are bolted in place and were manufactured with slotted bolt holes to allow for the precise mounting of each block, to ensure that the attachment points on the sliding interface and outer testbed are on the same vertical axis. This will ensure that the force sensors are vertical, and that no excess force is applied due to angle in the force sensors. The ball joint linkages ensure that, in the case that the surface upon which the tool takes measurements is not perfectly level, the force sensors are still in line with gravity. Again, this was found to not be entirely true as the linkages can rest in different positions due to high static friction, although it was recitifed with a strict alignment process.

Note the threaded rod and corresponding nut and attachment block "bumper" mentioned previously.

This block rotated down until it touches the testbed-side block (bottom) whenever the chain hoist is lifting the testbed. This was put in place to take the load in during lifting and prevent testbed from swinging into irregular positions under the single point load caused by the lifting chain hoist. Any time a measurement is taken, the bumpers are rotated off the testbed to ensure only the desired weight of the testbed and pod are transmitted through the load cell.

Forklift Slots

WASP features forklift slots to assist forklift operators when transporting WASP from one hangar to another. These slots were manufactured from rectangular sheets of 5/64" A36 steel that are welded into rectangular tubes and attached to the top members of the WASP frame via more welds, as seen in Figure 25.

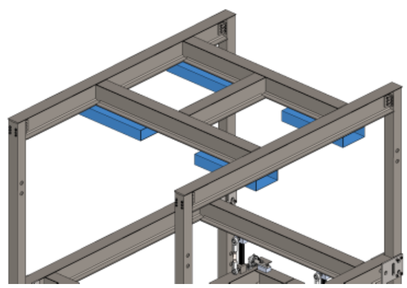

Figure 25: Forklift Slots (Blue) on the WASP Frame

Leg Leveling Mounts and Leveling Caster Wheels

WASP will be utilized in airplane hangars with concrete flooring that is not necessarily level. This poses a safety risk to the system, as the structural design was crafted under the assumption that WASP would be sitting on a level surface. Imagine sitting at a table with one leg that is shorter than the others. If the person on the shorter side pressed down, the longer leg would act as a fulcrum and tip towards the shorter side. This dynamic instability can pose a serious risk to both the WASP sensors and pod itself, not to mention any personnel nearby.

This problem was alleviated by installing leveling feet on all four legs of WASP. The legs of WASP are built out of hollow square tube, so a 3/8" A36 steel end cap plate will be welded into the bottom of the tubes. Prior to being installed onto the legs, the plates were drilled to provide clearance for a 1/2" bolt, and a 1/2"-13 hex nut was welded the interior side of the plate. the edges of the plate will be beveled to allow for the late to be welded to the legs. This is shown in Figure 26 below. In order to adjust these feet, WASP had to be lifted by a forklift and the lock nut on each leveling foot can be adjusted until the structure is determined to be level. Small deviations from level are accounted for via a rotation matrix in the CG equations.

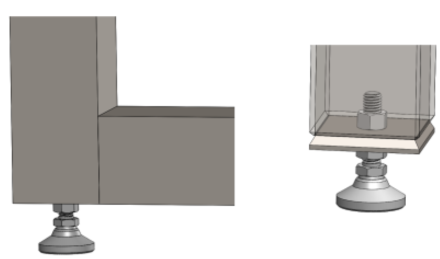

Figure 26: Leveling Feet Assembled (Left) and Transparent View (Right)

After the team toured the SNC facilities, it was made clear that the hangars that WASP will be deployed in are very crowded. The initial maneuverability plan of using a forklift was not practical in certain situations, such as maneuvering WASP within a hangar. Thus, the foot-design was finalized to support a substitution of the leveling feet with caster wheels that have an identical 1/2"-13 interface. These upgraded feet were installed two weeks before delivery to the customer. One concern with casters is that when WASP is performing a measurement with a pod attached, the caster wheels must be locked in some way to ensure that the structure is static. The caster wheels selected and installed, shown in Figure 27 below, feature built-in ratcheting leveling pads. These pads lift the structure off of the caster wheels when stationary and include adjustability to ensure the WASP structure is level. This solves the issues of leveling, maneuverability constraints, and inadvertent movement during testing all in one fell swoop. The leveling pads also have more surface area and a higher friction coefficient with common floors than the original steel levelers, creating a more dynamically stable structure.

Figure 27: Caster Wheels with Rubber Leveling Pads

WASP was delivered with the caster wheels installed. The original leveling feet were delivered as well, should the customer desire these replacements and/or found them to be better during testing.

3.2.4 Electronics

Electronics Hardware Flow

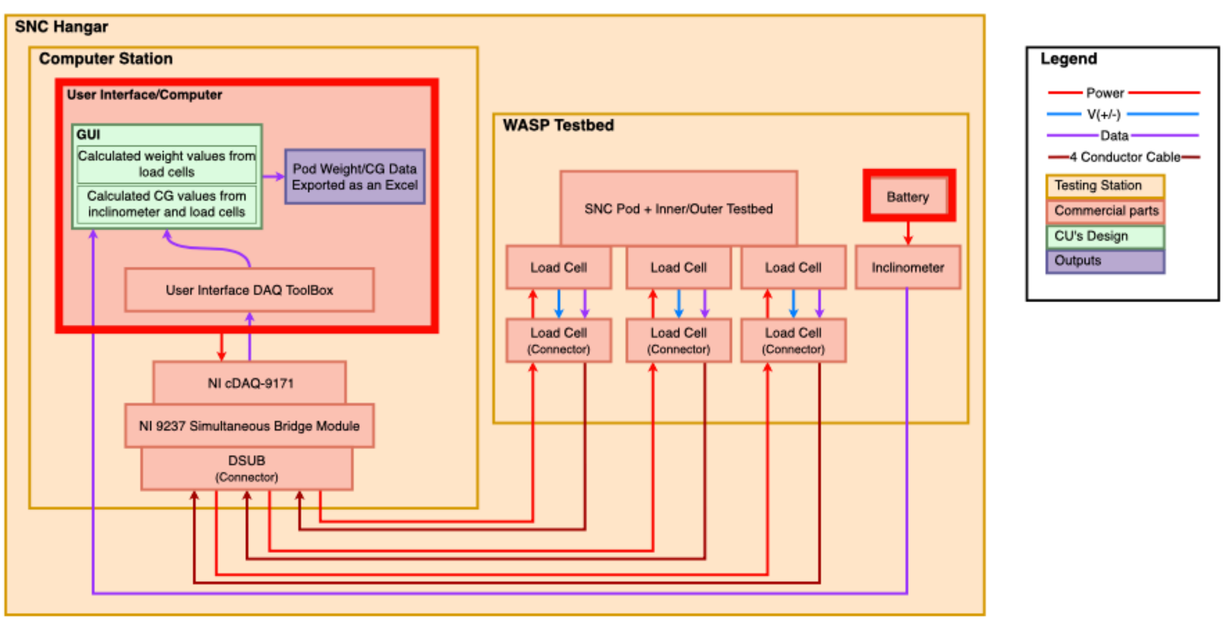

Figure 28: Functional Block Diagram of the Electronics

Shown in Figure 28, the electronics functional block diagram highlights the hardware flow of WASP. The red squares surrounding the computer and battery indicate the source of power for the load cells, inclinometer and DAQ system. Once the load cells are powered, weight from pod and outer and inner test bed will be distributed over three load cells. The voltage and data outputs will return to the DAQ system. The outputs go to the NI 9237 Bridge module. The NI 9237 Measurement system has signal conditioning and high sampling rate. Attached to the bridge module is the NI cDAQ 9171. The cDAQ controls the timing, synchronization, and the data transfer between the bridge module and the computer. Since the inclinometer is digital, data is collected from a visual readout and inputted directly into the computer. Data from load cells and inclinometer will be extracted and implemented into the graphical user interface (GUI). The GUI will be used to calculate the CG and weight data, display the data, and export the data to an Excel file.

Load Cells

Load Cell Selection Determination

The selection process for load cells considered the trade off between the allowable weight for the load cells and their accuracy capabilities. The intersection of solution space for each of these parameters for pod weights ranging between 200-2000lbs characterizes the solution space for the required load cells for this project.

First, the allowable pod weight ranges for load cell sets of full-span of operation (FSO) 500lbs, 1000lbs, and 2000lbs were computed. To do this analysis, the CG equations were back-solved to output the force seen on each of the three sensors for a specific pod weight and pod CG location. The maximum of this force multiplied by a factor of safety is understood to be the maximum force seen on single load cell. The pod is then deemed "weight allowable" for a load cell if the maximum force seen on single load cell is less than the FSO for the sensor. Figure 29 summarizes the findings for this analysis.

	Pod Weight Range Allowable		
Recommended Sensor Full-Span	FOS = 1.0	FOS = 1.5	FOS = 2.0
500 lbs	200-650 lbs	200-350 lbs	N/A
1000 lbs	200-1700 lbs	200-1000 lbs	200-650 lbs
2000 lbs	200-2000 lbs	200-2000 lbs	200-1700 lbs

Figure 29: Allowable Pod Weights for Various Load Cells

Second, the accuracy capabilities for the load cells were analyzed using a Monte Carlo simulation to predict the success rate of WASP capturing the weight and CG of the pod to the $\pm 0.1\%$ and ± 0.1 inch requirements, respectively. The analysis simulated random error in the load cells, angle measures, and measured lengths that were bounded by the manufacturer's given error tolerances. Initially, the bound was applied at one standard deviation away the mean of zero error, meaning that we would expect 68% of the simulated error to be between the given error bounds. This approach indicated that three sets of load cells with FSO of 500 lbs, 1000 lbs, and 2000 lbs would be required to span the full expected pod weight range of 200-2000 lbs. This information was presented at the Preliminary Design Review (PDR) for WASP, at which point the SNC customer indicated that they would like to purchase the 500-lbs and 1000-lbs sensors to enable the use of WASP for pods between 200-1000 lbs. Figure 30 summarizes the finding of the load cell solution space presented at PDR.

Legend
X = Weight not allowable (FOS=1.5)
< 90% Predicted Success
> 90% Predicted Success
> 95% Predicted Success

Customer confirmed →

	Load Cell Sensor Full-Span		
Pod Weight [lbs]	500 lbs	1000 lbs	2000 lbs
200	> 95%		
300	> 95%		
350	> 95%	> 90%	
400	X	> 95%	
500	X	> 95%	
600	X	> 95%	
700	X	> 95%	> 90%
800	X	> 95%	> 90%
850	X	>95%	>95%
900	X	> 95%	> 95%
1000	X	> 95%	> 95%
1100	X	X	> 95%
1200	X	X	> 95%
1300	X	X	> 95%
1400	X	X	> 95%
1500	X	X	> 95%
1600	X	X	> 95%
1700	X	X	> 95%
1800	X	X	> 95%
1900	X	X	> 95%
2000	X	X	> 95%

Figure 30: Load Cell Solution Space - PDR

Further research then indicated that this was a conservative assumption for the load cells, and that the random error should be modeled as being bounded by the manufacturer's given tolerances to 2.4 standard deviations (>99% error captured)[11]. It is important to note that the angle accuracy bounds used for this simulation is ±0.025 deg, from the Wyler Clinotronic Plus[12], and the length accuracy bounds used for this simulation are the manufacturing tolerances of ±0.040 inch. This change in load cell error simulation increased the predicted success rate for meeting accuracy requirements. Ultimately, Figure 31 summarizes the solution space for the load cells, indicating that it would be acceptable to use a load cell with an FSO of 1000 lbs for all pods weighing between 200-1000lbs. However, this change spurred by additional research occurred after SNC purchased two sets of load cells (FSO 500 lbs and 1000 lbs), so WASP will continue to recommend using the 500-lbs load cells for lighter pods.

Legend
X = Weight not allowable (FOS=1.5)
< 90% Predicted Success
> 90% Predicted Success
> 95% Predicted Success

	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%

Figure 31: Load Cell Solution Space - CDR

Load Cell Component Selection

The Omega LC103B-500 and LC103B-1K tension load cells have been chosen for their accuracy capability and competitive price. SNC has purchased a set of three of the -500 and -1K models of the load cell. Figure 32 depicts the Omega LC103B series load cell.

Figure 32: Omega LC103B Series S-Beam Tension Load Cell[1]

These load cells have an accuracy of ±0.02% FSO, meaning ±0.1 lbs for -500 load cell and ±0.2 lbs for -1K load cell, satisfying DR 1.1.1 and DR 2.1.1. The operating temperature is between -35°C to 65°C and a storage temperature between -40°C to 75°C. The safe overload capacity is 150% FSO and maximum overload capacity is 300% FSO. These load cells can operate with input voltage between 5V and 12V (DC), which is feasible with the USB-power source. Additional reasons why these load cells were chosen was for their interchangeability since the thread size is consistent for both models. Finally, these load cells are $208.00 each, which is desirable since six load cells are being purchased total.

Inclinometer

In order to measure the tilt angle of the inner testbed as well as the inherent tilt in the floor of the hangar, an inclinometer was proposed as a solution. The device will be installed on the lengthwise beam part of the inner testbed so that it can track the angle of the inner testbed. The inclinometer chosen is the Wyler Clinotronic Plus, owned by the customer and seen in Figure 33.

Figure 33: Wyler Clinotronic Plus Inclinometer

The Clinotronic Plus has an angle error of less than ±1.5 Arcmin which is about ±0.025 degrees, which surpasses the necessary accuracy requirement on the angle to meet the weight and CG accuracy requirements. This inclinometer can also measure up to ±45 deg, which is more than enough for the desired angle measurements. The Clinotronic Plus is powered by AA batteries and as long as they are replaced as recommended, power will not be a concern. This inclinometer, however, is a digital inclinometer which means the angle readouts will have to be inputted directly into the user interface by the user as opposed to working autonomously. The subsequent GUI design that addresses this issue will be discussed in the User Interface section. The angles that will be input into the GUI is the floor tilt angle as well as the testbed angle for the tilting phase.

DAQ/cDAQ System

WASP requires a data acquisition system to facilitate data collection from the load cells. The chosen DAQ system will utilize the NI cDAQ 9171 CompactDAQ Chassis (Figure 34) and the NI 9237 DAQ Bridge Module (Figure 35) that will interface with the load cells.

Figure 34: NI cDAQ 9171 CompactDAQ Chassis

Figure 35: NI 9237 DAQ Bridge Module

Some of the key specifications for the NI cDAQ 9171 are the FIFO size, timing accuracy, and timing resolution. This CompactDAQ Chassis has a reported FIFO size of 127 samples, a timing accuracy of 50 ppm of the sample rate, and a timing resolution of 12.5 ns [13]. The key specifications for the NI 9237 bridge module that was selected are its sampling rate and signal conditioning abilities. This DAQ samples at a rate of 50 kS/s, and uses 8th order filtering to condition the signal [14]. Since we are measuring the static load of the pod weight, we will not need to capture transient signals. Therefore, all of the timing and sampling specifications should be more than sufficient for our purposes. Similarly, the 8th order filter will be able to remove noise from the signal. In conjunction with our analysis on random error from the Monte Carlo simulation, these two data acquisition components will be sufficient for obtaining data from the load cells.

The cables from the three load cells will interface with the NI DAQ Bridge Module via a DSUB-37 connector, which will itself be installed in the CompactDAQ chassis. The chassis will interface via USB to the computer running the UI. The computer will have installed the necessary drivers and NI MAX application, which can then be used to configure the operation of the DAQ system.

3.2.5 Software

User Interface

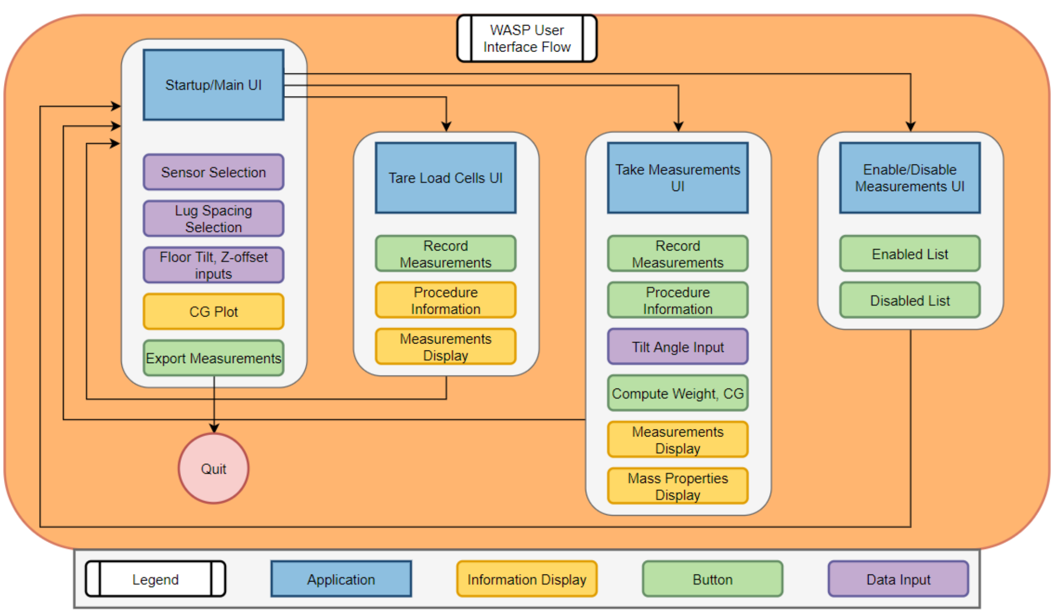

Figure 36: WASP GUI Flowchart

The WASP GUI is designed to flow with the normal operating procedure of WASP. Each of the applications packaged in the GUI is complete with diagrams and descriptions that remind operators of the procedures that must be carried out at each step, though it is not a complete procedure and should not be used in lieu of the user manual.

Main Menu

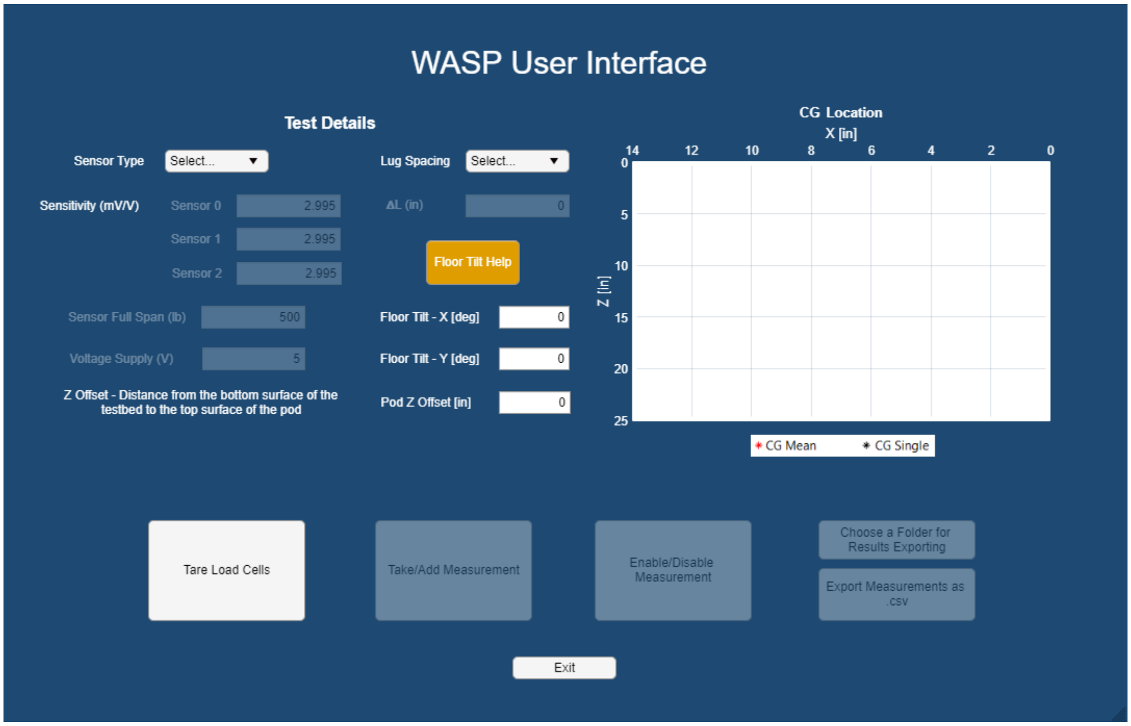

Figure 37: WASP GUI Main Menu

The main menu of the GUI houses buttons that open the three applications on the right, whose closure returns the user to the main menu, as well as important information about the test being performed. Upon startup, the user will select the sensor type, lug spacing used, and measure the floor tilt angle. After doing so, the user will then tare the weight of the testbed using the tare load cells application, at which point they will return to the main menu. When the desired pod is mounted to the testbed, the z-offset is measured and input into the proper numerical test box. Thereafter, the take measurements application will be used several times to record an array of measurements. Each of these measurements and the mean will appear on the CG plot, whose axes change depending on the lug spacing configuration. After a measurement is taken, a measurement may be disabled using the enable/disable measurements application, though it is not necessary to do so. After taking a measurement, the user has the option to export measurements as a .csv file to a desired folder, at which point the GUI will close, and the application ends. It should be noted that the buttons for the take measurements application, enable/disable measurements application, and exporting are disabled until the testbed has been tared (for take measurements) or a measurement had been taken (for enable/disable measurements and exporting).

Tare Load Cells Application

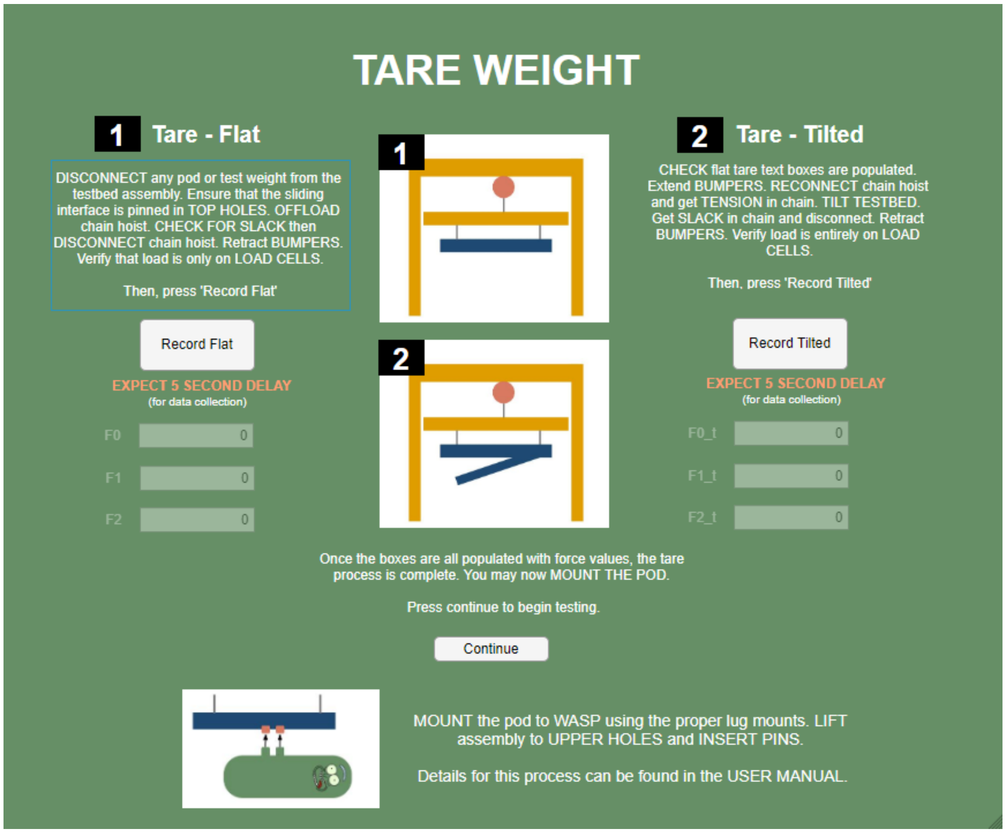

Figure 38: WASP GUI Tare Load Cells Menu

This application has two main buttons, 'Record Flat' and 'Record Tilted,' which use back end scripts and the MATLAB Data Acquisition Toolbox to take measurements from the load cells when no store is attached. The data on load cell sensitivity, full span of operation, and voltage supply is communicated from the main menu application on tare application startup. The average value of the force (in lbs) measured by the load cells during three seconds of sampling are displayed in the text boxes below the buttons. Diagrams and helpful explanations of the tare process are included as a reminder for operators. When the continue button is pressed, the data collected is returned to the main menu for later use.

Take/Add Measurements Application

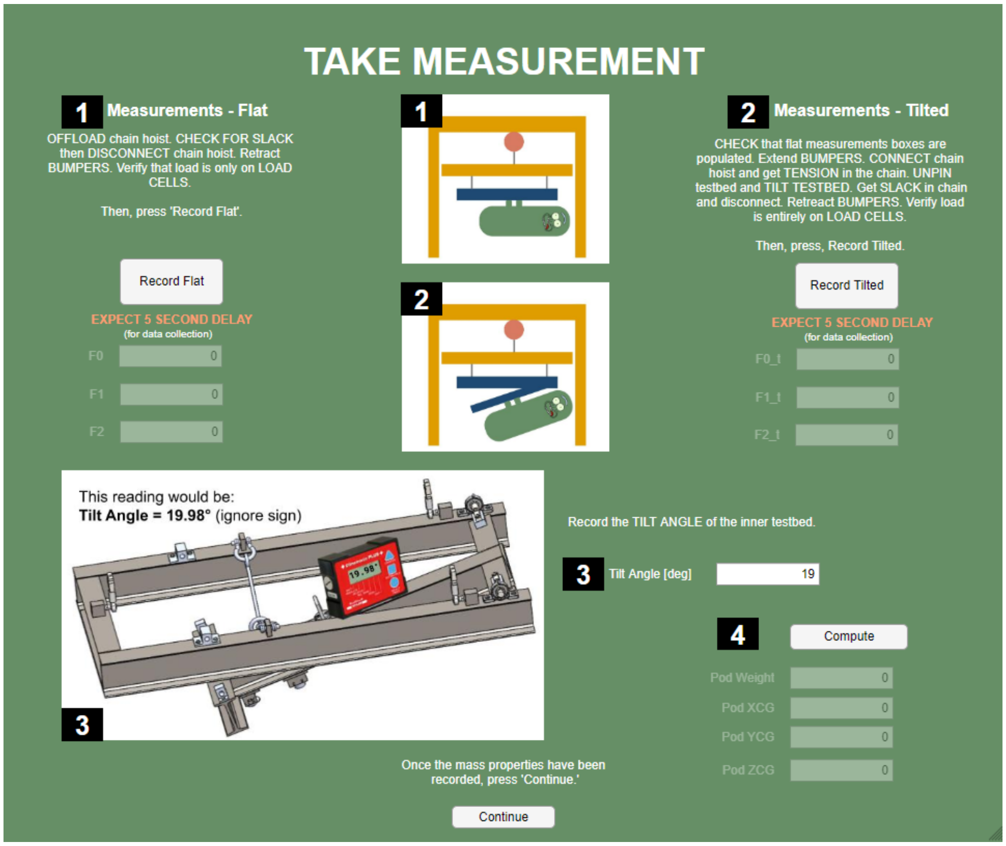

Figure 39: WASP GUI Take/Add Measurements Menu

The take/add measurements application is very similar to the tare weight application, though a bit more involved on the back end. When the application is first opened, the main menu application sends it the measurements from the tare process as well as the lug spacing, floor tilt values, and Z-offset. Similar to the tare weight application, there are two buttons for recording the load measured by the load cells, and in fact, the same back end script is used in both applications. After recording flat and tilted measurements, the user should input the tilt angle measured during the tilted measurement. When the compute button is pressed, the tilt angle is used in conjunction with the values that were sent to the take measurements application by the main menu application to compute the weight and CG of the store. This information is then displayed in the subsequent text boxes. When the user is satisfied with the measurement, they press continue and the weight and CG data is returned to the main menu application for plotting and exporting.

Enable/Disable Measurements Application

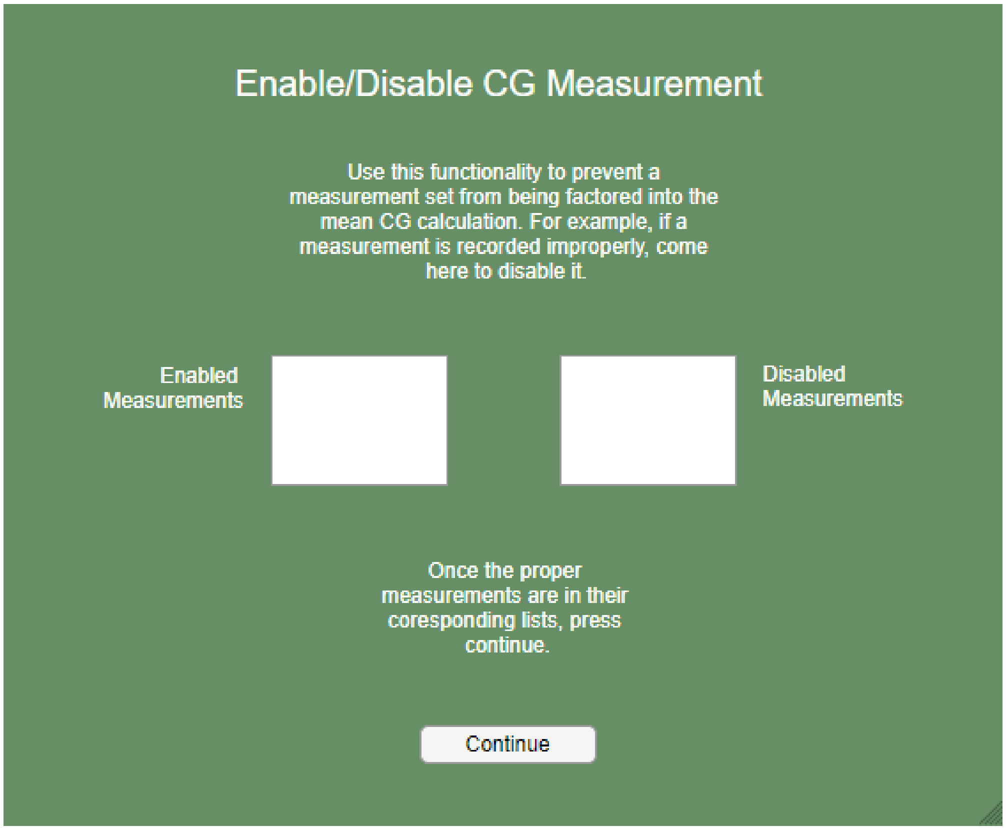

Figure 40: WASP GUI Enable/Disable Measurements Menu

This is the simplest of the applications in the WASP GUI. When it is launched from the main menu, it is given the data from all measurements taken since the start of the test. These measurements then populate two lists, enabled or disabled. By default, a new measurement is always enabled. If a measurement is moved from the enabled list to the disabled list, the data will remain from the measurement, but it will be flagged in the main menu as disabled, and it will not appear on the CG plot, nor will it be included in the calculation of the mean of all measurements. When the application is closed, the measurements in each column are flagged in the main menu as enabled or disabled accordingly.

After the measurements are taken and enabled as desired, the user can select a directory to export all collected data (including disabled measurements, still flagged). When data is exported, the application is closed, so data should not be exported until the test is complete and a sufficient number of measurements have been taken.

3.2.6 Safety

In order to prevent the incorrect usage of WASP, certain visual checks and human factors were taken into consideration. The items implemented can be seen described in Figure 41. Team safety during manufacturing and testing was also of the upmost importance. The safety subteam designed a procedure each team member must partake in when operating or working on WASP. This includes safety gear, correct usage, and protocols for electronics.

Visual Check	Implementation	Problem designed to solve
Color Coding and Numbering Pins and Pinholes	All done based on pin type not amount of pins	Preventing pins getting mixed up and misused
	Leg to Beam Pins - red	These pins need to be removed and inserted constantly through normal operation, red to mean "remove"
	Beam to Plate pins - black	These pins are only to be removed during maintenance, black decided upon to not catch the users eye
	Testbed pins - yellow	These pins are removed and reinserted during the tiltiing operation - yellow chosen to catch your eye but different than red so that the pins do not get mixed up
Graphic on testbed faces showing steps of operation		preventing operation performed in the wrong order
Warning/reminder on chain hoist attachment	Says "got slack"	to remind the user to offload the chainhoist before detaching it
Color Coding and Numbering the lug mount components	Coloring select locations on individual pieces that comprise a complete lugmount (pins, flanges)	to prevent the lug mount components from getting mixed up and loaded with the incorrect pod weights
	100lb lug mount - orange	
	1k lb lug mount - green	
	2k lb lug mount - light blue	
	tp lug mount - pink	
Color Coding the daq, wires, and load cell positions	Wire ends, daq ports, testbed force sensor attachments	preventing the wrong load cells getting plugged into the wrong location on the daq
	load cell 0 - yellow	
	load cell 1 - green	
	load cell 2 - light blue	
Labeling the load cells by their FSO	sticker on the load cell	preventing mixing up the load cells with each other as they all look identical
	500 fso - white	
	1000 fso - gray	
Adding hooks to the legs	welded to the side of the leg within reach	preventing misplacing the beam to leg pins
Adding "no push" signs to the testbed	Magnetic signs on WASP	preventing non-axial forces on the load cells
3D printed pin ends	cap that covers the pin providing an extra step needed to remove them	preventing maintenance only pins from being removed
Cable Management	White arrow direction from LC to DAQ. Velcro/Strap to secure cables to WASP frame. Color indication to match LC.	preventing cable damage and ease of use with LC and DAQ

Figure 41: Visual Checks Implemented

4 Manufacturing

Foster Greer, *Maddie Dube, Adam Elsayed, Matt Zola, Samuel Felice, Parker Simmons, Emma Markovich, Bailey Roker*

4.1 Manufacturing Scope

WASP is a large structure, complete with many custom parts and weld jobs that the machine shop could not tackle alone. Due to this, most of the WASP team received Return to Research (R2R) access to the building as having a full team hands on was essential. When planning out the manufacturing process, it was key to assume that every task will take longer than initially thought. Each task was broken down into a table to determine the order of the tasks, who would perform the tasks (machine shop or team), how long each task would take, and which tasks are dependent on each other. Using this method, a precedence chart could be created detailing the. Once the chart was created, the task lengths as well as a two week margin could be built in. This led to the development of the official manufacturing timeline seen in Figure 42. The manufacturing process was projected to take seven weeks and one thousand man hours. All in all, the total manufacturing process took around eight weeks and around 970 person-hours. The careful planning, setting specific team member schedules, and having a strict timeline allowed manufacturing to end only slightly after the deadline, even after significant unforeseen delays were incurred.

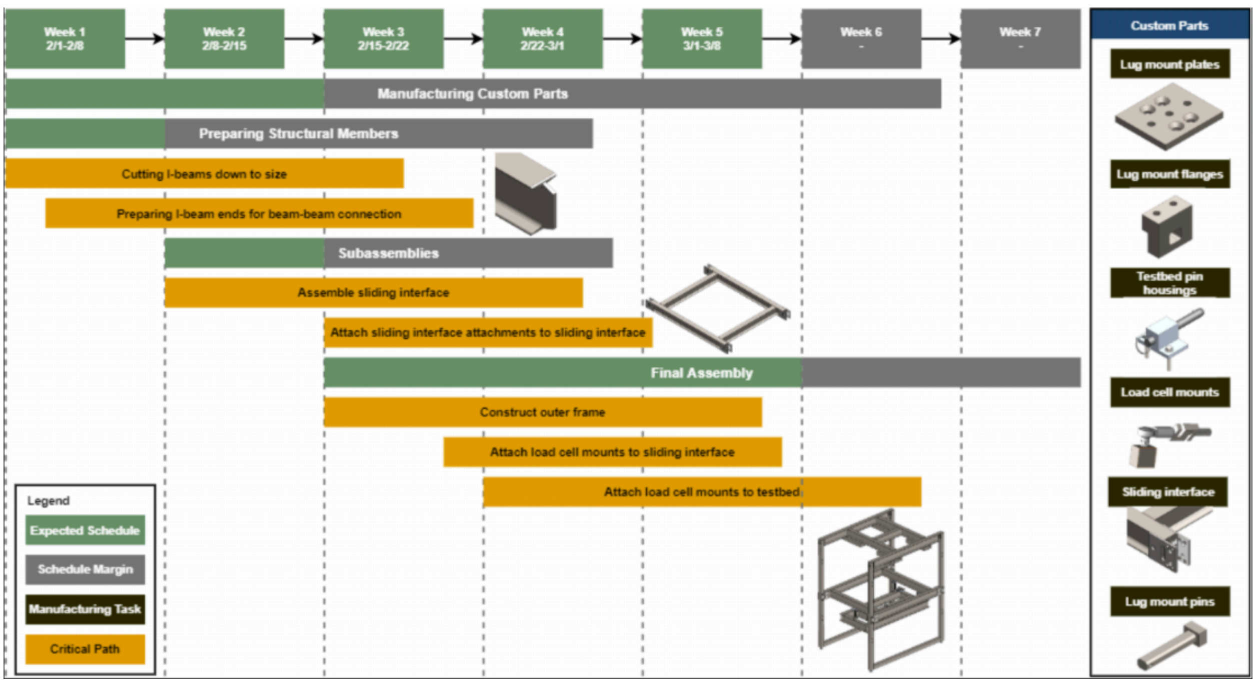

Figure 42: Manufacturing Timeline

4.2 Structural Manufacturing

Due to the mechanical nature of this project, structural part creation and assembly embodied the majority of manufacturing. Two months were dedicated to the fabrication of the WASP structure, which is shown completed in Figure 43.

After a two-week delay caused by R2R approval process, the manufacturing team spent approximately three weeks creating basic parts - this was mainly comprised of beam cutting and beam end preparation (Figure 44). Aerospace shop machinists completed smaller components sent by the team via a job-shop model. This included the lug mounts, pin housings, and other smaller custom components.

Figure 43: WASP Structure

Figure 44: WASP Beam Preparation

After part creation was completed, the assembly phase began. This is discussed in depth in Section 4.5, but at a high level this involved two phases: sub-assembly and full system assembly. Sub-assembly was comprised of welding and bolting beams and smaller components together, which led to the creation of the outer frame, sliding interface, and testbed (Figure 45).

Figure 45: WASP Frame Side and Sliding Interface During Subassembly Stage

Assembly was the final step of putting these three major components together, after which testing began. The outer frame and sliding interface are shown being assembled in Figure 46.

Figure 46: WASP Frame and Sliding Interface Being Assembled

4.3 Electrical Manufacturing

The electrical manufacturing for this project focused on wire harnessing between the data acquisition system and load cells. Two harnesses were designed with four different types of point of contact: wire connection to data acquisition system, data acquisition wire crimped to an intermediate connector, wiring connected to the load cell, and wiring from the load cell crimped to the intermediate connector. Harnesses were designed based on load cell harnessing requirements (4 wires). A schematic to show harnessing is shown in figure 47

The load cell came with an attached 6m cable, so only crimping was needed to complete the load cell harness. The 4-pin female connectors were used on the load cell free ends (Figure 48). The data acquisition harness required soldering intermediate connecting wires to a DSUB-37 connector, then collecting four wires to form the male component of the load cell connector. This harness was encased in a protective backshell both for strain relief and ease of use (Figure 49). Wiring was used from the AES facilities.

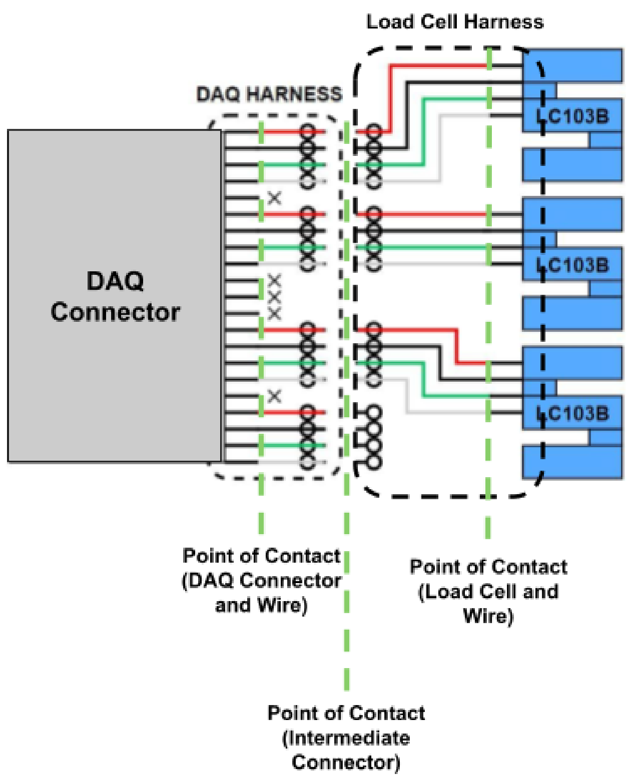

Figure 47: WASP Load Cell/Data Acquisition Harnessing

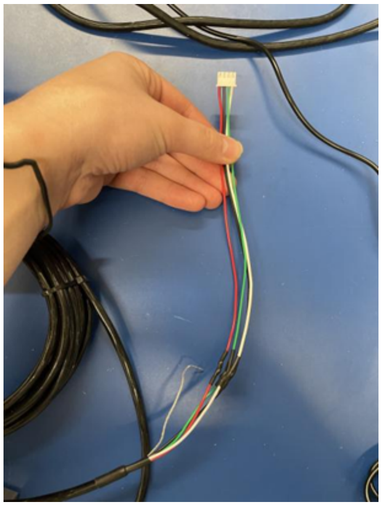

Figure 48: Load Cells to Female 4-Pin Connector

Figure 49: DAQ to Male 4-Pin Connector

4.4 Software Development

The software for the GUI and the back end scripting was all done in MATLAB and the MATLAB App Designer.

Software development for this project was largely done organically, without significant planning beforehand, as the GUI is quite simple. The back end scripting was developed first, to ensure the functionality of the DAQ system and the capability for the team's system to communicate with the load cells. The equations used for computing the mass properties from the measurements were developed even earlier to analyse potential error via the Monte Carlo simulation. The GUI was developed on top of these functions, with additional functionality and bug fixes being added as necessary during the course of operations.

4.5 Integration

With the manufacturing of many different components throughout the structural manufacturing, electrical manufacturing, and software development, integration of each component into a full functioning system was necessary. Due to the amount of manufacturing that was completed on this project, components were grouped into larger subsystems.

Structural subsystems were broken into the frame, sliding interface, outer testbed, and inner testbed. To integrate these systems together the sliding interface was initially installed into the frame of the structure. This can be seen in Figure 50. To ensure correct sliding functionality, sliding braces were created aboard the sliding interface. This allowed for the sliding interface to move up and down the legs of the frame uniformly. A chain hoist was next integrated into the system to allow for the movement of the sliding interface.

Figure 50: Sliding Interface Integration

The next step in integrating the structural subsystems revolved around the combination of the inner and outer testbed. To complete this, axle bearings were implemented at the end of the outer testbed to allow for the inner testbed to rotate. This can be seen in Figure 51.

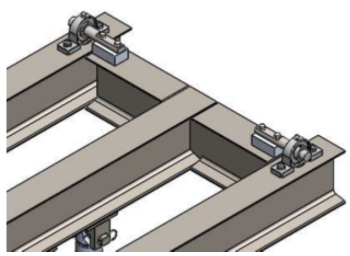

Figure 51: Inner and Outer Test Bed Connection

With the completed testbed, integration into the frame and sliding interface system was done via load cells. Three attachment points on the bottom of the sliding interface and three on the top of the testbed were created to allow the load cells to be installed and complete the integration of the WASP subsystems. The completed structure can be seen in Figure 43.

With this complete, the WASP structure was fully integrated with the exception of the software and electronics. Shown in Figure 52, the integration of the software and electronics can be seen. Designed in MATLAB, the GUI is first connected to the National Instruments Data Acquisition System via the user computer and USB. From there, the DAQ harness is used to connect to each of the load cells already integrated within the structure.

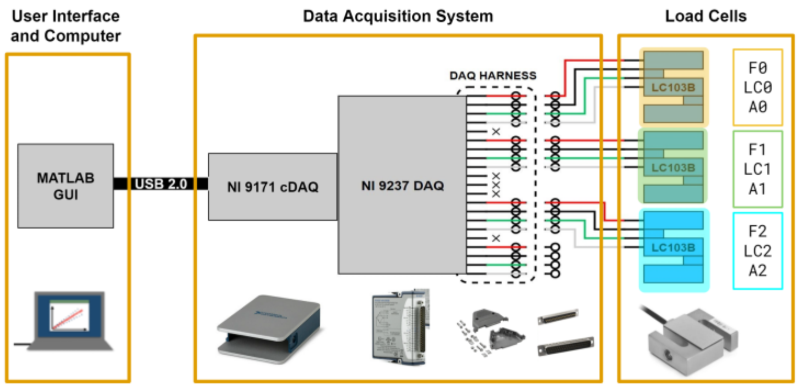

Figure 52: Electronics and Software Integration

4.6 Manufacturing Lessons Learned

Throughout the grueling manufacturing process, the team took valuable lessons of what was planned correctly and what could've been done better. The sheer size and structural integrity concerns of WASP's design presented a large scheduling concern; a significant amount of time was going to be needed to complete all of the different fabrication and assembly tasks, so scheduling and time management constituted the main concern for the manufacturing portion of this project. When the manufacturing was still in the schedule development phase, large margins and overestimates of task length were built in to allow for minor set backs. This was a crucial step that allowed the team to work through small issues as they arose, without impacting the schedule. Unfortunately, what was overlooked in this planning phase was considering a plan for when major setbacks occurred. Immediately from the start, the two week margin that had been built into the schedule was used up, as team members waited for access to the shop to be granted. After that point, any further disturbances to the schedule (such as not knowing the schedules of the shop machinists or experiencing difficulty with the functionality of the sliding interface) would cause delays further down the line, and impact other aspects of the project, such as testing. In the future, it is important to realize that if the entire schedule margin is taken up early, it would be beneficial to try to work a new, additional margin into the schedule. It is important to always expect small delays to occur as unforeseen issues arise. One beneficial strategy the WASP team found useful in handling this time crunch, and ultimately being successful, was creating a very strict manufacturing schedule for each person that was designed for at least two team members to be in the shop from 9am to 4pm. Each schedule was equipped with a time sheet that allowed the manufacturing hours for each person to be recorded on a weekly basis. This provided close monitoring of how the team's weekly hours contributed to the overall hour based estimate of the completion of WASP.

Moving away from simply schedule-based issues, there were many other lessons that were learned throughout this process. One was how to communicate and order parts from the machine shop staff. Many intricacies of how this works were learned. As an example, we realized that asking for tight tolerances on a part where it wasn't needed would only delay the fabrication of a part and waste time. Especially on a time-constrained project, allowing for looser tolerances on less critical parts can be very beneficial.

The last lesson that some team members learned the hard way was to always keep safety in mind. With most members of the manufacturing team putting in at least thirteen hours a week (some spanning up to thirty hours), comfortability gained with the machine tools proved to be a detriment. A healthy fear of the tools operated is necessary to avoiding injuries.

5 Verification and Validation

Adam Elsayed, Samuel Felice, Ansh Jerath, ***Aidan Kirby****, Bailey Roker*

5.1 Design Verification

5.1.1 Testing Scope

Level	Test	Model/Process Validated	Equipment/Facilities Used
Component	**Lug Mount Tensile**	FEM Model	Modified Lug Mount, EM MTS
	Load Cell Characterization	Monte Carlo Simulation	WASP Load Cells + DAQ System, EM MTS
	Component Checks	N/A	None
Sub-System	**E&S Functionality**	Software Flowchart	WASP DAQ System
	Structural Integrity	FEM Model	Weight, Strain Gauges, WASP DAQ System, AES Forklift
System	**Measurement Accuracy**	Monte Carlo Simulation	SNC Test Article
	System Accreditation	CONOPS	SNC Test Article, Volunteer Engineers

Figure 53: Overview of WASP Testing Scope

The design of WASP was verified through the systems engineering process, starting from the individual component level and working up to the full system accreditation. Each test was designed to verify that the component or system being tested performs well enough such that the following system can perform as needed. Due to time and budget constraints, it was not be possible to verify each and every component through testing (such as individual screws and bolts). Based on the critical project elements and preliminary analysis, the load cells and lug mounts were selected for further testing on the component level. Next, the electronics and software subsystem and structure subsystem were each tested independently. Finally, the entire integrated system was verified. Figure 53 shows the summary of all tests conducted on WASP, including the specific model or process being validated, and any specialized equipment that was necessary to conduct the test. Figure 54 shows the testing plan organized according to the project objectives. Each project objective is addressed by at least one major test, and in many cases more than one test to ensure these objectives were rigorously assessed. The structural integrity and measurement accuracy were identified as the most crucial and difficult project objectives, which is why those objectives are highlighted in gold. These areas are where most of the team's effort in testing and analysis were directed.

Project Elements	Level 1	Level 2	Level 3
Structural Integrity	Support 1000 lbs with FOS of 2.0	Support 2000 lbs with FOS of 2.0	
Mounting and Interfacing	Connect to 14" and 30" pod lug configurations		Modular Capabilities to connect future pod lug configurations
Measurement Accuracy	Measure weight within ±0.1% and X CG and Z CG locations within ±0.1"	Measure weight within ±0.1% and X CG, Y CG, and Z CG locations within ±0.1"	
User Interface	Measurement tool will output data to be manually entered into the software tool to perform calculations	Measurement tool will autonomously input data to the software tool to perform calculations.	The measurement tool will autonomously collect and analyze data and export results to an Excel-compatible file.
	The software tool will deliver the weight, X CG, and Z CG values averaged over at least 2 and up to 5 measurement sets	The software tool will deliver the weight, X CG, Y CG, and Z CG values averaged over at least 2 and up to 5 measurement sets	The software tool will deliver the weight, X CG, Y CG, and Z CG values averaged over more than 5 measurement sets
Test Operation	Test completed by 3 engineers	Test completed by 2 engineers	
	Test completed in 1 hour	Test completed in 0.5 hours	
	Test engineers will be able to successfully perform test with guide of engineer familiar to tool	Test engineers will be able to successfully perform test by following test procedure	
Transportation	Tool is maneuverable by 3 team members	Tool is maneuverable by 2 team members	

Figure 54: WASP Testing Scope Relative to Project Objectives

5.1.2 Load Cell Characterization Test

To ensure that the accuracy requirement for weight and CG will be met, it is important to verify that the accuracy of the load cells match what has been reported by the manufacturer. Thus, the load cell characterization test was devised.

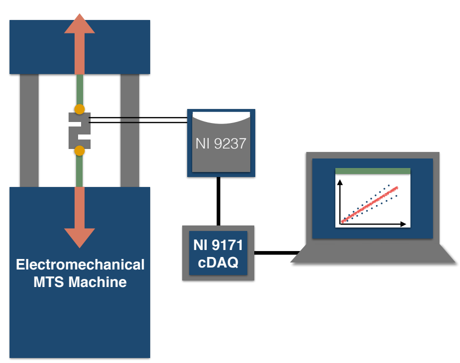

Figure 55: Load Cell Characterization Test Setup

This test is broken out into two portions. Firstly, the load cells are mounted into the CU Boulder AES department's electromechanical (EM) MTS machine. This tensile testing machine is programmed to load the sensor continuously in a linear fashion to the maximum rated load, then back down to zero load. While the test is being performed by the MTS machine, the sensor is connected to the NI 9237 bridge module, the NI 9171 cDAQ, and then to a laptop so as to record the load data sensed by the load cell. The highest sample rate possible (10 Hz) is used on both machines so as to collect as many data points as possible within a reasonable time frame. This process is repeated multiple times. This data is used to perform tests on linearity and sensitivity. The next test involves loading the load cells up to 20% of the full span of operation and recording load data for one hour to examine the impact of drift on the measurements.

Sensitivity and Linearity

The applied load versus sensor output results were analyzed for their implications in the characterization of the load cell linearity and sensitivity. Figure 56 plots the applied load as sensed by the MTS machine in lbs versus the load cell output in V/V.

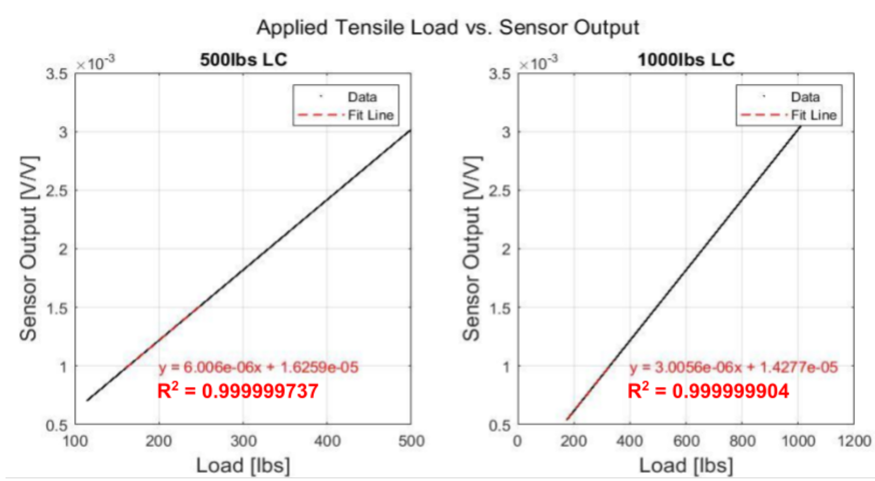

Figure 56: MTS Applied Load vs. Omega Load Cell Output Plot

The linearity results, summarized in Figure 57, confirm that the load cell response is highly-linear. This retires risk in the load cell accuracy category and supports the manufacturer's reported error specifications. Moreover, this test was used to confirm the validity of using the manufacturer's provided sensitivity value. Figure **??** summarizes the sensitivity characterization for the 500-lb and 1000-lb load cell by comparing the expected slope (conversion factor) and the one detected in the test. Importantly, the combined uncertainty between the MTS machine and Omega load cells is 0.07% of the applied load. The discrepancy between the expected and actual sensitivity values was less than this uncertainty bound, so the team has no reason to believe the manufacturer's sensitivity specifications are incorrect. Therefore, the manufacturer's sensitivity values were used moving forward in the computation of sensed loads.

Load Cell	Y-Intercept	Slope	R-squared value
500-lb	16.259 [μV/V]	6.006 [V/V]/lbs	**0.999999737**
1000-lb	14.277 [μV/V]	3.006 [V/V]/lbs	**0.999999904**

Figure 57: LCC - Linearity Results

Load Cell	Sensitivity (mV/V)	Expected Slope ([μV/V]/lbf)	Measured Slope ([μV/V]/lbf)	Difference (% load)
500-lb	2.9980	5.9960	6.006	**0.056 < 0.07***
1000-lb	3.0024	3.0024	3.006	**0.040 < 0.07***

*expected combined accuracy of MTS Machine (0.05%) and Omega load cell (0.02%)

Figure 58: LCC - Sensitivity Results

Drift

The results of the drift test are displayed in the Figure 59. A breakout of the takeaways is found in Table 6.

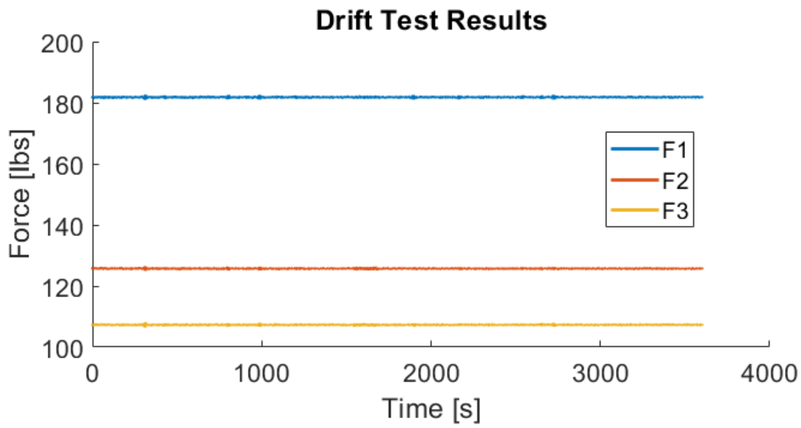

Figure 59: Drift Test Data

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Table 6: Load Cell Characterization Summary

Error Source	**Magnitude**	**Comments**
Load Cell Combined	0.02% FSO	Normal distribution with σ = Magnitude/2.4
Load Cell Temperature Drift Error	0.002% FSO	Drift error applied to both zero offset and sensor output

Ultimately, because the total drift seen in an hour is less than 0.005% of the FSO of the sensors, it is determined that drift is not a concern during the allotted 60 minute testing time. Based on the results of this test, it is determined that there are no identifiable problems with the purchased load cells, which could inhibit the accuracy of WASP specified in DR 1.1 and 2.1, which state that WASP must measure the weight and CG of pods within ±0.1% and ±0.1" respectively. These DRs will be fully assessed on the system level in the Measurement Accuracy Test.

For Load Cell Characterization Test data files, see the project archive T-5 LCC. For the final test procedure, see T-9 Official Test Procedures.

5.1.3 Lug Mount Tensile Test (LMTT)

The 2000-lb class lug mounts were predicted to have the lowest safety factor on the entire structure, with a conservative finte element analysis (FEA) predicting safety factors as low as 1.5 (Figure 60). DR 3.1 states that all structural components shall have a safety factor greater than 2.0 against yield for the heaviest possible loading conditions. As a result, the team manufactured an additional 2000-lb mount that was tested until failure in the Lug Mount Tensile Test.

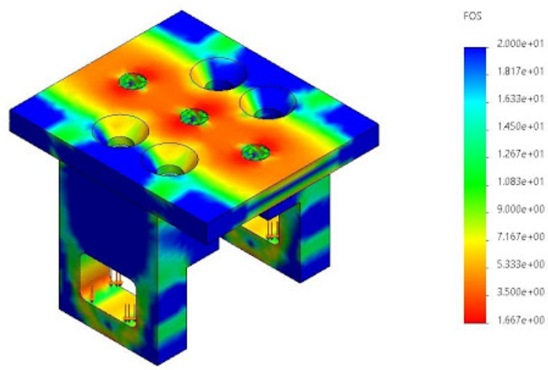

Figure 60: Most Conservative Analysis of a 2000lb Lug Mount

This test required use of the electromechanical MTS machine in the AES department at CU. The mount was clamped on one end via a bolt while the lug pin was inserted through the mount flanges and clamped on the other end via a bolt that went through the pin itself, as shown in Figure 61. Note the testbed simulant piece; this component was introduced to simulate the inner testbed beam to replicate the actual loading that the mount will see in operation. This test simulates a level loading scenario, where the lowest safety factor against yield was predicted to be 1.7 based on the FEA model (Figure 60). Although this does not capture the most critical loading scenario (tilted pod), it can be used to validate the FEA models and boost confidence in the predicted factors of safety.

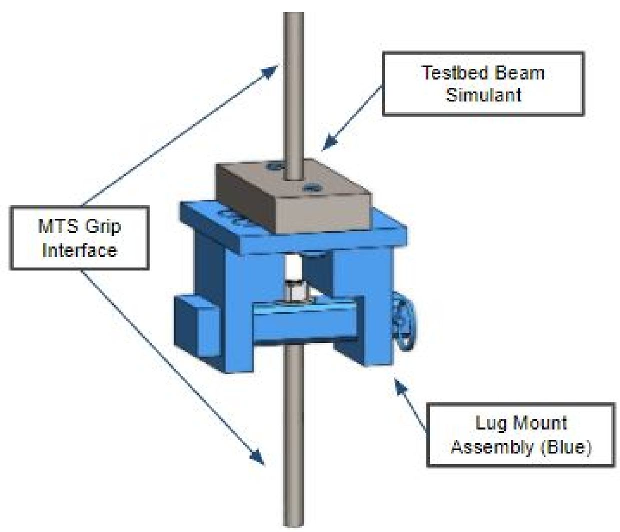

Figure 61: Clamping Setup for the LMTT

Force and time data were collected from the MTS machine software throughout the test, during which the specimen was loaded in tension until the failure of the interface bolts (Figure 62). Yielding and failure were analyzed and compared with the FEA model. The component failure is visualized in Figure 62.

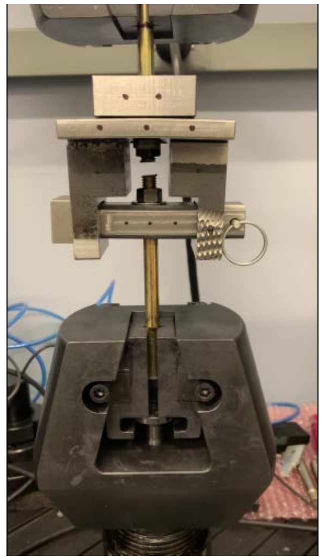

Figure 62: End of Lug Mount Tensile Test

Figure 63 portrays the force-displacement graph measured by the MTS machine during the LMTT.

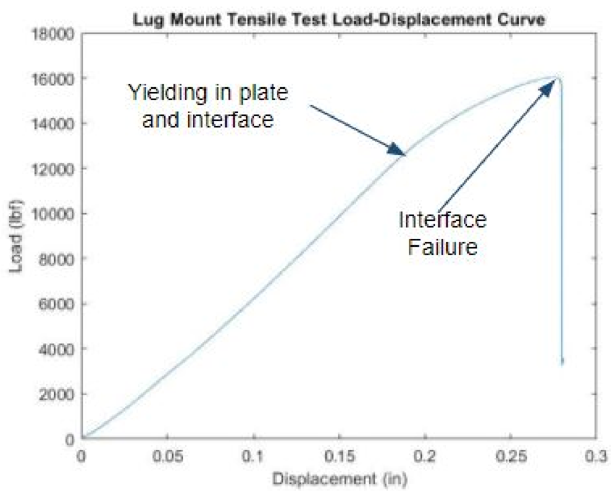

Figure 63: Force-Displacement Measurements from the LMTT

This graph shows that yielding does not begin in any part of the structure until subjected to 13,000 lbs of tensile load. Close inspection of the video recorded during this test reveals that at this point, the top plate of the lug mount began to bend (as predicted by the finite element analysis shown above). However, there is a large discrepancy between the predicted yield load (3,400 lbs. - 6,000 lbs.) and experimental one (13,000 lbs.). Although unexpected, it became clear after investigation that this discrepancy should not have been surprising. There are various limitations of finite element analysis that resulted in the overprediction of stress. First off, the model assumed the bolt holes in the top plate were fixed in place. However, these are nothing but clearance holes for bolts being driven into the testbed. In reality, they can displace as needed to keep the mount in its lowest energy state possible, given the loading. If actually fixed, as predicted by the FEA, very large amounts of stress would concentrate in the region around the holes (as seen in Figure 60). Also note that the SolidWorks FEA model assumes that the entire lug mount is one fused piece of metal. In reality, it is an assembly, connected by bolts. Thus, sharp corners (which in a single part would be locations of high loading) were much less susceptible to stress concentrations. Along the same lines, the lug mount flanges and associated bolts have some finite surface area that provides reactions, which prevents the top plate from bending as quickly. All of these factors came together to make the mounts much safer than originally expected.

It is interesting to note that a simple bending analysis of the top plate resulted in a safety factor of 3.2 (expected failure load of 6,400 lbs.). Even this analysis was overpredicting stress, despite the fact that it did not incorporate holes in the plate. Again, this was due to the fact that the load on the plate was not a point load, but a distributed load across the flange connection bolts, and that the flanges provided increased stiffness and internal reactions that prevented plasticity until much higher loads than expected.

This test was used to verify FR 3 (and address CPE 1) for the lug mount specifically. An experimental safety factor of 6.5 was calculated, making it clear that this sub-assembly can safely handle the expected loads of 2000 lbs. or less.

For Lug Mount Tensile Test data files, see the project archive T-4 LMTT. For the final test procedure, see T-9 Official Test Procedures.

5.1.4 E&S Functionality Test

Confirming the core functionally of the electronic hardware and software being used by WASP is required before the measurement accuracy test can be performed (which requires measurements to be taken from the load cells using the hardware and software). This test includes confirming DAQ system compatibility with the computer and load cells, as well as extracting data measurements from three load cells simultaneously.

To set up the test, a computer with the required scripts to connect with the NI 9171 cDAQ and the NI 9237 bridge module is needed. Once obtained, the NI 9171 was attached to the computer and the NI 9237. Then, the load cells were added into the system to start testing. For best testing practices, testing the load cells was done using an iterative process. First, one load cell was soldered to the bridge module and testing was done to confirm data extraction was successful. Then, each successive load cell was connected and tested until all three load cells were shown to work simultaneously. As shown in Figure 64, the three arbitrary load cells had to be compatible with the NI 9237 and feature the same 4 conductor-cable format as the LC103B load cells. While accuracy is not important for this test, acquiring data that makes sense is necessary. This includes differentiating tension and compression forces applied to the load cells, which can be applied by hand. The NI 9237 bridge module uses a DSUB-37 connector to read in power and data lines from the load cells. These lines were soldered to the DSUB-37 connector in the correct configuration. Once configurations were complete, the scripts on the computer collected data for a specific amount of time (3 seconds). During this window of time, forces were applied to the load cells. All load cells saw a fluctuation in force output to confirm real time data. When testing two or more load cells, force output would fluctuate for all load cells to confirm data is extracted by the computer simultaneously.

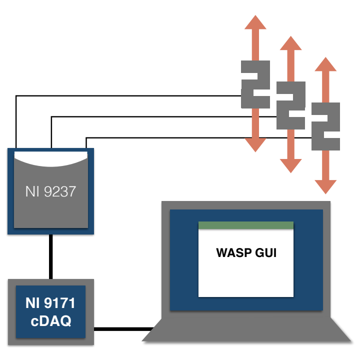

Figure 64: E&S Functionality Test Setup

Testing was done in the electronics lab in the Aerospace Department facility. The DAQ system WASP will used for all testing is stored in this lab. Soldering tools are provided by the lab so the team can connect the power and data lines on the load cells correctly to the NI 9237.

The software for this test can be outlined in four steps: initialization, data collection, averaging, and graphing. Using MATLAB software and toolboxes, the ES functionality script can NI bridge module configurations. For this test, the NI 9237 bridge module uses the full-bridge configuration for all load cells attached. The script is designed to configure all ports on the bridge module. Next, the data collection time period is defined in seconds. The script is ran and data is collected. Once data is returned, equations for converting voltage values into force values are used. This data is averaged and graphed.

For the final test procedure, see T-9 Official Test Procedures.

5.1.5 Structural Integrity Test

The objective of the Structural Integrity Test is primarily to address design requirements 3.1 and 3.3, which state that WASP must have a safety factor of 2.0 against yield for the heaviest pods of 2000 lbs. and be able to lift pods out of their cradles. While the dynamic loading caused by the chain hoist has already been shown to be negligible, the configuration the WASP is in during lifting is of particular concern; the pod, testbed, and sliding interface are all primarily supported by the chain hoist because the sliding interface cannot be pinned into the legs while sliding up and down. In Figures 65, 66, and 67, heatmaps of the testbed assembly from the FEA model are shown in all three loading configurations experienced by the structure during regular operation.

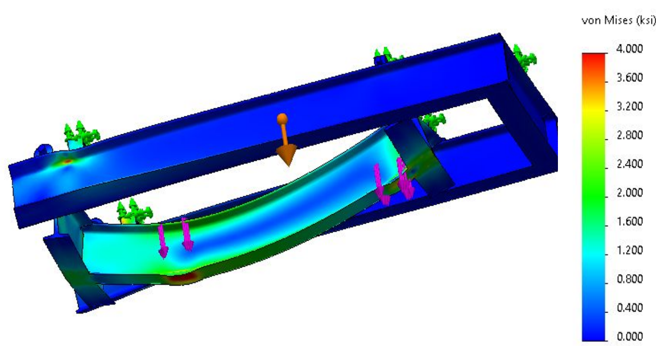

Figure 65: Testbed Assembly in Level Configuration Under 2205 lbs. of Load

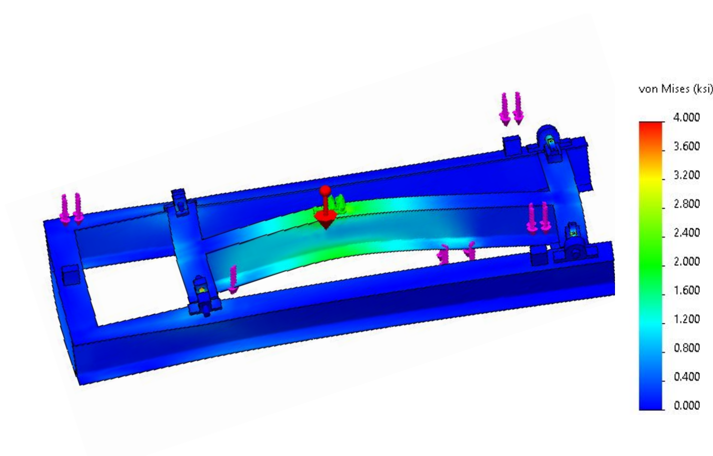

Figure 66: Testbed Assembly in Transient Configuration Under 2205 lbs. of Load

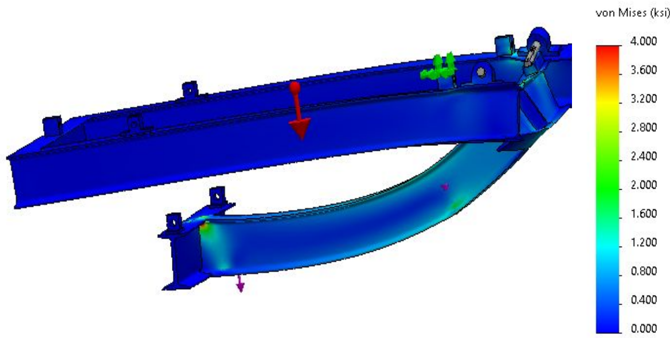

Figure 67: Testbed Assembly in Tilted Configuration Under 2205 lbs. of Load

To test the integrity of the structure, a 1,300 lb. steel tabletop was attached to WASP via chains running through the 2,000 lb. class lug mounts. Then, steel blocks were incrementally loaded onto the weld table until a combined load of 2,205 lbf was applied to WASP. This process was performed for each configuration shown in Figures 65, 66, and 67. The setup for this test is shown in Figures 68 and 69 for the level, pinned scenario.

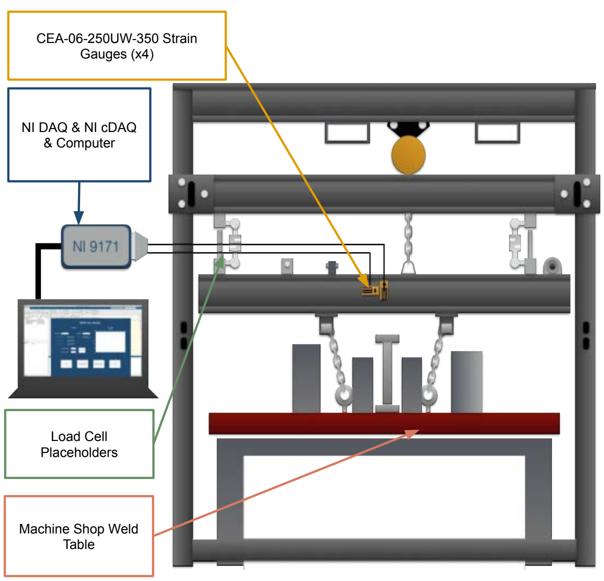

Figure 68: Structural Integrity Test Setup

Figure 69: SIT In Action

A type II full bridge of CEA-06-250UW-350 strain gauges was placed on the center of the inner testbed to measure the bending strain for each loading configuration. The expected Von Mises stress values, and corresponding safety factors at this location is shown in Table 7 for the maximum applied load in each configuration according to the SolidWorks FEA model.

Table 7: FEA Predicted Stress and Factor of Safety at the Center of the Inner Testbed

Configuration	Von Mises Stress [psi]	Safety Factor
Level	385	93.5
Transient	971	37.1
Tilted	223	161.4

The results of this test are shown in Figure 70. Each plot shows the applied load to WASP in pounds on the horizontal axis, and stress at the center of the inner testbed in pounds of force per square inch (psi) on the vertical axis. The measured bending strain values from the strain gauge bridge were converted to stress using Youngs Modulus of the A36 Steel (29,000 ksi), and these points are shown as the blue stars. A best fit line is fitted to this data in red, and the corresponding R-squared values are given below. The gold dashed line shows the predicted stress from the FEA model at each applied load.

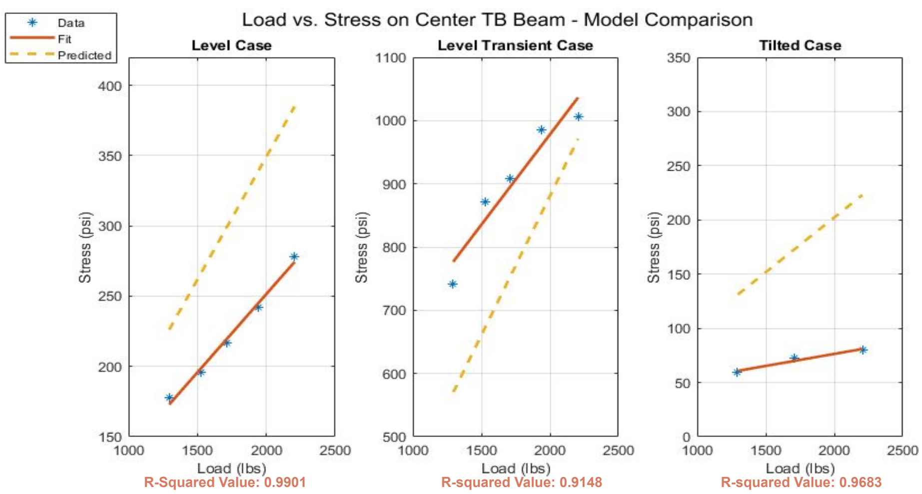

Figure 70: Structural Integrity Test Results

The data matches the trends of the model, but there are some noteworthy discrepancies due to some inherent limitations of the strain gauges and the FEA model. The type II strain gauge bridge measures bending strain but rejects axial strain [15]. This is especially apparent in the tilted case where the inner testbed saw a significant axial load during the trials that was not accounted for in the strain gauge measurements. Additionally, the strain gauges report average bending strain over the applied area, not strain at one specific point in space like the FEA model does. Generally, the conservative modeling techniques seen during the Lug Mount Tensile Test are carried over to the Structural Integrity Test. Fixed geometry between components causes increased stress near the junctions, which is not realistic because in reality there is some movement between different pieces (which alleviates this stress concentration). Therefore, the model tends to overpredict the stress, as seen in the level and tilted cases. An exception to this is seen in the transient case, where the model underpredicts stress. The largest contributor to this discrepancy is that the ballast weight added to prevent the Sliding Interface from jamming was not modeled in SolidWorks, and therefore not modeled in the FEA model. Since the transient configuration relies on the chain hoist to support the testbed assembly and the sliding interface, this added weight and moment would increase the bending stress on the inner testbed beam. Based on hand calculated estimates, shown in Equation 12 contribute roughly an additional 200 psi to the measured bending stress in the transient configuration only. As can be seen in Figure 70, this more than accounts for the discrepancy between the FEA model and the strain gauge data.

$$\sigma \; = \; -y\frac{M}{I} \;\longrightarrow\; \sigma \; = \; -(3\;in.)\frac{(24\;in.)(65\;lbs.)}{(23.2\;in^4)} \; = \; 201.7\;psi \tag{12}$$

Additionally, the transient configuration is particularly difficult to model using FEA. Because the actual load carried by the chain hoist in this configuration is unknown, the chain hoist attachment point on the testbed assembly was fixed in space, and the force sensor attachment points had the estimated distribution of the sliding interface weight applied to them (which does not include the ballast weight). In reality, these attachment points are more fixed in space, and the chain hoist would be unfixed because it is moving everything up and down. While this modeling is not far from reality, it certainly does not represent the actual loading scenario. Table 8 compares the predicted maximum stresses with the measured stresses at this location, along with the associated safety factors.

Table 8: Structural Integrity Test: Comparison of Predicted and Measured Safety Factors

Configuration	FEA Predicted FOS	Measured FOS
Level	93.5	129.5
Transient	37.1	35.8
Tilted	161.4	450

In terms of verifying DR 3.1; theres no way to ensure a safety factor of 2.0 everywhere on the structure without loading WASP to 4000 lbs. The interfaces between different components are difficult to predict using FEA (as explained above), which means that even if we validate the model overall, it cannot be fully trusted to estimate FOS everywhere. The only way to validate this requirement with complete certainty would be to load WASP to 4000 lbs. in each configuration, which was not feasible given the timeline and budget constraints of the project. The actual applied load of 2200 lbs. does ensure a FOS of greater than 2.0 for 1000 lbs. pods, which is currently the largest pod used by the customer, and the level 1 project objective. The 2000 lb loading scenario is ensured with a FOS of at least 1.1, but unfortunately could not be tested further. The measured strain gauge values can be extrapolated to predict the safety factor at this location under a 4000 lbs. load, which is shown in Figure 71.

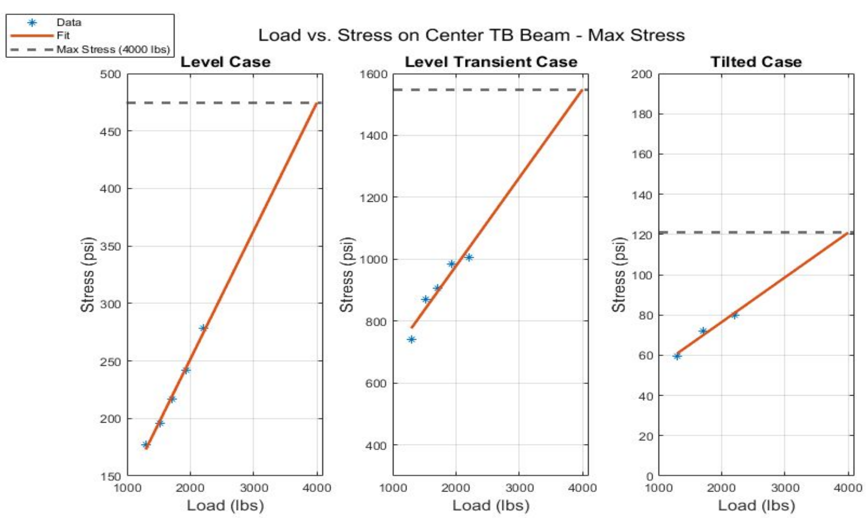

Figure 71: Structural Integrity Test Extrapolated Results

The worst-case scenario, the flat transient case, still gives a safety factor of greater than 23 at this location. This is high enough to where the limitations of the model and the measurements are not concerning, but again this only accounts for one particular point on the structure, not every location. This emphasizes the fact that there is no reason to believe that the structure would yield under 4000 lbs. load, but there were no means to physically demonstrate that it does. To mitigate this, the lug mounts were separately which had the lowest predicted safety factor on the structure. The Lug Mount Tensile Test showed that the model was overly conservative for that component and is no longer a structural concern. The relationship between the physical testing and the FEA model has also been demonstrated, which does predict a safety factor of greater than 2.0 everywhere on the structure. For this reason, the level 1 project objective is satisfied, but the level 2 project objective is left as open.

For Structural Integrity Test data files and analysis code, see the project archive T-6 SIT. For the final test procedure, see T-9 Official Test Procedures.

5.1.6 Measurement Accuracy Test

The Measurement Accuracy Test (MAT) was conceived to investigate and verify the accuracy capabilities of the tool. The test is designed to verify DR 1.1 and 2.1, which state that WASP must measure the weight and CG of a pod within ±0.1% and ±0.1" of the true values respectively. The setup for this test is shown in Figures 72 and 73. The model being validated in this test is the Monte Carlo Simulation, which compiled all given and measured error sources to predict the repeatability of satisfying these accuracy requirements. The Monte Carlo Simulation results for the given test article is shown in Figure 74 using 10,000 simulations. It is important to note that the lowest predicted success rate is the weight accuracy, because this test article is near the minimum of the pod weight range for WASP. Since load cell error is given as a percentage of the full span of operation, a lighter test article will have a higher ratio of error to weight.

This test consists of two phases, during which the operating procedure for the tool is followed to collect measurement sets for the CG for a test article. Phase 1 utilizes an unaltered test article in a forward and reversed configuration (Figures 75 and 76). Phase 2 utilizes an altered test article also in forward and reversed configurations (Figure 77 and 78). In both cases, the pass criteria is defined in terms of the consistency of the identified CG location for the forward and reversed configurations of the respective test article. Importantly, accuracy is evaluated at the single-measurement and single-test level. The single-measurement level considers each recorded measurement set to be independent, while the single-test level considers the average CG measurement between 3-4 measurement sets as recommended in the operating procedure.

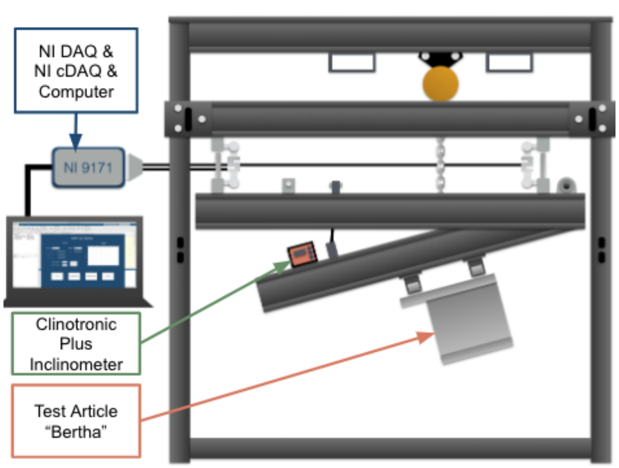

Figure 72: Measurement Accuracy Test Setup

Figure 73: MAT In Action

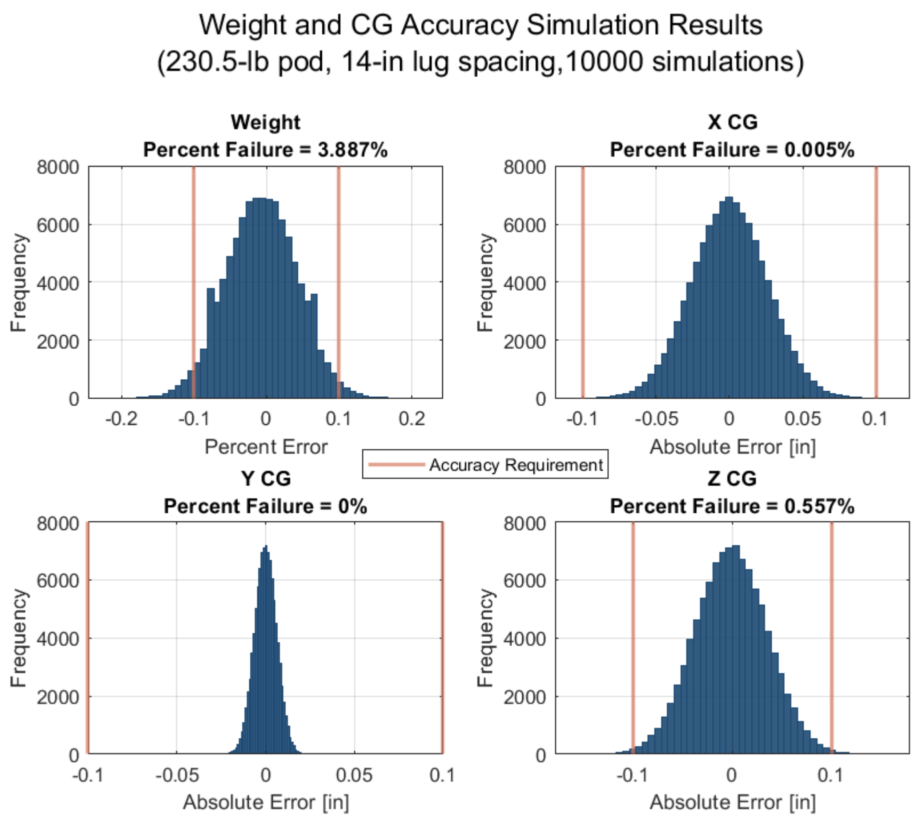

Figure 74: Monte Carlo Simulated Repeatability for the Test Article

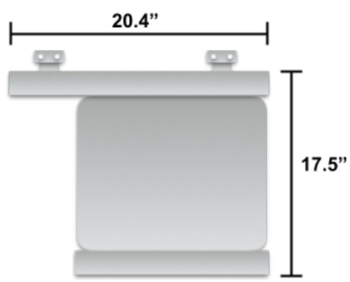

Figure 75: Unaltered Test Article (forward)

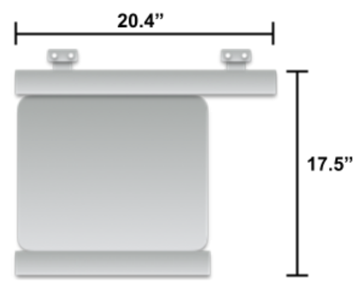

Figure 76: Unaltered Test Article (reversed)

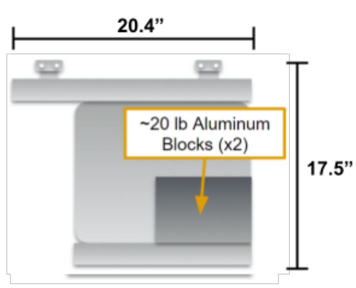

Figure 77: Altered Test Article (forward)

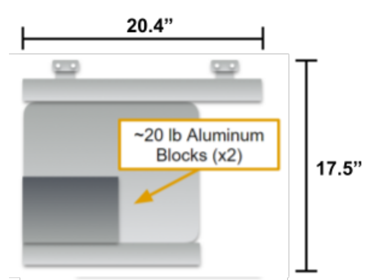

Figure 78: Altered Test Article (reversed)

The pass criteria for Phase 1 and Phase 2 of this test are equivalent and are summarized in Table 9. Employing the forward and reversed configurations of the test articles enables evaluation of consistency in measurements for X and Y CG, since the measurement is reported with respect to the lug closest to the axle (as pictured Figures 75-78 above). Using this geometry, the X CGs for backwards test article cases are adjusted to be relative to the same lug as the forward cases. The two Y CG measured should sum to 0.0 inches since the test article is symmetric about the Y-axis. The Z CG pass criteria takes a different form, since it is not possible to flip the test article upside-down while maintaining mounting capabilities. Therefore, the Z CG pass criteria is defined as having no discrepancy in measured value between the forward and reversed configurations, when considering ±0.1-inch error bars.

Table 9: Error sources and their magnitudes

Quantity	**Pass Criteria**
X CG	No discrepancy between the forward and backward measured X CG relative to the same lug with ±0.1 inches error bars
Y CG	Sum of forward and reversed Y CG is 0.0 ±0.1 inches
Z CG	No discrepancy between forward and reversed Z CG with ±0.1 inches error bars

During Phase 1 testing, a major source of random error was discovered to exist in the positioning of the testbed relative to the load cells and the rest of the structure. Specifically, the design assumed that the frictionless nature of the ball-socket swivel joints would allow and encourage the load cells to hang perfectly vertical and aligned with gravity. Testing revealed that these joints developed significant friction due to the heavy loads applied to them, which manifested in supporting multiple "equilibrium" resting positions for the testbed that varied by up to 0.75 inches in radius. By implementing a testbed position check into the test procedure, this random error was reduced by at least a factor of two, bringing random variance from 0.4 inches to less than 0.2 inches. With this change in procedure, another round of testing was performed. Results for X, Y and Z CG measurements for Phase 1 and Phase 2 testing are shown in Figures 79 and 80. The left plot shows single-measurement results and the right plot shows single-test results. Each color of data point is representative of the complete test to which it it corresponds. Lastly, the light-gray data points and dashed-box are results obtained before the procedure change was made, and were therefore not considered in final accuracy capability analysis or conclusions.

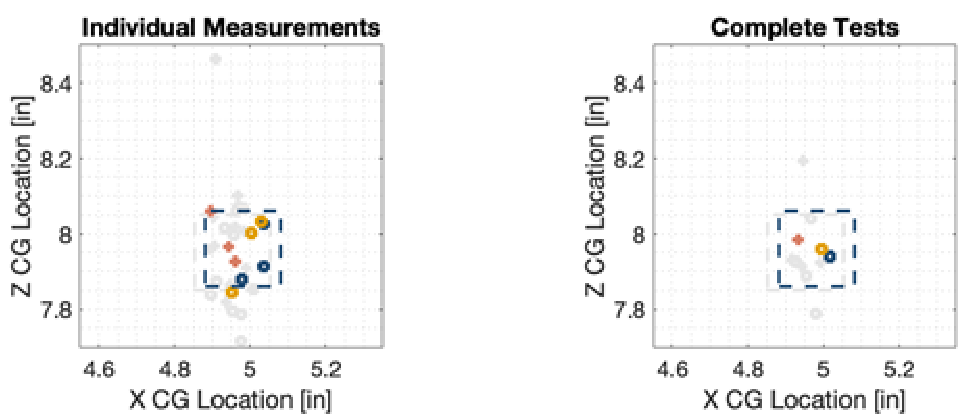

Figure 79: CG Results for Unaltered Test Article

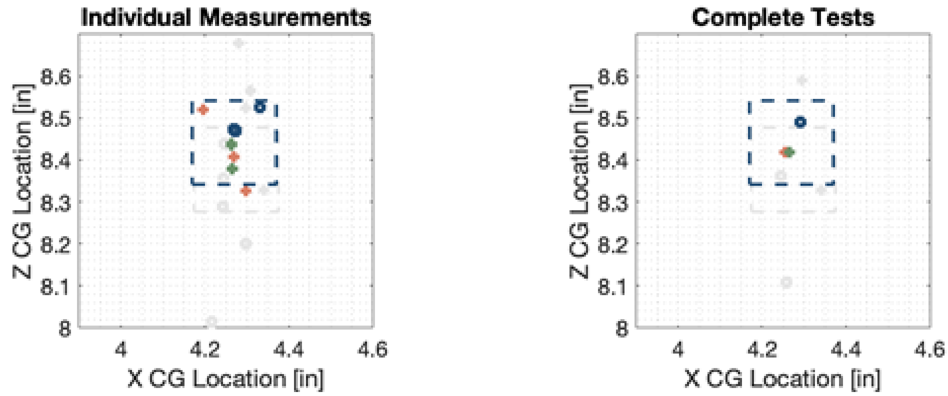

Figure 80: CG Results for Altered Test Article (all rounds of testing)

To statistically evaluate the accuracy capabilities of WASP, the results are extrapolated to predict the accuracy capabilities for 95% (2 standard deviations from the mean) of measurements and complete tests performed. Results for X and Z CG are depicted in Figure 81, and X and Y CG are shown in Figure 82. The test data is plotted in black and the 2-standard deviation bound is illustrated as a red dashed line. This figure also includes the observed percentage of results within the accuracy bounds of ±0.1 inch.

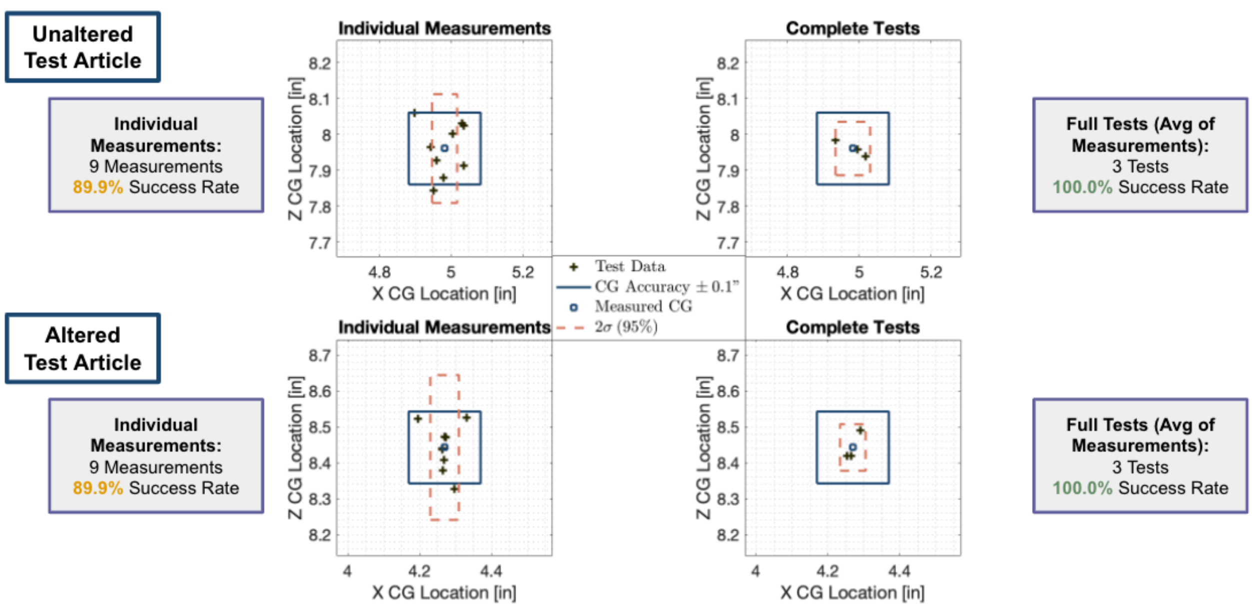

Figure 81: Predicted Range of X and Z CG Measurements for 95% of Individual Measurements and Tests

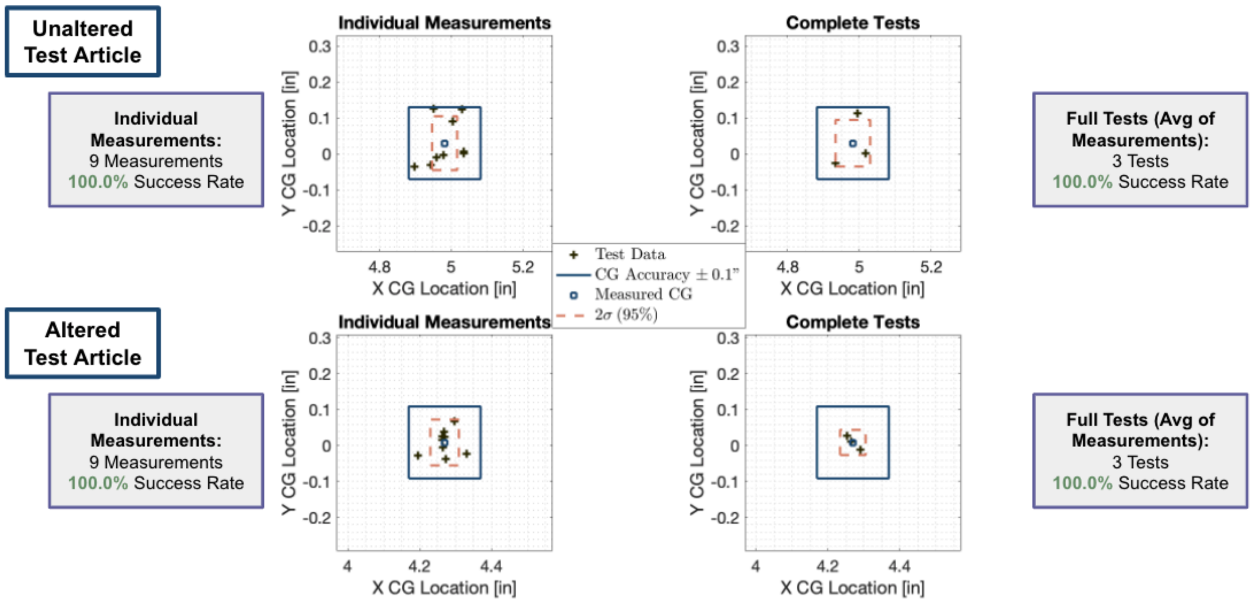

Figure 82: Predicted Range of X and Y CG Measurements for 95% of Individual Measurements and Tests

It is important to note that individual measurements satisfy the accuracy requirement about 90% of the time, while Complete Tests, which average 3-4 individual measurements, achieve the accuracy requirements for 100.0% of tests. This result confirms the anticipated benefit of the utilizing three or more measurement sets per test, which is explicitly defined in the operating procedure for the tool. Additionally, it is observed that that the Z CG has the largest variance of the three coordinates, which is both predicted by the Monte Carlo simulation in Figure 74 and is expected since the Z CG equation depends on the largest amount of independent variables with independent error. From this data, it is determined that the CG can be reliably measured within the accuracy tolerances for even the lightest pod weights.

The other major objective of this test was to determine the ability of WASP to accurately report the pod weight. The results of the weight portion of this test is shown in Figures 83.

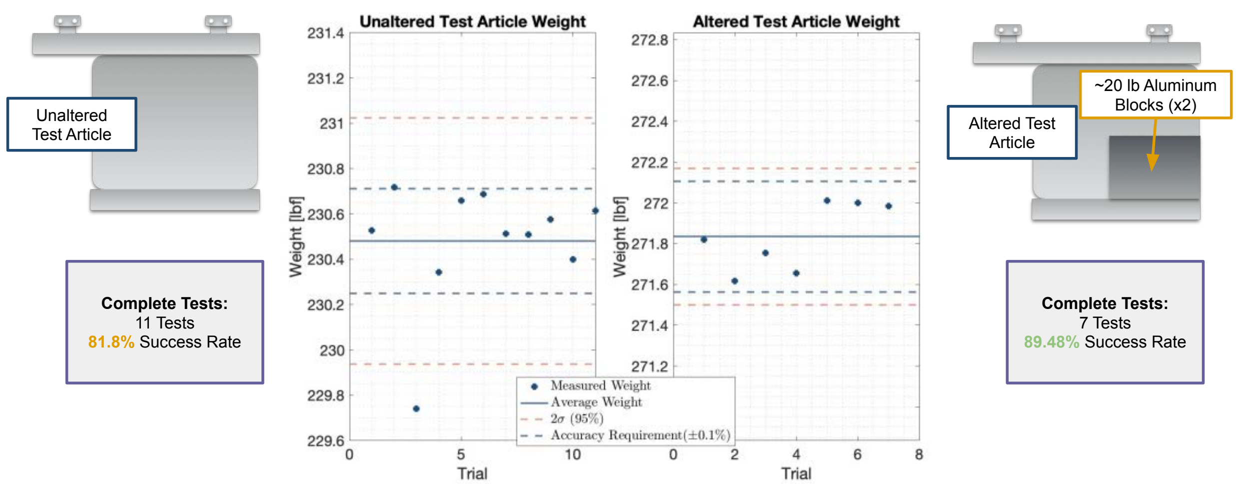

Figure 83: MAT Weight Results

As seen in Figure 83, the weight measurements tend to cluster around the measured average, with the exception of one outlier point for the unaltered test article. This point is more than 4 standard deviations from the mean when not included in the standard deviation calculation, and is visibly much greater than the observed noise of the system. For these reasons, this point is believed to be caused by a procedural error while testing. Other similar instances were observed throughout the testing process, particularly where a piece of hardware was left resting on the testbed during the load cell tare. A pin, ruler, or inclinometer left on the testbed during the load cell tare will cause the weight of the pod to be undervalued because the "zeroed" value of the load cells will be too large. In other similar cases, the data was immediately thrown out once the error was observed by the operators. The group is confident that this point went unnoticed during the very compact testing schedule, and was not identified until the analysis phase. While 0.8 lbs. is not much when compared to daily experience, it can make a substantial difference when dealing with the small accuracy tolerances required for the WASP system. Figure 84 shows the weight results with this outlier point removed from the data set. It is immediately visible that the observed repeatability now matches much closer to what was predicted by the Monte Carlo Simulation, and what was observed for the altered test article trials. While the success rate of 90% for the altered test article is at the lower bounds of what was expected, this is still deemed acceptable due to the low number of trials and the light weight of the test article, which poses a worst-case-scenario for the weight accuracy. Figure 85 shows a summary of the accuracy and repeatability result for the Measurement Accuracy Test, including a comparison to the measured SNC values for the unaltered test article. The SNC values were less accurate because of the measurement process utilized by the customer prior to WASP. Based on these results, it was determined that WASP satisfied DR 1.1 and 2.1, and satisfies the highest level of the accuracy project objective.

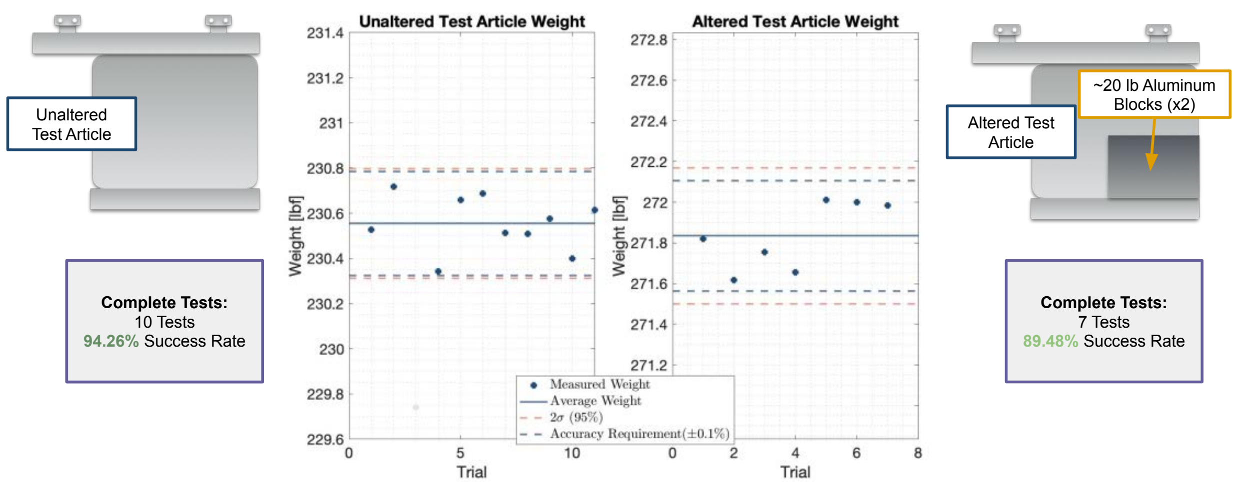

Figure 84: MAT Weight Results - Without Outlier

Accuracy			
Test Article →	Unaltered (SNC)	Unaltered (WASP)	Altered (WASP)
X CG [in]	4.61	4.98	4.27
Y CG [in]	0.00	0.03	0.01
Z CG [in]	7.39	7.96	8.44
Weight [lbf]	231.7	230.55	271.87

Repeatability/Success Rate (Unaltered)		
	Monte Carlo Simulation	Measurement Accuracy Test
X CG	100.0%	100.0%
Y CG	100.0%	100.0%
Z CG	99.5%	100.0%
Weight	96.2%	94.26%

Figure 85: MAT Results Summary

For Measurement Accuracy Test data files and analysis code, see the project archive T-7 MAT. For the final test procedure, see T-9 Official Test Procedures.

5.2 System Accreditation

The final test conducted was the System Accreditation test, which assessed DR 6.1 and 6.3, stating that the test procedure needs to be completed by 2 engineers in under 30 minutes. To test this, three different groups of two volunteers operated WASP using the developed procedures to measure the weight and CG of the test article. This allowed an evaluation of the written test procedures to see if accurate measurements could be completed in the timeframe by engineers who did not design and build WASP. Its important to note that a test is defined as the moment a pod is attached to WASP, to the moment its detached. Although the setup and tare procedure times were tracked, the defined test time was of particular interest during this testing. Based on some ergonomic and observed estimates by the team, the predicted time breakdown for a full test is shown in Figure 86.

Procedure	Time
Tare Procedure	12 mins
Mounting Procedure	7.5 mins
Measurements	25 mins
Dismounting Procedure	5 mins
Total	30 mins

Figure 86: Procedrure Time Breakdown

Overall, the results of this test were very promising. These results are shown in Figure 87. The first group easily finished all three measurement sets within the 30 minute testing slot. The second group completed one measurement set, but was not able to complete the dismounting procedure due to their class schedules. Their extrapolated test time for all 3 measurement sets is roughly 27.5 minutes, which does not include the dismounting procedure. The dismounting procedure was observed to take 2.5 to 3 minutes based on the other groups. The third and final group also faced schedule constraints, but were able to complete one full measurement set and the dismounting procedure. The extrapolated time for this group, including the dismounting procedure, is 25 minutes. All groups were able to produce measurements that satisfied the accuracy requirements discussed during the Measurement Accuracy Test. It is also important to emphasize the fact that these operators arrived not know what WASP was or how it worked, and they were still able to meet these time requirements on the first try. From experience, the group has observed a very steep learning curve in terms of operating WASP, and is fully confident that the trained SNC operators will be able to consistently meet these testing requirements. The System Accreditation test provided valuable user feedback that was utilized to make the procedure manual even more effective and user-friendly. This test also allowed WASP team members to practice training unfamiliar users in preparation for training the SNC engineers during delivery.

Procedure (2 Engineers)	Group 1 Time	Group 2 Time	Group 3 Time	Projected Time
Tare Procedure	11.66 mins	18.30 mins	12.50 mins	12 mins
Mounting Procedure	9.37 mins	14.03 mins	7.50 mins	7.5 mins
Measurement Time (# Completed)	21.82 min (3)	9.15 mins (1)	7.50 mins (1)	25 mins
Dismounting Procedure	3.00 mins	DNF	2.50mins	5 mins
Total (Measurement and Dismount)	**24.82 mins**	**~27.45 mins**	**~25 mins**	**30 mins**

Figure 87: System Accreditation Results

For System Accreditation data files and observations, see the project archive T-8 SA. For the final test procedure, see T-9 Official Test Procedures.

5.3 Summary of Additional Checks

Alongside the major planned test, the team also conducted numerous smaller verification checks on components and subsystems that did not warrant full procedures or data collection. During the manufacturing phase, each shop-produced and team-produced component was thoroughly inspected using precision calipers to ensure that the dimensions were consistent with the dimensions and tolerances given in the CAD drawings. This allowed defect pieces to be re-fabricated before any structural or accuracy consequences could take place. Another check conducted during manufacturing was the sliding check for the sliding interface, which ensured that the Sliding Interface could slide up and down the legs without posing a risk to operators. This check was initially unsuccessful, and allowed the team to address the associated problems before testing the full system. The electronics and software manufacturing process also featured numerous checks including conductivity verification on electronic hardware, and function-level checks on the Matlab software for the GUI. Overall, these checks were widely successful in helping the team identify problems as early as possible. This allowed for more cost and time efficient solutions to come to fruition, as opposed to discovering these problems later on during the formal testing phase where design changes would be more expensive and less elegant.

6 Risk Assessment and Mitigation

Ansh Jerath, *Foster Greer, Aidan Kirby, Emma Markovich, Parker Simmons, Matthew Zola*

6.1 Risk Identification

In order to identify the risks associated with this project, the team split the type of risks into different categories. The technical risks for WASP included both major subsystems (structure and electronics & software), as well as the manufacturing risks. Logistical risks were categorized as challenges resulting form COVID-19 public health safety guidelines and restrictions. Safety risks were identified as risks that involved the safety of the system as well as the engineers. Finally, financial risks were assessed to be any challenge to staying under the teams budget limit. Each risk in each of these categories were identified by the team's familiarity with the WASP system and associated impacts. The design, electronics and systems teams all understood the structure and its subsystems to identify possible risks. The same method was applied for safety, logistical and financial risks which the safety and project management side handled respectively. The systems team conducted a scoring of all identified risks to assess impact, likelihood and mitigation efforts. All of WASP's risk descriptions and mitigation efforts can be seen in Appendix C. The following figures show the before and after mitigation matrices for technical, logistic, safety and financial risks. Once again, each risk has an associated number which can be seen in Appendix C.

6.2 Technical Risk Matrices

		Impact Level			
		Low	Mild	Medium	High
Likelihood Level	High			14	13
	Medium		12, 15, 17	4, 5, 8, 9, 10, 11	1, 2, 6, 7, 16
	Low		18		3

Figure 88: Technical Risk Matrix - Pre-Mitigation

		Impact Level			
		Low	Mild	Medium	High
Likelihood Level	High				
	Medium	12	14		
	Low	11,15,17,18	7,8,10,13	4,5,9,16	1,2,3,6

Figure 89: Technical Risk Matrix - Post-Mitigation

6.3 Logistical Risk Matrix

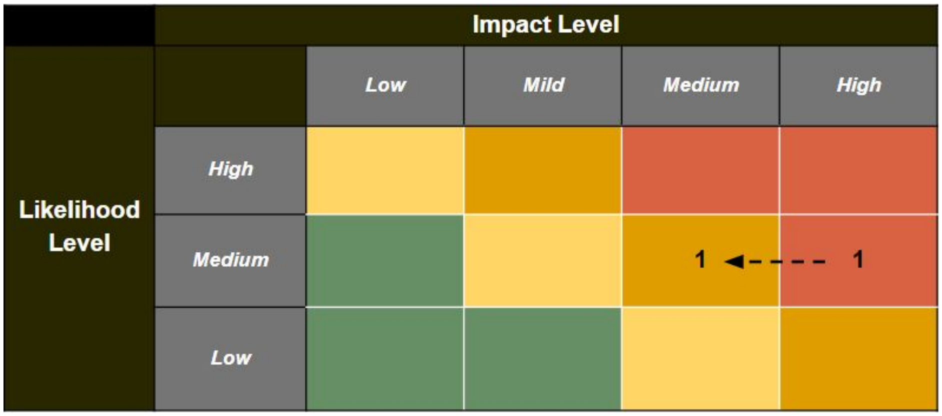

Figure 90: Logistical Risk Matrix

6.4 Safety Risk Matrix

Figure 91: Safety Risk Matrix

6.5 Financial Risk Matrix

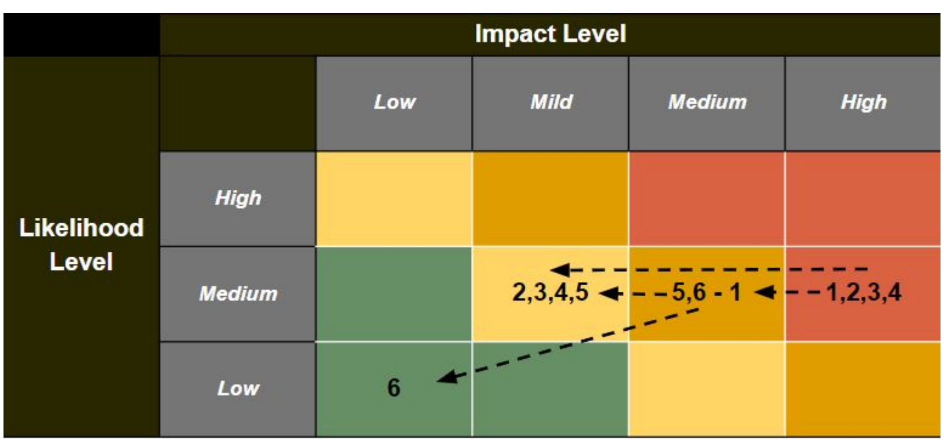

Figure 92: Financial Risk Matrix

6.6 Risk Tracking and Mitigation

After identifying and putting a plan in place to mitigate all of WASP's risk, the team had to implement the mitigation plan and track our risks. The team realized that most of our risks had very little chance of occurring because of the planning and implementation of the mitigation techniques for each risk at the start. The team opted to focus on the risks that had a higher likelihood of occurring which mainly including manufacturing and schedule-related risks. These risks were always tracked as the team was constantly making sure our parts and beams were the correct length (quality checks), carefully angle grinding and welding as well as communicating any delays we were experiencing due to manufacturing, testing or other schedule bearing issues. As for mitigating these major risks, the team did implement mitigation techniques and the full list can all be seen in Appendix C.

6.7 Risk Outcomes and Impacts

Most of the risks that the team analyzed did not happen. Most of the risks were very well thought out and the team focused on applying mitigation techniques, especially risks that would have project critical impacts. However, there were some risk that did come to fruition. These risks were primarily manufacturing and scheduling/COVID-19 risks. At the start of the semester, the 2-week margin that we had built into the manufacturing schedule was used due to school precautions in order to reduce the spread of COVID-19. Luckily, the team was able to manufacture quickly and finish with very little delays. Similarly, we did have scheduling issues for our testing period. This was due a combination of tests taking longer than expected due to test setup issues, schedule miscommunications with the shop and internal schedule conflicts. This risk caused us to lose time for testing but the team was able to conduct every test successfully. The other major risk(s) were manufacturing, specifically risks associated with dimensions like beam lengths and connections. Welding and angle-grinding caused dimension mismatches with the CAD model which is not ideal. This caused issues with our CG equations as well as functionality issues. The team was able to troubleshoot these issues but these manufacturing issues did arise.

7 Project Planning

Foster Greer, ***Emma Markovich****, Matthew Zola*

7.1 Organizational Chart

The WASP team has two different organizations, one for Design Synthesis (first semester) and one for Design Practicum (second semester). The goal of the two organizations is to provide necessary support to the subteams that have the most demanding work load. For Design Synthesis, team efforts focuses on structural design and general design analysis. For Design Practicum, team efforts will focus on manufacturing and testing.

The organizational chart for the WASP team for Design Synthesis is shown below (Figure 93). We are broken up into six subteams: (from left) Systems, Structural Design, Analysis, Electronics & Software, Test, and Safety. Each team member has a unique lead position and is a part of three subteams. The Lead Systems Engineer is Ansh Jerath, Lead Structural Design Engineer is Adam Elsayed, Manufacturing Lead is Foster Greer, Lead Design Analyst is Samuel Felice, Lead Electronics & Software Engineer is Bailey Roker, Lead Test Engineer is Aidan Kirby, and Lead Safety Officers are Maddie Dube and Parker Simmons. The WASP team is managed by Project Manager Emma Markovich and Financial Manager Matthew Zola, and advised by Dr. Francisco Lopez-Jimenez.

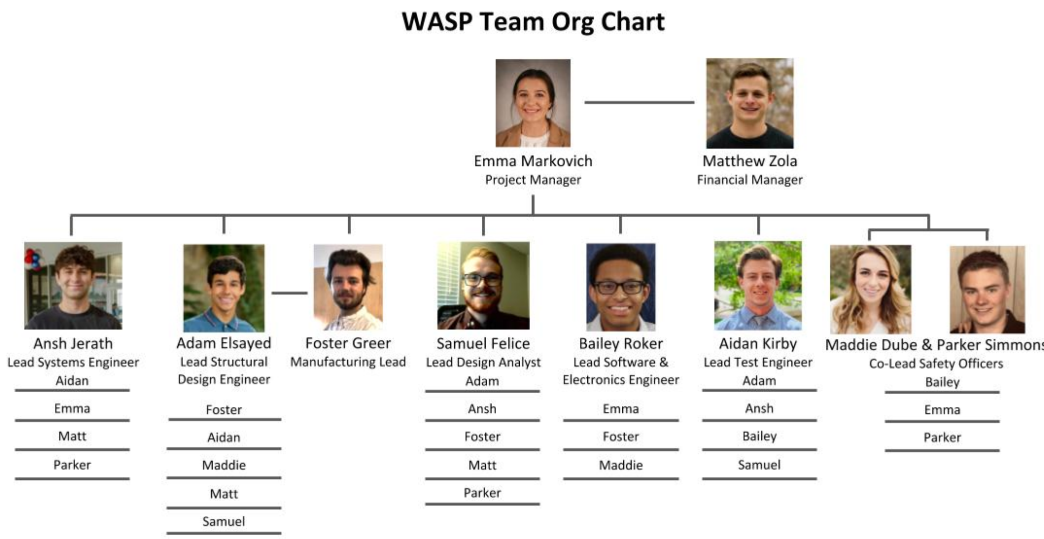

Figure 93: WASP Organizational Chart - Design Synthesis (Fall 2020)

The organizational chart for the WASP team for Design Practice is shown below (Figure 94). The same subteams exist, with the exception of Structural Design. This team has shifted to become the Manufacturing subteam, led by Foster Greer. Additionally, the Systems and Test subteams have combined efforts to from the Systems Engineer, Integration, and Test (SEIT) subteam, co-lead by Ansh Jerath and Aidan Kirby. Combining these two teams is the natural and best choice, as many of the tasks for the teams overlap or are closely coupled. All WASP team members are a part of the SEIT team, both providing extra support for testing set-up, performance, and tear-down, and ensuring all team members are involved in project operations through the entirety of the project. Each team member maintains their unique lead position while subteam membership has been adjusted appropriately to execute second semester tasks.

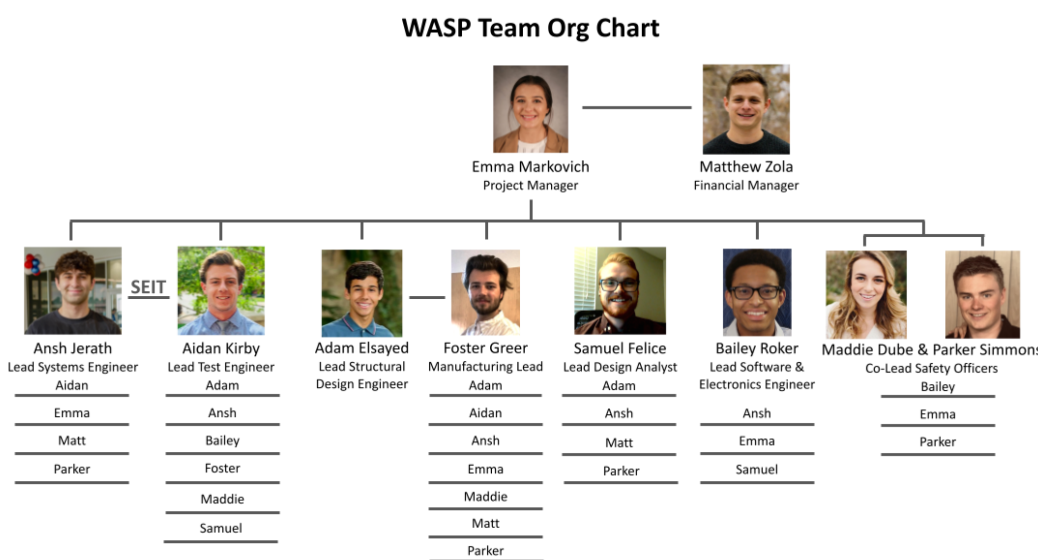

Figure 94: WASP Organizational Chart - Design Practicum (Spring 2021)

7.2 Work Breakdown Structure

Figure 95 summarizes the work breakdown structure for team WASP, as well as offers a visualization of the status of the project at the end of the design synthesis process (December). Since WASP is physically comprised of two main work products, structure and electronics & software, it was in the best interest of the team to instead divide major tasks into working subteams that support the main work products. With this, work tasks are broken down into six categories: Management, System-Level, Electronics & Software, Structures, Manufacturing, and Integration & Testing. The chart below illustrates that the bulk of the design and planning work was completed in the Fall semester (dark green tasks), and that the team's focus for the Spring semester shifted to the hands-on build and test phase of the project (white tasks). Such dramatic shift in work-type distribution motivated the mid-project team organization restructure, discussed previously.

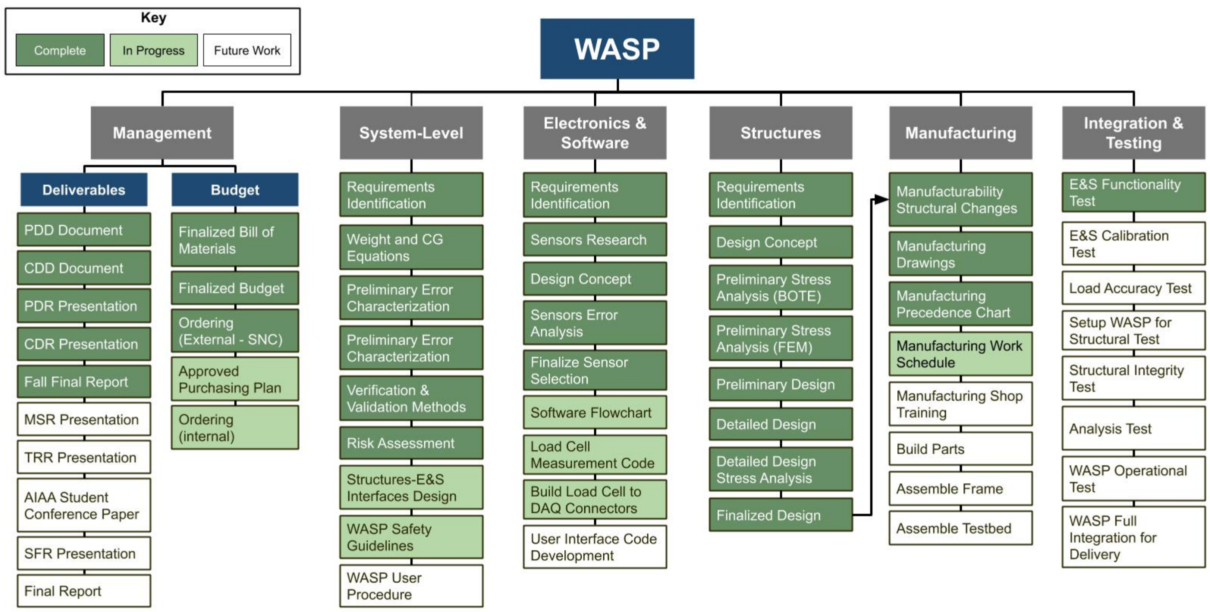

Figure 95: WASP Work Breakdown Structure - December 2020

Figure 96 demonstrates the end status for Project WASP. Please note, a final manufacturing task was added, "Full Structure Integration", a structural component test was added, "Lug Mount Tensile Test", and some Testing tasks reflect the updated name for the test. With great pride, the team can report that all anticipated tasks were completed, with the exception of the conference paper. The team decided to submit a conference paper to the Society of Allied Weight Engineers (SAWE) conference in October 2021, and therefore are working to further refine this paper for submission. Importantly, the work breakdown structure highlights key work tasks and product for the final deliverable, and therefore does not include some course-related tasks such as the AES Senior Design Symposium. For a visualization of the timeline and completion dates of working tasks, please see the next section Work Plan.

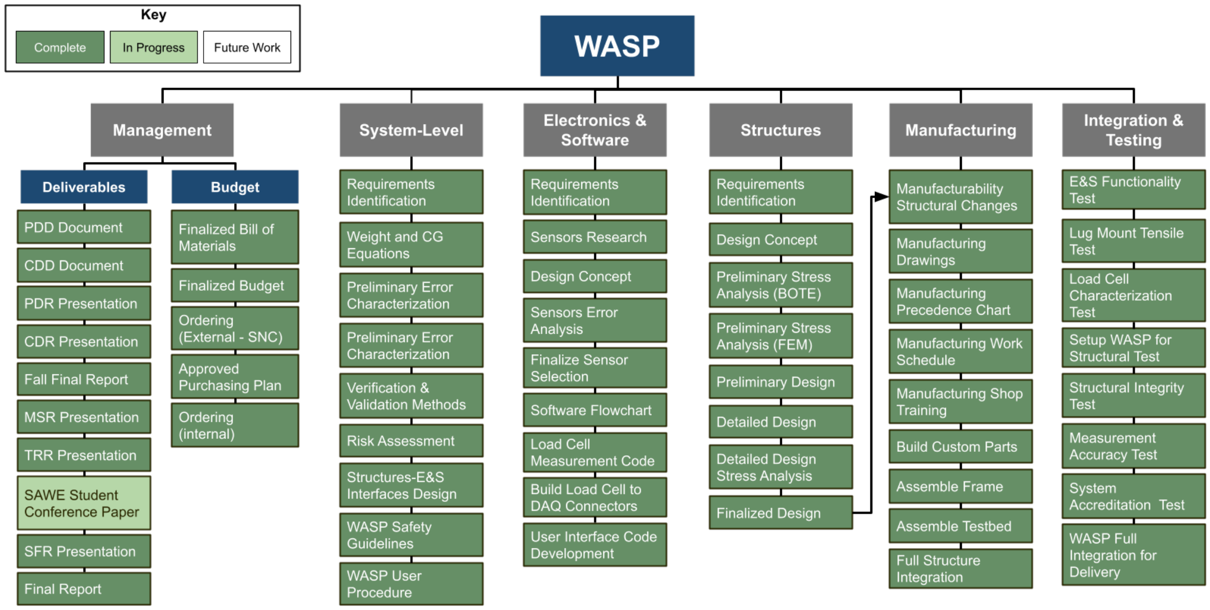

Figure 96: WASP Work Breakdown Structure - May 2021

7.3 Work Plan

Figures 97 and 98 describe the major work tasks and their timelines for the Fall and Spring semesters, respectively. The Gantt Chart groups tasks by subteam, each denoted by a unique color. The darker version of the color represents expected task duration while the lighter version of the color represents built-in margin. Black arrows indicate major dependencies between major tasks and red text and arrows map out the critical path for WASP. Orange diamonds indicate major milestones for the project, including reviews, papers, and other deliverables, and the bright green vertical line respresents the actual completion date of the work task. In the Spring semester chart, the light red shading indicates the two weeks lost of the R2R approval delay. Full-page Gantt Charts are available in the attached documentation.

Given the large manufacturing scope of the project and the COVID-19 on-campus restrictions, it was necessary to carefully plan the timeline and build in margin to the Spring semester schedule. As discussed more in the next section, the manufacturing plan was developed in collaboration with Matt Rhode to ensure its feasibility, which resulted in a five week plan plus two weeks of margin primarily for hiccups in assembly. The rule of thumb for margin allocated for testing tasks was 100% margin. Most tests were estimated to require a week of time to complete, therefore earning a week of margin. The System Accreditation Test was the exception, since the team anticipated this test to last two weeks to allow adjustments were made to better the functionality and operation of WASP.

The critical path for the fall semester highlights the design finalization of both the structural, electronics, and software designs, which ultimately leads to a period of formal review. Detailed component selection and integration of individual components into feasible systems were completed in parallel by the Structures and Electronics & Software teams. This finalized design was necessary for the Critical Design Review to ensure the project was deemed acceptable to begin the manufacturing phase.

The critical path for the spring semester starts with manufacturing the WASP structure. Once manufacturing and assembly is complete, the User Interface code can be adjusted appropriately to reflect the manufacturing tolerances achieved, such as the load cell misalignment issue discussed in Section 3.2.2. Once the User Interface was corrected and finalized, the project moved into full-system testing. This task included testing both the accuracy of the tool and the feasibility of its operation within the objectives. Finally with WASP fully-functional, it is ready to be delivered to the customer.

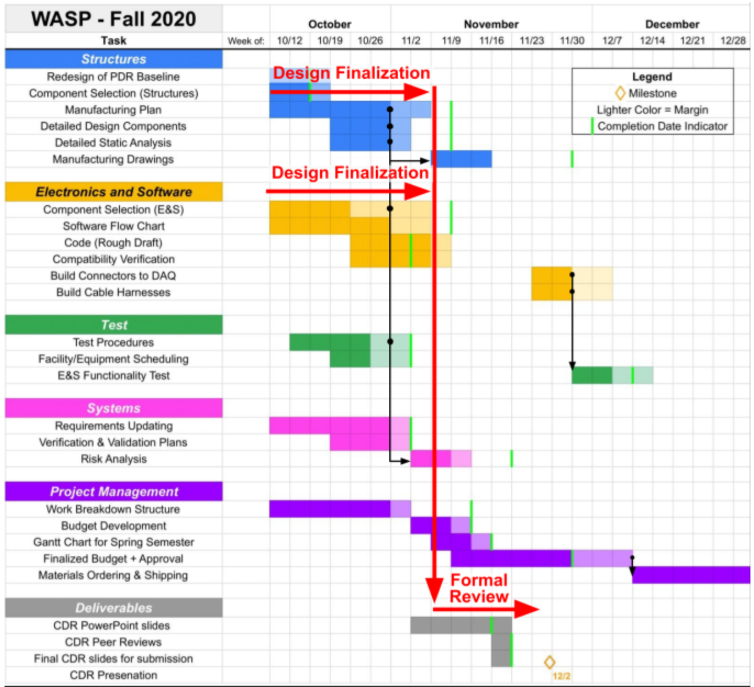

Figure 97: WASP Gantt Chart - Fall 2020

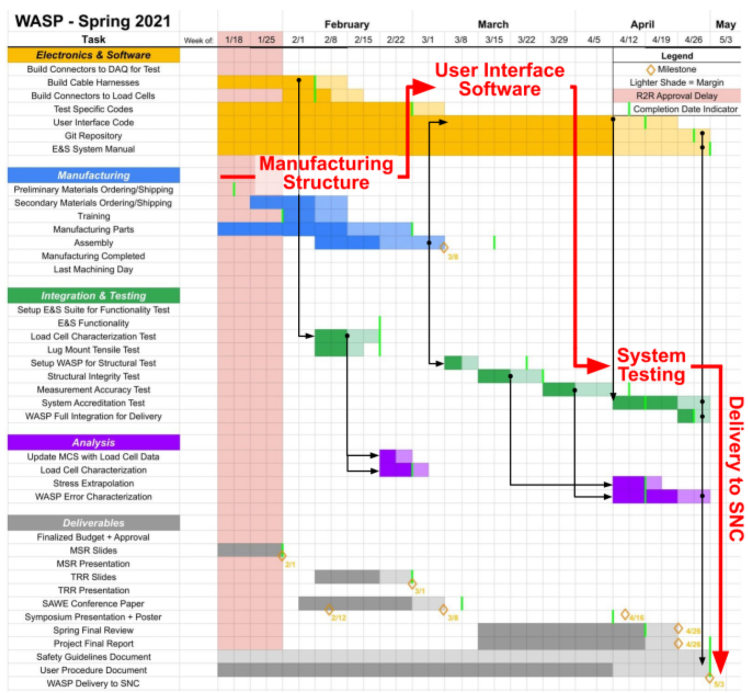

Figure 98: WASP Gantt Chart - Spring 2021

7.4 Manufacturing Plan

Due to the nature of WASP, there will need to be a significant focus on manufacturing next semester, and thus careful planning is required to ensure manufacturing is completed on time. Figure 99 shows a high level plan for manufacturing WASP next semester. The time intervals in green denote the "expected" five week schedule, which was based off of conservative estimates for the time needed to complete each manufacturing task. The time intervals that are in grey denote the two week margin that has been added to the schedule to ensure that manufacturing is completed before the testing schedule or other tasks down the line are impacted. The next thing to note is the tasks highlighted in yellow. These are the tasks that have been identified as being part of the critical path, which are the most time-dependent tasks that will be completed.

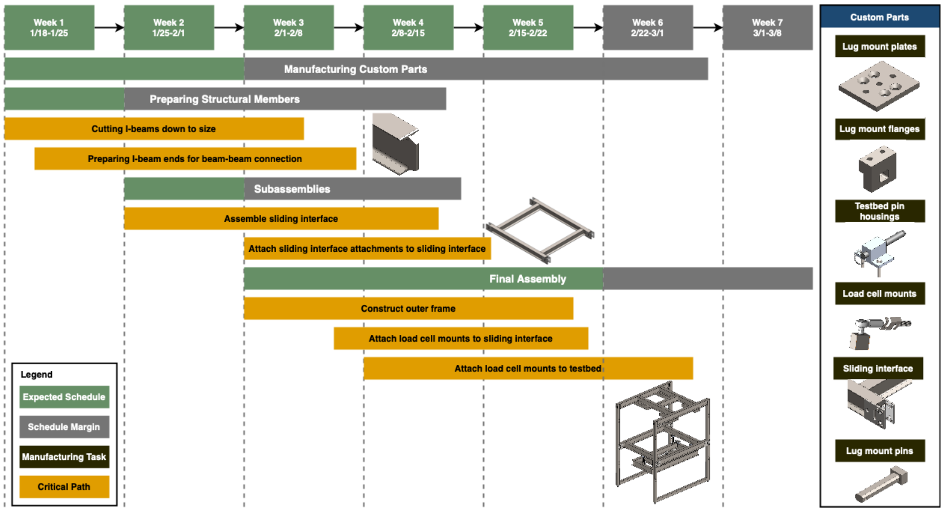

Figure 99: WASP Manufacturing Plan

Conservative estimates were made to determine how many hours will be required from the WASP team and from the machine shop faculty to complete the tasks in this schedule. It was found that a maximum of 60 hrs per week will be required from the team to complete the manufacturing within the 5 week expected schedule. Among the 7 members of the manufacturing subteam, there is a potential availability of up to 150 hours throughout the week during shop hours. The team also estimates that WASP will require no more than 180 total hours of work from the machine shop personnel. From discussions with Professor Rhode, the machine shop manager, it is understood that up to 200 total hours of work will be available from the shop faculty to aid in WASP manufacturing. Therefore, even under the current COVID-19 restrictions, the team expects this manufacturing schedule to be feasible. The additional two week margin is included in the schedule and the team will make a push to begin manufacturing early (by submitting part drawings and materials to the machine shop over break) to increase confidence that this manufacturing plan will be feasible.

7.5 Cost Plan

Below is a detailed overview of the financial budget for the duration of the project along with estimates for reference. Costs have been split into four categories, which are further broken down in subsequent figures

Subsystems Overview		
Subsystem	Estimated Expenses	Actual Expenses
Raw Materials	$1,886.74	$2,381.41
Hardware	$1,627.22	$1,978.54
Electronics	$145.68	$0.00
Other Expenses	$500.00	$342.42
Total	**$4,159.64**	**$4,702.37**
Margin	**16.81%**	**5.95%**

Figure 100: Budget - Subsystem Overview

This first section encompasses all of the raw materials and metal stock that must be purchased to manufacture and assemble the WASP structure (Figure 129). A majority of the items were purchased from Metals Supermarket, which is a local metals distributor in Golden, CO. The remaining items were from online wholesalers such as McMaster-Carr. There is a roughly $500 discrepancy between the estimated raw material expenses and the incurred expenses, which is mainly due to the fact that the costs of raw metal are highly volatile and the team had to get new quotes prior to making the final order.

The hardware section (Figure 130) includes all of the fasteners and commercial off the shelf hardware required for WASP. All of the fasteners are from McMaster Carr and the remaining items (chain hoist and trolley) are from an online vendor. Once again, there is about a $350 delta on these expenses. This time, the discrepancy is due to additional hardware needing to be purchased to remedy design flaws found in the sliding interface and tilting mechanism.

The electronics section (Figure 131) includes all of the electronic hardware required to interface with the sensors provided by the customer as well as strain gauges required for structural testing. The team originally had set aside $145 for these expenses, but we were able to obtain them from the AES electronic shop free of cost.

The last section, labeled "Other Expenses" (Figure 132), encompasses all of the zero-line items as well as miscellaneous expenses that do not fit in the other categories. Most notably, this includes the shipping expenses for the previous sections. It should be noted that $500 was originally set aside for this section, however the shipping costs did not end up being as high as expected.

In conclusion, WASP was manufactured and tested under budget with a margin near 6%. Significant effort was spent amongst the WASP team as well as the customer in order to minimize expenses and stay under budget.

7.6 Test Plan

Due to the unusually large magnitude of manufacturing associated with this project, it was essential to overlap the manufacturing and testing schedules to ensure the project was completed on time. This structure allowed for the component level testing to take place concurrently with the final assembly. The Load Cell Characterizations tests and the Lug Mount Tensile Test both required the use of the AES Department's electromechanical MTS machine, the use of which was coordinated with Pilot Lab Coordinator KatieRae Williamson. The team was able to schedule extensive time one this machine because most other senior project teams had not begun testing at this point early in the spring semester. Nonetheless, these tests were delayed by numerous external factors, and an added week of margin was used for both tests. While delays are never fully expected, this testing structure did anticipate possible complications, and allowed even more time than the allotted margin for troubleshooting and running additional trials.

The three major tests that required manufacturing to be completed - Structural Integrity Test, Measurement Accuracy Test, and System Accreditation - were scheduled to begin immediately after manufacturing. Once again, unforeseen complications during manufacturing delayed the start of these tests by one week. Fortunately, the team was able to start preparing for these tests as the last components were being installed. The Structural Integrity test was able to be completed in one day, which essentially saved the testing schedule. The machine shop weld table and forklift were required to conduct this test, and were arranged with

Test	Actual Start Date	Actual End Date	Equipment/Facilities Used
Lug Mount Tensile	2/8/2021	2/18/2021	Modified Lug Mount, EM MTS Machine
Load Cell Characterization	2/23/2021	2/23/2021	WASP Load Cells + DAQ System, EM MTS Machine
E&S Functionality	12/1/2020	12/1/2020	WASP DAQ System
Structural Integrity	3/29/2021	3/29/2021	Weight, Strain Gauges, WASP DAQ System, AES Forklift
Measurement Accuracy	3/30/2021	4/14/2021	SNC Test Article
System Accreditation	4/14/2021	4/15/2021	SNC Test Article, Volunteer Engineers

Figure 101: WASP Test Schedule Overview

the AES Machine Shop Coordinator Matt Rhode. This was easy to arrange because the team was in close contact with the shop staff throughout the entire spring semester.

The Measurement Accuracy Test was allotted two weeks in total, and as anticipated, used the full time available for testing and calibration. This test required the SNC provided test article, which was arranged and delivered a few weeks in advance to avoid delays. Following the Measurement Accuracy Test was the System Accreditation; this test required six non-WASP volunteers to conduct full tests on the SNC test article. Coordination of these volunteers consisted of reaching out to other senior design teams, and began two weeks in advance to ensure enough volunteers would be available at the necessary testing time. The team wanted to include the results of System Accreditation in the Spring Final Review (SFR), so the trials were stacked over the course of two days. While the entire manufacturing and testing process was incredibly compact, the team and vigilance towards the schedule allowed everything to be completed on time. Figure 101 shows an overview of the testing schedule.

8 Lessons Learned

Emma Markovich

8.1 Technical: Your Final Design is not your Final Product

No matter how much effort your team puts into refining the final design for the project, changes stemming from manufacturing and testing are inevitable. For WASP, this important lesson was realized in both the structure and the electronics and software suite. Manufacturing tolerances were difficult to meet, especially on a project with such a grand size, resulting in small design adjustments to accommodate these discrepancies. Moreover, WASP suffered from the tilting and binding of the sliding interface and the varying rest/equilibrium positions of the testbed, which were both significant problems rooted in the discrepancy between the derived model and the real scenario. It is important to expect the project will need design changes and plan appropriately both in timeline and budget.

8.2 Technical: "All Models are Wrong, Some Models are Useful"

In the famous words of Professor Matt Rhode, "All Models are Wrong, Some Models are Useful". WASP endured both benefits and consequences of this statement. On the positive side of things, the final measured accuracy of WASP closely matches the Monte Carlo simulation. However, the operating procedure had to change to include checking testbed alignment in order to recover this accuracy. While the Monte Carlo simulated four types of relevant error, it also failed to consider some error sources that were revealed during testing. In a slightly different way, the Lug Mount Tensile Test revealed that the model of the lug strength underpredicted performance by nearly four times. On the negative side, the model for the sliding interface plastic moment-combatting plates overpredicted the moment-balancing capabilities of the design. This error resulted in structural and safety issues when the sliding interface suddenly tilted, and ultimately challenged the functionality of WASP as the team is recommending that the customer leaves the sliding interface pinned whenever possible. Team and external expert collaboration as well as performing test where possible are key methods in developing "useful" models.

8.3 Financial: Raw Materials are Like Stocks

The cost of raw materials fluctuates with the state of the economy, in a similar manner to the stock market. WASP suffered a major financial hit when the quote for the price of the steel beams increased by about 25% over a couple of weeks. Further, be sure to ask or check the validity of timeframe for the validity of the quote from the supplier. This expense increase was not anticipated, and was therefore taken from the allotted budget margin. It is important to remember that if you are needing to procure raw materials, do it as early as possible while not sacrificing quality of order (with respect to know needed parts).

8.4 Schedule: Sometimes, 100% Margin Still is not Enough

Schedule delays are unavoidable and are just the reality of nearly all projects. For this reason, plan a significant amount of margin into the schedule. If it is difficult to estimate the time needed for that task, give it 100% margin just to cover your bases. Nevertheless, unpredictable challenges (such a global pandemic or local tragedy) or internal delays may put pressure on the project timeline, leading to a failure to meet even conservative 100% margins. It is important to remember not to feel nervous about using margin in schedule if it means the final product benefits.

9 Individual Contributions

9.1 Maddie Dube

Safety Team co-lead. The fall semester I worked on design and analysis tasks as well as logistical tasks for the team. The logistical tasks comprised of logo design, color pallet creation, Conops design, as well as team activity planning which was defined as a safety subteam lead task. For the structures design portion, I worked and aided others on the conceptual design for the lifting mechanism, frame design, hardstop design, lug mounting, and was the safety advisor to this subteam. For the electronics and software subteam, I researched line loss and sensor types, while working directly with the design of the User Interface and how it will be operated. For the analysis subteam, I worked heavily on the beam bending hand calculations as well as taking the lead on the connection analysis (ie: cleats and welds). For the FFR report, I worked on the conceptual and detailed design sections relevant to sensors, User Interface, and welding connections.

The spring semester I put considerable hours into the manufacturing process. I had some of the most machining hours on the team and even learned how to TIG weld to help the build process go quicker. Another big task that was a part of manufacturing were the necessary redesigns that took place throughout the manufacturing duration. Concurrently with manufacturing, I was working on the safety team to develop "visual checks" for WASP. These dealt with some human factors research and how to eliminate user error. Once the manufacturing process ended, I switched to aiding the testing team with the testing process.

9.2 Adam Elsayed

Structural design lead. Worked (with others) on the structural design (both conceptual and in CAD), the structural analysis of beams, pins, and lug mounts, and the test procedures for the lug test and structural integrity test. Did plenty of manufacturing, and helped Aidan carry out the LMTT, SIT, MAT, and SAT. As for the PFR report, edited the final design section, worked on the structural design subsection, as well as the structural manufacturing subsection and lug mount tensile and structural integrity tests in the V&V section.

9.3 Samuel Felice

Analysis subteam lead. Provided insight on design decisions from structural and accuracy standpoints. Worked frequently on the computer aided design and oversaw any finite element models created on those parts. Reviewed all back of the envelope and hand calculations. Helped design test procedures for the structural, accuracy, and load cell accuracy validation tests. Created, modified, and utilized a high fidelity Monte Carlo system to analyze error in the WASP system. Wrote the equations WASP uses to calculate the weight and CG of each pod. Completed several subsections in FFR, including parts of the project objectives and functional requirements, detailed design, and verification and validation.

9.4 Foster Greer

During fall semester, I Contributed as a member of the structural design and analysis teams, as well as the electronics and software team. I Worked on the design of WASP components and structure, and performed calculations to structurally analyse the frame members and other structural components on WASP. I Aided in the preliminary design of the electronics and software system, focusing on data acquisition. As the manufacturing subteam lead, I had focused on collaborating with Matt Rhode to ensure all of our parts were be able to be manufactured during the spring semester, and formed a preliminary manufacturing schedule to ensure we will be able to complete the project on time.

In the spring, I focused all of my efforts on manufacturing. Along with other team members, a very detailed plan for manufacturing WASP was created. I also worked closely with the aerospace machine shop staff to order the custom parts that were needed. Many organizational tools were created to help keep the team's manufacturing efforts on track, including a progress update sheet and daily schedules for each team member. As manufacturing lead, I oversaw (and, of course, participated in) all of the phases of manufacturing. These included manufacturing parts (both through the machine shop staff's efforts and our own team members), subassemblies, final assembly, and final quality checks at each stage of the process. Once the main portion of manufacturing was complete, I joined the SEIT team to aid in testing, and completed any further manufacturing tweaks that were needed as testing progressed. For this report, I contributed to the manufacturing portion, focusing on the scope, structural manufacturing, and "lessons learned", as well as helping to review other sections as needed.

9.5 Ansh Jerath

During the fall semester, I assisted the design/analysis team with beam calculations as well as tasks related to design such as welding. Calculations were done on beams, shear pins and the overall shear pin system. Similarly, led the team in risk analysis as well as other overarching high level systems tasks (like wiring plan) not including project manager tasks. Finally, assisted in developing testing procedures and V&V plans for next semester. For FFR related items, polished up the FRs and DRs as well as wrote the test description for measurement accuracy. Similarly, reviews were done of the Project overview.

During the spring semester, most of my work was either manufacturing or testing. With the new format of the systems and testing team, combining to SEIT, I helped with testing as well as managed systems main task, the User Manual. I assisted with all tests but took a lead with the strain gage application for the SIT. I also was the primary analysis engineer for the SIT data. Like I mentioned earlier, I was the main person responsible for the User Manual and I also was the primary person for cabling and other systems-related issues. As for manufacturing, I helped with any manufacturing Foster (our manufacturing lead) had for us. I angle grinded, conducted quality checks and helped with the overall assembly of WASP. On top of that, I helped with all class deliverableS like the MSR, TRR, FFR, SPF and the PFR.

9.6 Aidan Kirby

During fall semester, I led the Testing team and also worked on both the Structural Design and Systems teams. For the Design team, I initially worked on evaluating different design alternatives for lifting and tilting, and creating functioning design concepts from different design alternatives. After this I worked with others in the initial sizing and detailed design of the structure including several BOTE analyses on beam and leg components. For Systems I helped with the identification of CPEs, FRs, DRs, and structural risks. For testing I facilitated weekly meetings, coordinated research and informational meetings with PAB members, lab staff, and sensor manufacturers. I also worked with my team to develop all of the proposed test procedures.

For the spring semester, I was a co-lead for the Systems Engineering, Integration, and Test (SEIT) subteam, as well as a manufacturing team member. For manufacturing, I worked in the shop 5 days per week on the assembly of WASP's structure and worked on troubleshooting problems that arose during fabrication with others. As the SEIT testing lead, I also planned, coordinated logistics, and conducted (with the help of others) all of the tests performed on WASP. Additionally, I conducted weekly meetings with my other co-lead, and was responsible for the preparation of all testing related material for TRR, SFR, the SAWE conference paper, symposium, and PFR. For the PFR, I wrote the sections for Testing Scope, Structural Integrity Test, Measurement Accuracy Test, System Accreditation, Summary of Additional Checks, and the Test Plan. I also helped edit and review all of the Verification and Validation section.

9.7 Emma Markovich

I led the WASP team from a management perspective. I organized and hosted tri-weekly team meetings (two lab meetings and one end-of-week team tag-up). With the help of subteam leads, I scheduled major deadlines and tracked team status with respect to these deadlines. Further, I initiated and managed the relationship with the customer, including bi-weekly regularly status-update meetings, in-depth technical meetings, a team SNC hangar tour, and general communication/action item tracking. I also communicated and scheduled meetings with our PAB advisor. Finally, I oversaw and handled project management related tasks such as the team organization, task breakdowns, Gantt Chart, and budget (with much help from Matthew Zola).

I also contributed technically on the Systems, Electronics Software, Analysis, Manufacturing, Testing, and Safety subteams. I primarily owned/worked on the load cell, inclinometer, and DAQ/cDAQ hardware research and selection, as well as heavily supported the WASP accuracy capabilities analysis (which is rooted in electronic component error analysis study). Additionally, I aided in requirements development, V&V, and structures-E&S interfacing. I was the assigned E&S safety officer, meaning I reviewed all E&S design work for hardware and personnel related safety concerns. With respect to FFR, I wrote/developed the following sections: Specific Objectives, User Interface Software Conceptual Design, Load Cells Detailed Design, E&S Technical Risks, Logistical Risks, Organizational Chart, Work Breakdown Structure, and Work Plan. Finally, I also was the final editor on all deliverables (PDD, CDD, PDR, CDR, FFR, MSR, TRR, SFR, PFR, SAWE paper, User Manual), including checking spelling/grammar, acronyms, references, formatting, and that the deliverables included all required information.

During the manufacturing phase, I helped prepare raw materials for assembly by cutting I-beam to the design length and shape and drilling and tapping holes in the beams for fasteners. Lastly, I was a primary engineer on the Measurement Accuracy Test, which consisted of measuring the weight and CG of a test article, analyzing results for accuracy, and identifying and mitigating sources of error.

9.8 Bailey Roker

I work with others on electronic design, safety documentation for testing and testing procedures. I led the electronics design for WASP. I help assisted Aidan with reviewing the testing procedures and emphasized key safety concerns for each test. On the safety team I was assigned to overlook dangers and concerns during testing. For the FFR, I worked on the electronic functional block diagram as well the flowchart. I completed the test plan for WASP's electronics functionality. I reviewed the project's specific objectives, concept of operations, WASP's high level functional block diagram, the baseline design for WASP, and the critical project elements.

9.9 Parker Simmons

I worked along side the systems, testing, manufacturing and safety teams. My systems work included integration with the safety team to ensure all safety components were integrated successfully. Along side this, my systems work was heavily on the SAWE conference paper, user manual, and other project reports(documents and presentations). Working hand in hand, testing work revolved around supporting the testing leads during the lug mount tensile test, measurement accuracy test, and systems accreditation test. As apart of the manufacturing team my work consisted of going into the shop around 12 hours a week for most of the semester to ensure the completion of the WASP structure. As a co-lead to the safety team I helped with the implementing safety checks, team activities and ensuring safety was covered in the user manual and other documents. For FFR, my tasks were writing project purpose, requirement flow down, manufacturing integration, and risk identification.

9.10 Matthew Zola

I helped ensure that the product being manufactured matched the CAD design, and facilitated any design changes when they came up. As the financial manager, I made all of the purchases and logged them as expense reports in the Concur system. Additionally, I help with the structural integrity test by helping correlate the experimental data with FEM simulations. Finally, I assisted with manufacturing and testing as much as I could get into the shop. For the report, I wrote the cost analysis section and assisted with the structural design sections.

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Appendix

Appendix A: Design Alternatives and Trade Studies

The following section describes the design concepts considered during the first month of the project to address the most critical aspects of the problem being solved.

Structures

A.1 Testbed Configuration

To mount the ISR pod onto the frame for testing, a testbed with lug mounts and force transducers had to be included in the design. This testbed design is the method by which weight and inclination measurements will be completed. These measurements will be used to calculate the CG location. A method for attaching the pod and force sensors to the frame that does not introduce a significant amount of uncertainty to the calculation of CG is important for remaining within accuracy the tolerances. The following three options were considered when selecting the testbed design.

Direct Connection to Frame

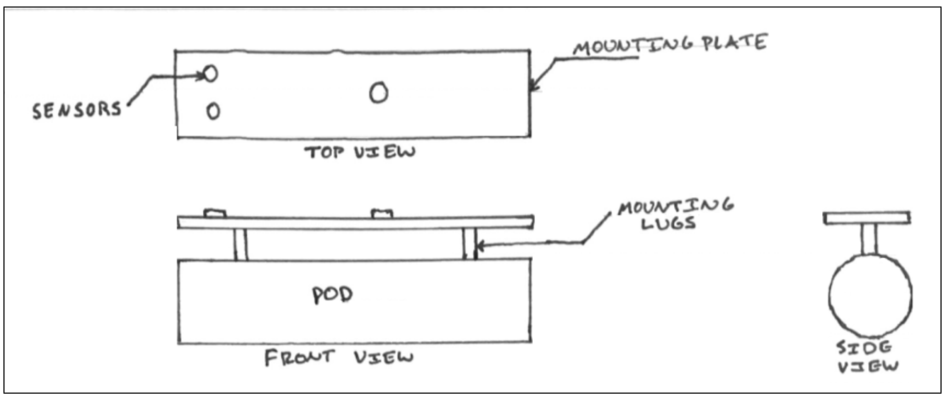


Figure 102: Direct Connection to Frame

The first design option considered for the testbed is the direct connection to the frame. In this concept, the ISR pod is mounted onto a plate by the lugs included on each pod. This plate is then mounted directly onto the top of the frame by force transducers. The largest problem with this design is that the force transducers must rotate with the pod. This introduces a large degree of complexity to the calculation of CG, as well as the potential to damage the force sensors by loading them in ways they are not designed to be loaded (i.e. shear). Table 10 summarizes some of the pros and cons of the direct connection to frame design option.

Table 10: Pros and Cons - Direct Testbed

Pros	Cons
Lightweight	Force sensors rotate with pod
Very simple implementation	Separate tilting mechanism

Indirect Connection to Frame

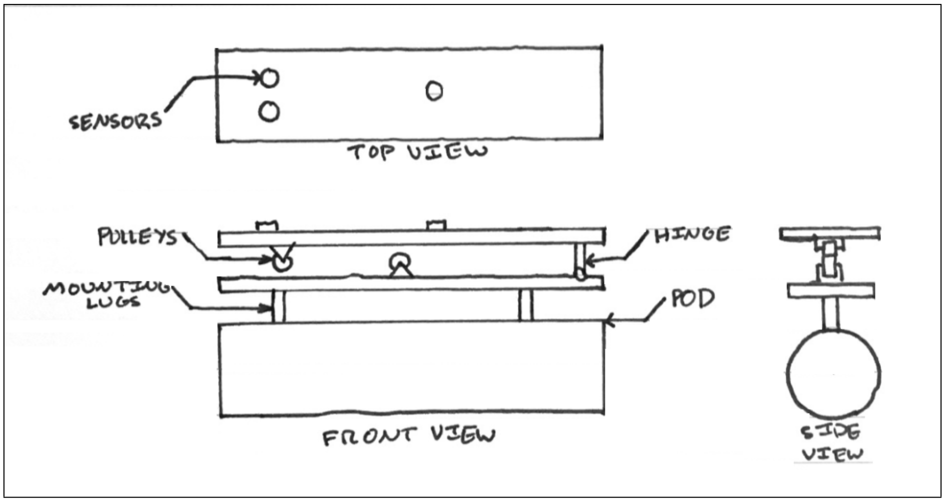


Figure 103: Indirect Connection to the Frame

The second design alternative considered for the testbed is designed to solve the problem of the sensors moving with the ISR pod. With the indirect connection to the frame, the pod is mounted onto a plate by its lugs. This plate is mounted onto another plate through a tilting mechanism, such as a pulley system shown in Figure 103, and the second plate is, in turn, mounted onto the WASP frame by force transducers. This design is more complex and much heavier than the direct connection because it includes more plates. The major advantage is that the force transducers remain completely static during testing and are loaded axially.

Table 11: Pros and Cons - Indirect Testbed

Pros	Cons
Tilting mechanism included in testbed	Heavy
Force sensors static during testing	Complex implementation

Hybrid Connection to Frame

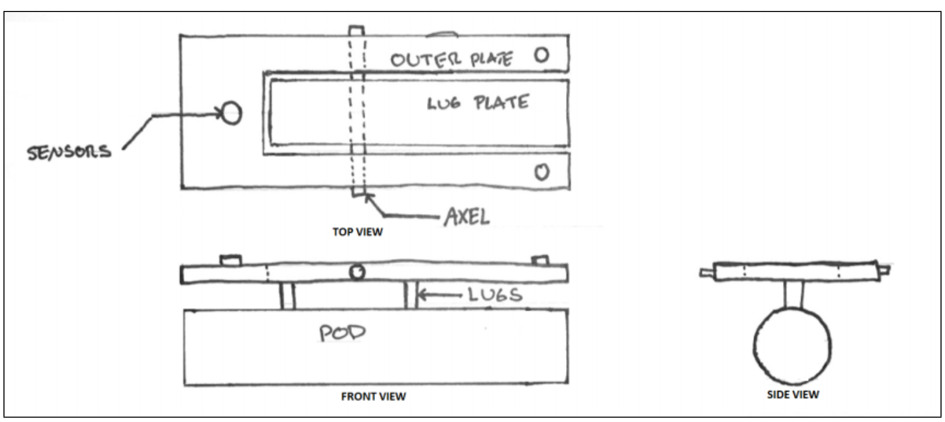


Figure 104: Hybrid Connection to Frame

The hybrid design, pictured above in Figure 104, attempted to solve both the problems of the direct and indirect connection methods by simplifying the tilting design of the indirect connection method. In this design, the ISR pod is again mounted onto a lug plate. However, the hybrid connection design mounts the lug plate onto the outer, static mounting plate by an axle, allowing it to rotate about the Y-axis without adding significant complexity. The only major disadvantage of this design is that it limits the number of locations at which force transducers could be placed, which might influence the sensitivity of the analysis of CG.

Table 12: Pros and Cons - Hybrid Testbed

Pros	**Cons**
Tilting mechanism included in testbed	Large plates
Force sensors static during testing	Limits sensor attachment locations
Relatively simple implementation	

Trade Metrics

With these options in mind, the following scoring system was employed in a trade study:

Table 13: Considerations and Weights for Testbed Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Degrees of Separation Between Force Sensors and ISR Pod	20%	**FR 2, DR 2.1**	Any errors in tilt angle and X CG cause errors in the Z CG calculation. These errors can be greatly reduced by having there be as few components between the force sensors and the pod as possible.
Weight	15%	**FR 1, DR 1.1, FR 2, DR 2.1**	The testbed weight directly affects the accuracy of measurements. Any weight applied to the load sensors other than the pods themselves is disadvantageous because it decreases the effective full scale of each sensor. Thus, the true full scale accuracy is lower than anticipated. For example, if a load cell is rated for 1000 lbs with a full scale accuracy of ± 1 lb (0.1%) but the testbed weight is 100 lbs, the load cell will effectively be rated for 900 lbs with a full scale accuracy of ± 1 lb (0.111%). A low weight is desirable to keep the accuracy of weight measurements as high as possible.
Complexity	15%	**Time and Resources**	Simplistic designs greatly increase the chances of successfully completing this project in the allotted nine month time frame. Complex designs would have to be rushed and adequate analysis would be very difficult to complete, leading to problems with safety and usefulness.
CG Measurement Accuracy	30%	**FR 2, DR 2.1**	Load sensors must be positioned such that simple, reliable equations can be formed for CG determination. Correctly using load sensors is extremely important to ensure accuracy and repeatability of measurements are maintained. Since accuracy is one of the most important aspects of this project, this metric is weighted strongly.
Stability	20%	**FR 1, DR 1.1, FR 2, DR 2.1, DR 3.1, FR 7**	The stability of the testbed with respect to the frame affects both safety and accuracy of measurements. For example, if the testbed were to sway, it could cause structural failure as the device will be designed to withstand specific static loads. Swaying can also introduce error in force measurements.

These metrics were ranked in the following way:

Table 14: Testbed Metric Rankings

Metric	1	2	3	4	5
Degrees of Separation between Sensors and Lugs	≥ 5	4	3	2	1
Weight	$\geq$ 2 plates + moving parts	N/A	1 place + moving parts	N/A	1 plate
Complexity	>20 parts	16-20 parts	10-15 parts	6-9 parts	1-5 parts
CG Measurement Accuracy	Testbed geometry adversely affects the accuracy of the CG calculations and poses a risk to the sensors	N/A	Testbed geometry adversely affects the accuracy of the CG calculations	N/A	Testbed provides the optimal geometry to ensure the load sensors have the least amount of uncertainty
Stability	Testbed has no static points of contact with the frame	N/A	Testbed has one static point of contact with the frame	N/A	Testbed is connected directly to the frame

With the metrics defined, a trade study (shown in Table 15) was conducted.

Table 15: Testbed Trade Evaluation

Metric	Weight	Direct	Indirect	Hybrid
Deg. of Separation	0.2	4	3	3
Weight	0.15	5	1	5
Complexity	0.15	4	1	3
CG Measurement Accuracy	0.3	1	5	5
Stability	0.2	5	1	3
Total	1.0	3.45	2.6	3.9

According to this study, the hybrid testbed configuration was most likely to lead to project success. Justification for the assigned ratings are given below.

Direct Connection

Deg. of Separation: 4 - In the direct case, there are (conceptually) only two components between the force sensors and pod: a plate, and lug mounts.

Weight: 5 - This concept does not have any moving parts within the testbed, and there is only one plate.

Complexity: 4 - It was the belief of the designers at the time the trade study was conducted that the only components that needed to be designed were the lug mounts, an interface piece between the mount and the pod (such as a pin), an interface between the mounts and the plate, the plate, the load cell attachments to the plate, and the load cell attachments to the frame. This totals to 6 parts, which according to Table 14 has a ranking of 4.

CG Measurement Accuracy: 1 - This method introduces several accuracy issues, including moments and shear on the force sensors. Creating equations that take these into account when they cannot be adequately measured would have been virtually impossible.

Stability: 5 - The testbed plate would have been directly connected to the frame via the load cells in this case.

Indirect Connection

Deg. of Separation: 3 - In the indirect case, there are two plates and lug mounts between the sensors and pod.

Weight: 1 - This concept included two plates and moving parts between them.

Complexity: 1 - This design would have included multiple pulleys, a cable, a hinge, lug mounts, interfaces between the mounts and the bottom plate, interfaces between the load cells and plates, and two plates. Overall, it would have realistically ended up being more than 20 individual parts.

CG Measurement Accuracy: 5 - In this case, the load cells would have always been loaded axially since they were sandwiched between the frame's top and a static plate.

Stability: 1 - The testbed plate would have been connected to the frame via a hinge and cable, neither of which are fully static with respect to the frame.

Hybrid Connection

Deg. of Separation: 3 - As with the indirect case, the hybrid concept features two plates and lug mounts, leading to three degrees of separation between the load cells and the pod.

Weight: 5 - While there are technically two plates and an axle in this design, the plates and axle combined would have been the same size as one of the plates in the other two concepts, and thus this was treated as a single plate.

Complexity: 3 - Here, two plates, an axle, lug mounts, and all the interfacing were required to make this design work. Since there were no pulleys, it was determined that there would likely be between 10 and 15 parts to successfully create this design.

CG Measurement Accuracy: 5 - In this case, the load cells would have always been loaded axially since they were sandwiched between the frame's top and a static plate.

Stability: 3 - The testbed plate would have been connected to the frame via a hinge and cable, neither of which are fully static with respect to the frame.

A.2 Lifting Mechanism

SNC has requested that the lug mounts be the only point of rigid connection between the ISR pods and WASP. Therefore, the pods are suspended from the lug mounts in most designs. Thus, a reliable, safe, and robust mechanism had to be developed to lift these large pods. A chain hoist, hydraulic system, and pulley system were all considered. Their functionality as well as benefits and weaknesses are described below.

Chain Hoist

The chain hoist in Figure 105 is a simple device in which an extremely compact pulley/gear system is used to decrease the amount of force required to lift an object. Generally, one chain loop is attached to the object being lifted while another is free to be pulled by a person. The chain hoist has a trade-off between force required and distance lifted. That is, the hoists employ a gear box to transform a small force over a long distance into a large force over a short distance [10]. Figure 106 portrays how a chain hoist may be employed for WASP. An off-the-shelf hoist can be connected to the frame and then attached to the testbed.

Figure 105: Generic Chain Hoist

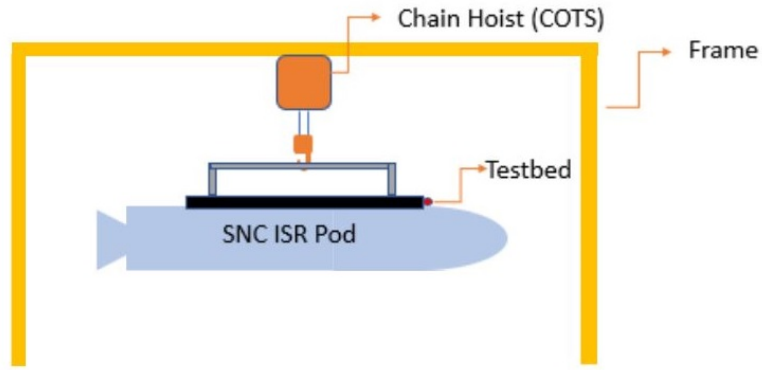


Figure 106: Chain Hoist Lifting Mechanism on WASP

The benefits and drawbacks associated with using a chain hoist are shown in Table 16. The main advantage of using a chain hoist is that it would be an off-the-shelf, reliable component that would require little design to interface with the frame and testbed. A major disadvantage is the long lifting time associated with the force-distance trade-off discussed above.

Table 16: Pros and Cons - Chain Hoist Lifting Mechanism

Pros	Cons
Component off the shelf	Long lift time
Internal braking	High concentrated point load on frame
Simple design/implementation	Difficult to use for tilting
Affordable	

Hydraulics

A hydraulic system leverages high pressures and the near-incompressibility of fluids to move objects. For WASP, this would manifest as pistons inside hollow, static legs that could lift extendable legs on the frame. A motor-pump combination would drive the pistons up and down through high-pressure tubes and control valves. A reservoir would contain liquid at atmospheric pressure and would be used to relieve piston pressure when lowering the ISR pods. Figure 107 illustrates this concept.

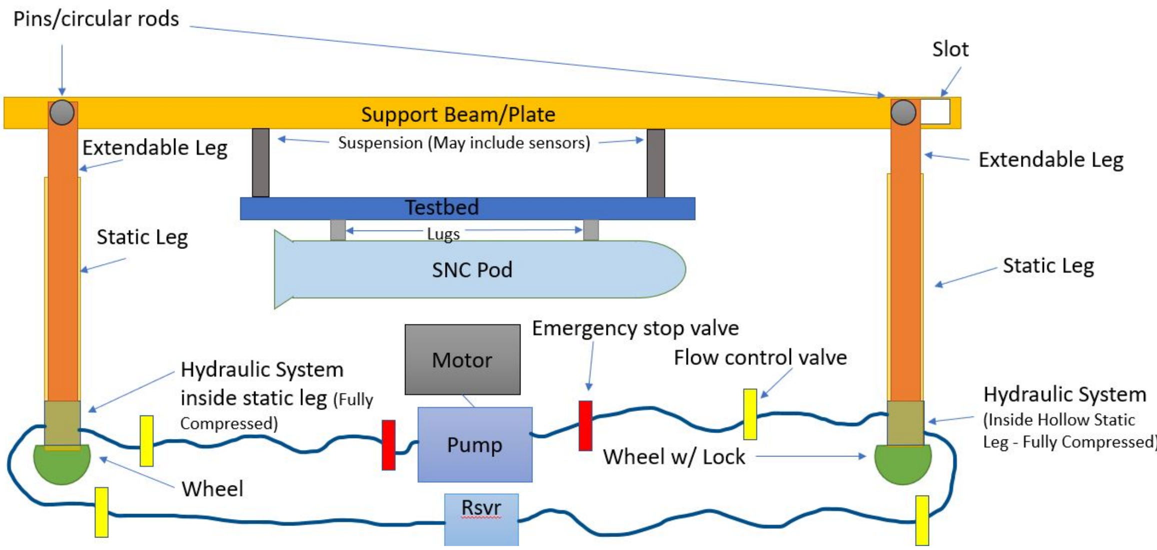


Figure 107: Hydraulic Lifting Mechanism on WASP

A hydraulic system offers the best choice for smooth, easy lifting. However, such a method would be extremely expensive relative to the other methods presented. Furthermore, with this team's current experience with hydraulics and the number of components associated with such a mechanism, the chance of failure is relatively high. The pros and cons of using hydraulics are summarized in Table 17.

Table 17: Pros and Cons - Hydraulic Lifting Mechanism

Pros	Cons
Components off the shelf	Very expensive
Smooth, powerful lifting	Many components/points of failure
	Significant design time required

Pulley System with a Brake Winch

The final lifting design considered is a pulley system with a brake winch. The brake winch is an off-the-shelf crank system with internal braking that would allow a set of cables to lift the testbed. The pulleys would decrease the total force the brake winch would have to impart on the cable to cause lifting. Figure 108 portrays how this system may be employed for WASP.

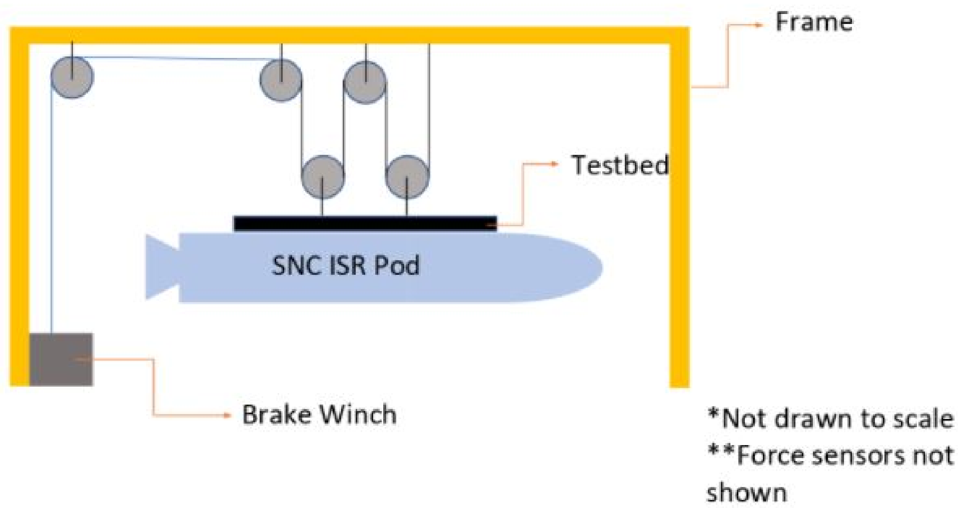


Figure 108: Pulley Lifting Mechanism on WASP

A pulley mechanism would be very similar to a chain hoist. The positive differences are that the lift time would not be as long with pulleys and the load would be more evenly distributed along the frame. Some negative differences are the added costs of various pulleys and cables, and it would require much more integration into the design than an off-the-shelf component. A full list of advantages and disadvantages for a pulley system are given in Table 18.

Table 18: Pros and Cons - Pulley Lifting Mechanism

Pros	Cons
Distributed load across the frame	Moderate cost
Off-the-shelf components pulleys	Cable design required
Simple interfacing design	Significant human exertion may be required

Trade Metrics

The following trade was completed to ensure a safe, reliable, and effective lifting method that fit budgetary and time constraints was chosen. Four metrics were explored, including cost, design/integration complexity, exertion required to enable lifting, and introduction of error. See Table 19 for the rationale behind the use of these metrics. Note that the maximum allowable load is an important quantity to consider during design, but was not included in the metrics because any of the lifting mechanisms considered could be designed/selected to support the necessary loads.

Table 19: Considerations and Weights for Lifting Mechanism Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Cost	20%	**Budget**	Due to the high loads involved in this project, the lifting mechanism will have to be made of high-strength materials and components. Thus, budgetary issues are a major concern. While specific dollar amounts cannot be determined at this point in the design process, the number of components required to implement each mechanism is an adequate indicator of cost.
Complexity of Design/Integration	30%	**FR 5**	Given the accelerated schedule for the design of WASP, complexity of design and integration must be taken into account to ensure the project is successfully completed in the given time frame. This metric is weighted at 30% because mission success depends more heavily on completing the project on time than it does on cost.
Required Exertion	20%	**DR 6.2**	The amount of force required to lift the ISR pods is a limitation in design - technicians and engineers cannot be expected to perform unreasonable manual labor (as defined in Table XIX of [9]).
Introduction of error	30%	**FR1, DR 1.1, FR2, DR 2.1**	Error in the weight, X CG, and Y CG measurements can be introduced if the testbed is not level or wobbling during level measurement collection. Some lifting design alternatives are based on chains and/or cables which could lead to such error. Since the accuracy requirements are extremely strict, this metric is weighted at a large value of 30%.

Table 20 features the metric ranks used for the lifting mechanism trade study.

Table 20: Lifting Mechanism Metric Rankings

Metric	1	2	3	4	5
Cost	5+ high-cost off-the shelf components and additional structural support required	N/A	2-4 high-cost off-the shelf components and additional structural support required	1 high-cost off-the shelf component and additional structural support required	No high-cost off-the-shelf structural components
Complexity	Components must be designed/selected and significant frame/testbed design will be associated with the lifting mechanism	N/A	Components require some significant interface/integration design and some frame/testbed design will be associated with the lifting mechanism	Components require some significant interface/integration design	Components can be easily connected to the rest of the frame without significant integration design
Required Exertion	>75 lbs	55-75 lbs	35-55 lbs	<35 lbs	None
Introduction of Error	Significant swaying and noticeable tilting of mounting interface after lifting	Mounting face could be noticeably tilted after lifting	Significant swaying	Small oscillations after lifting that die out quickly, mechanism can be locked once lifted	No swaying or tilting after lifting, mechanism can be locked once lifted

Table 21 holds the lifting trade evaluation.

Table 21: Lifting Mechanism Trade Evaluation

Metric	Weight	Chain Hoist	Hydraulic System	Pulley System
Cost	0.2	4	1	3
Complexity	0.3	4	1	3
Required Exertion	0.2	3	5	3
Introduction of Error	0.3	4	5	4
Total	1.0	3.8	3.0	3.3

The chain hoist appeared to be the most practical method for lifting pods in this project considering all requirements as well as budgetary and time constraints. The exact scoring of each design alternative based on these metrics is outlined below.

Chain Hoist

Cost: 4 - The chain hoist system only requires one high-cost off-the-shelf component (the chain hoist itself). According to Table 20, this got a ranking of 4.

Complexity: 4 - The chain hoist will require some significant interfacing design and integration, but theoretically would work with any of the frame and testbed designs.

Required Exertion: 3 - It is estimated from BOTE calculations that the engineers or technicians using WASP would exhibit no more than 35-55 lbf to lift the heaviest pods using the chain hoist, which got a score of 3 according to Table 20.

Introduction of Error: 4 - The chain hoist could lead to small oscillations and swaying of the testbed during transient states. However, the testbed can be locked in place after lifting, so this systems was scored at 4.

Hydraulics

Cost: 1 - The numerous high-cost off-the-shelf components required for the hydraulics system would include the motor, pump, reservoir, control valves, and sealed legs. This got a score of 1 according to Table 20.

Complexity: 1 - Because the hydraulic system would directly drive the design of the frame, this also got a score of 1.

Required Exertion: 5 - The engineer or technician using WASP would only have to press a button to lift and lower pods, requiring negligible force. According to Table 20 this got a score of 5.

Introduction of Error: 5 - Because the frame would essentially act as the lifting mechanism, the testbed would not be subject to any possibly swaying or oscillations.

Pulley System with a Brake Winch

Cost: 3 - A pulley system would require the purchase of pulleys and cable. These two items got this system a score of 2 in terms of cost according to Table 20.

Complexity: 3 - Both the frame and the testbed would need to interface with multiple pulleys. This gets a score of 3 according to the metric.

Required Exertion: 3 - The expected force required from the WASP operators was the same as that of the chain hoist, so the pulley system also gets a score of 3 in this category.

Introduction of Error: 4 - Also similar to the chain hoist, the cables introduce the possibilities of swaying and oscillation into the design. However, the testbed could again be rigidly connected to the frame once lifted so this got a score of 4.

A.3 Tilting Mechanism

To measure the center of gravity of an object in three dimensions with load sensors, some sort of tilting is necessary. Load measurements in a level configuration give no indication of where the CG is in the third dimension - the moment balance required to keep the system static would be the same for a given X and Y CG, regardless of where the Z CG was. Thus, an additional set of load measurements at a tilt angle is required to determine the Z CG, as represented in the following equations, taken from [2].

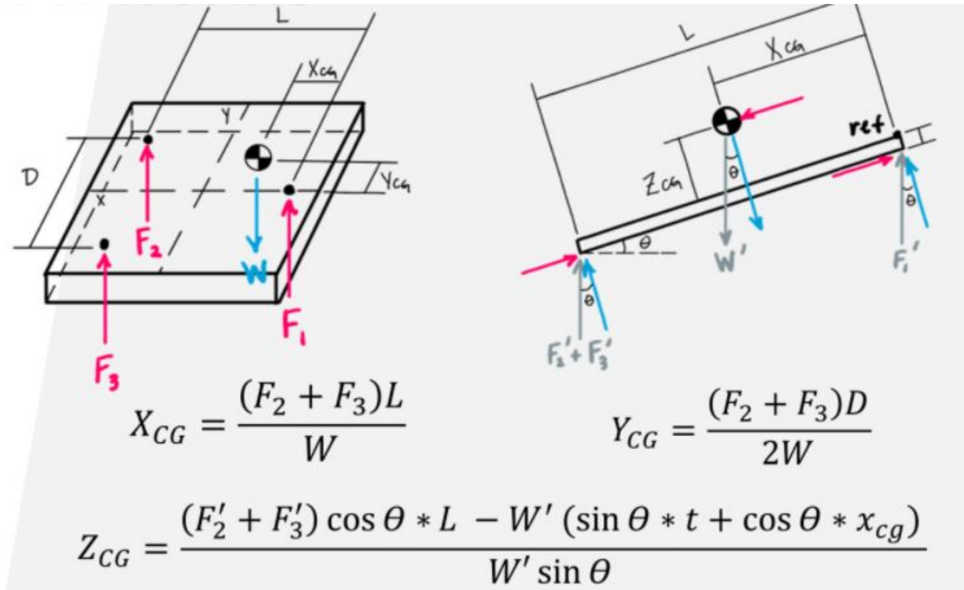
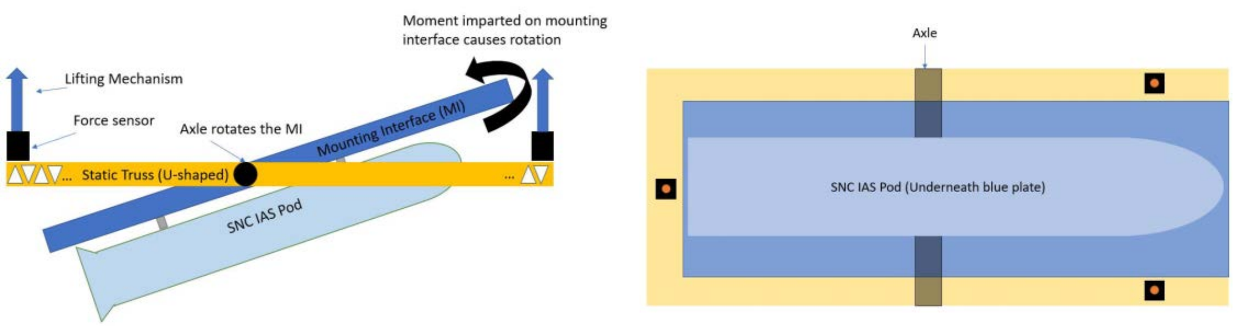


Figure 109: Generic CG Determination Equations Using Load Sensors [2]

Four methods for tilting are described below. It should be noted that the locations of the load sensors in the following sketches are for visual purposes only and were subject to change as the design matures. Furthermore, there is significant overlap between this trade and the testbed configuration trade discussed above, since the tilting mechanism is either integrated or directly interacts with the testbed. Thus, there were some compatibility issues between some of these concepts and those discussed in the testbed configuration. These are discussed in the baseline conceptual design section after the trade studies.

Suspended Mounting Interface with Axle

The first tilting design features two elements connected by an axle. The external element is a static truss or plate (outer testbed), while the internal one is an ISR pod-mounting interface that rotates with the pod (inner testbed). When a moment is applied to the inner testbed, the system rotates, as shown in Figure 110.



Front View

Top View

Figure 110: Axle-Based Tilting Mechanism

This system offers a simple, safe, and effective method to tilt the pods while minimizing force sensor error (discussed in Section 5). Pros and cons associated with this method are listed in Table 22.

Table 22: Pros and Cons - Axle-Based Tilting Mechanism

Pros	Cons
Force sensors do not rotate	Robust braking system required to prevent unwanted rotation
Simple design	High shear stress on axle
Inexpensive	

Suspended Mounting Interface with No Axle

The second mechanism considered for tilting the pods involved a testbed suspended from cables or chains from which the force measuring system would be connected, pictured in Figure 111. Tilting the testbed would be achieved by lowering the chain/cable on one side of the testbed.

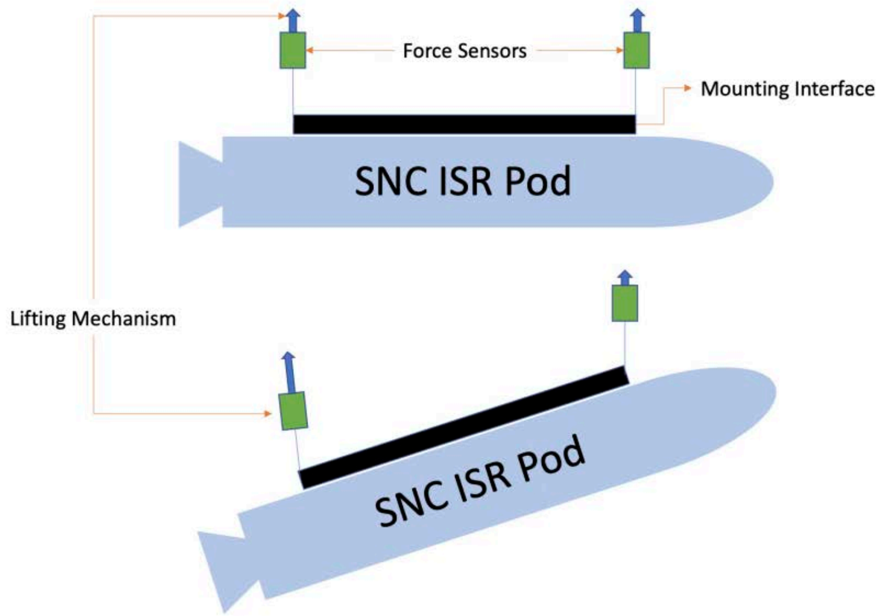


Figure 111: Suspended Testbed Tilting Mechanism

This design would be simple and cost-effective to design and implement. However, the CG calculations would be difficult and potentially inaccurate due to tilting of the measurement axis of the sensors. The complete list of pros and cons for this design are shown in Table 23.

Table 23: Pros and Cons - Suspended Testbed Tilting Mechanism

Pros	Cons
Simple design	Force sensors rotate
Easily integrates with cable lifting system	High stress points between chain/cable and testbed
Inexpensive	

Parallel Plate Suspension

This concept improves upon the suspended testbed design concept by preventing the force sensors from rotating. Two interface plates are suspended with force sensors in between, as shown in Figure 112. As the upper plate is tilted, the lower plate also tilts while keeping the force sensors perpendicular to the ground.

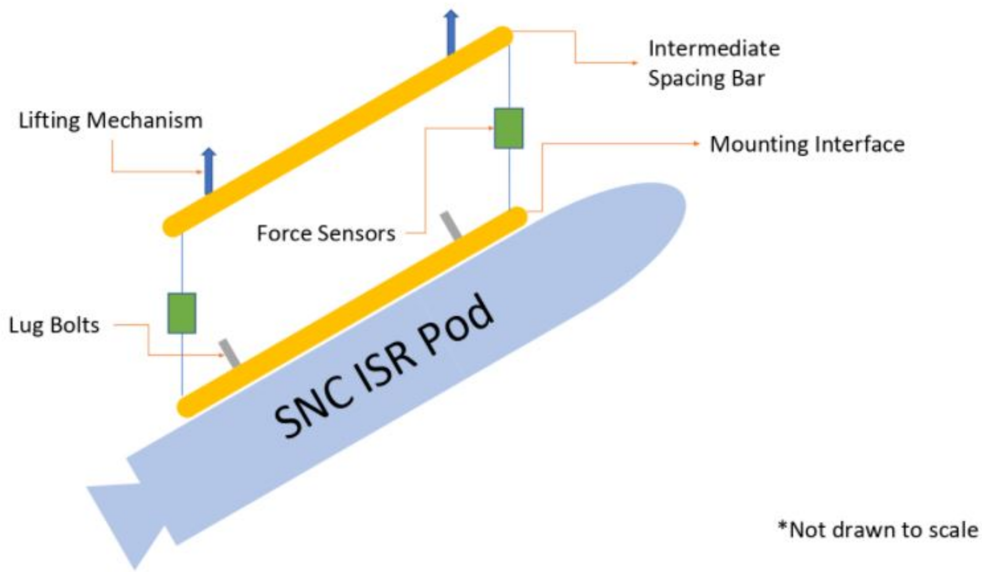


Figure 112: Parallel Plate Tilting Mechanism

This design would simplify the CG calculation compared to the suspended plate design, while remaining fairly inexpensive and simple. The downside would be adding the weight of an additional plate to the lifting mechanism and the high-stress connection points. The pros and cons of this design are outlined in Table 24.

Table 24: Pros and Cons - Parallel Plate Tilting Mechanism

Pros	Cons
Force sensors do not rotate	Multiple high-stress connection points
Simple design	Prone to swaying
Inexpensive	

Cradle Platform Tilts Pod from Below

This concept involves rolling the cradle and ISR pod onto a platform and rotating the entire platform into the air, shown in Figure 113.

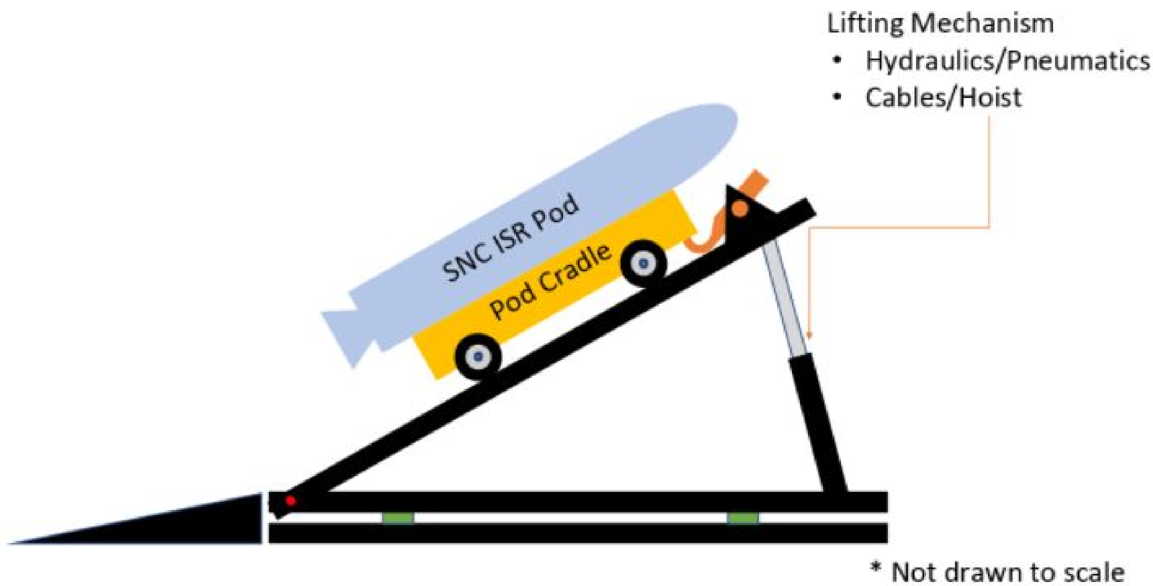


Figure 113: Cradle Platform Tilting Mechanism

This abstract design allows for the use of compression load cells without an extremely heavy frame, which would improve the accuracy of the load cell measurements. However, rigidly securing the pod and cradle to the platform would be difficult, and the design would not interface well with any lifting mechanism. Furthermore, the weight and CG of the tilting mechanism and pod cradle would both have to be known very accurately so that they could be tared from the measurement of the pod CG. The pros and cons are displayed in Table 25.

Table 25: Pros and Cons - Suspended Testbed Tilting Mechanism

Pros	**Cons**
Force sensors do not rotate	Difficult to interface with lifting mechanism
Compression load cells with lower frame weight	Pod/cradle must be rigidly secured
Eliminates need for mounting interface	Cradle weight/CG must be known and accounted for
	Cradle/Tilting Mechanism CG would have to be known beforehand.

Trade Metrics

The tilting must be precise, safe, simple, and feasible in order to satisfy all requirements. To encapsulate these considerations, four metrics (cost, design complexity, CG calculation accuracy/complexity, and stability) were created. Table 26 describes the reasoning for using these four metrics. Table 27 shows the ranks associated with each tilting trade metric.

Table 26: Considerations and Weights for Tilting Mechanism Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Cost	15%	**Budget**	The tilting mechanism will require actuation and structural support capable of rotating over 2000 lbs. The components associated with actuation and support will add additional strain to the budget. This is weighted at only 15% because the tilting design is relatively inexpensive compared to the lifting mechanism, sensors, and other aspects of WASP.
Complexity of Design	30%	**Time and Resources**	With little time to produce a robust weight and balance device, design complexity plays a significant role in the selection of a baseline design. The tilting mechanism is a critical aspect of WASP, and a simple concept allows more time for analysis and safety considerations.
Complexity and Accuracy of CG Calculation	35%	**FR 1, DR 1.1, FR 2, DR 2.1, FR 6**	The calculation of CG relies heavily on how sensors are loaded. If a sensor is being loaded in unexpected ways, such as shear, bending or torsion, simple moment balance equations based on normal force measurements will not return accurate results. Furthermore, loading a sensor in such ways will lead to damage and the repeatability of test results will be compromised.
Stability	20%	**FR1, DR 1.1, FR 2, DR 2.1, DR 3.1**	Here, stability is a measure of how static the connection between the tilting mechanism and frame is. The stability of the tilting mechanism with respect to the frame is important to consider as safety is a significant concern in this project. Furthermore, a less stable tilting mechanism is prone to additional movement during testing, which can cause repeatability and accuracy issues.

Table 27: Tilting Mechanism Metric Rankings

Metric	1	2	3	4	5
Cost	Requires multiple actuators and structural components	N/A	One actuator and structural component	N/A	No actuators; only requires structural support
Complexity of Design	Lifting mechanism and/or testbed must be designed to support the functionality of the tilting mechanism	N/A	Lifting and tilting mechanism are independent of each other	N/A	Tilting mechanism can be incorporated into any lifting mechanism
Complexity of CG Calculation	Force sensors rotate and the tilting mechanism adds significant weight to force sensors	Force sensors rotate but tilting mechanism does not add significant weight	Force sensors do not rotate but the tilting mechanism adds significant weight to the sensors	N/A	Force sensors do not rotate and the tilting mechanism does not add significant weight to the sensors
Stability	Tilting mechanism has no static points of contact with the frame	N/A	Tilting mechanism has one static, or multiple quasi-static, point(s) of contact with the frame	N/A	Tilting mechanism is connected directly to the frame

The trade evaluation for tilting is in Table 28.

Table 28: Tilting Mechanism Trade Evaluation

Metric	**Weight**	**Suspended w/ Axle**	**Suspended w/o Axle**	**Parallel Plates**	**Pod w/ Cradle**
Cost	0.15	3	3	3	1
Complexity of Design	0.3	3	1	1	5
Complexity of CG Calculation	0.35	5	2	5	3
Stability	0.2	3	5	5	3
Total	1.0	3.7	2.45	3.5	3.3

According to this study, the concept of rotating the suspended mounting interface using an axle was the most advantageous conceptual alternative, and was ultimately used when the structure was designed (although the testbed is now lifted from the inner plate, not the load cells). Rationale for all of the ratings in Table 28 are given below.

Suspended Inner Testbed with Axle

Cost: 3 - Although two plates and an actuator are required for this design, the cost was assumed to be relatively low. This is because the outer plate does not require much material, and the actuator using for tilting can also be used for lifting.

Complexity of Design: 3 - Since the CDD, there have been upgrades to this concept. In particular, both lifting and tilting use the same mechanism. However, because both lifting and tilting require additional components in this setup, it is not simple enough to rank as a 5.

Complexity and Accuracy of CG Calculation: 5 - The force sensors do not rotate and this concept is one of the lightest, meaning the accuracy will be relatively good.

Stability: 3 - The testbed has 3 connections to the frame in this case via the load cells. However, the load cells themselves move during lifting with this conecpt, and thus they can only be considered static during measurements. As such, the stability was awarded a value of 3.

Suspended Testbed with No Axle

Cost: 3 - This concept features a single plate and an actuator to lift one side more than the other.

Complexity of Design: 1 - Since the testbed is directly attached to the frame, it can only be tilted if the lifting mechanism lifts one side of the entire frame more than the other.

Complexity and Accuracy of CG Calculation: 2 - The single plate is relatively light, meaning that more of the full span of operation of the load cells can be applied to the pod (better accuracy). However, the load cells can have moments and shear forces on them, leading to innaccuracies.

Stability: 5 - The testbed would be directly attached to the static frame in this case.

Parallel Plate Suspension

Cost: 3 - If the intermediate spacing bar is the top of the frame, this design only requires a single plate and an actuator.

Complexity of Design: 1 - Both the testbed and lifting mechanism would have to be designed around this to ensure that it works.

Complexity and Accuracy of CG Calculation: 5 - The force sensors would always be axially loaded in this case, and the lower plate would not introduce much weight.

Stability: 5 - Although indirectly, the mounting interface would be connected to the frame in a rigid way in this concept.

Cradle Platform

Cost: 1 - Creating a massive floor plate that can move up and down and rotate would cost a significant amount of money. Additionally, a stationary plate would be required for the load cell configuration to function as intended.

Complexity of Design: 5 - This concept practically eleminates the need to lift. Even so, both lifting and tilting can be accomplished by the same device here.

Complexity and Accuracy of CG Calculation: 3 - Although the force sensors would always be loaded axially, the entire structure would be placed on the load cells, forcing higher FSO force sensors and thus decreasing accuracy.

Stability: 3 - Here, the tilting mechanism is a plate that connects to the stationary plate via a single axle.

A.4 Maneuverability

Caster Wheels

The first maneuvering design involves the use of caster wheels, seen in Figure 114. The caster wheels would mount directly to the legs or base of the frame to allow for easy maneuvering around the aircraft hangar. These wheels also allow for WASP to change orientation without additional design or materials. Caster wheels are readily available, can support large loads, and can be purchased with a locking mechanism to ensure there is no movement during testing. They would provide a simple way for only a few engineers to maneuver WASP. The pros and cons of using caster wheels can be seen listed in Table 29.

Figure 114: Caster Wheels

Table 29: Pros and Cons - Caster Wheels

Pros	**Cons**
Relatively affordable	Locking mechanism may not hold WASP completely static
Readily available	Wheels are not the most reliable
High load bearing ability	
Can easily move and reorient WASP	

Forklift Slots

The second maneuvering design would be the addition of forklift slots into the structure of the frame, as shown in Figure 115. An engineer would then be able to lift and maneuver WASP by use of a forklift. Implementing this design would require very little redesign to the frame and would not be complex to manufacture. The frame also would remain completely static during testing, eliminating the risk of measurement errors due to translational movement during the test procedure. The downside of this design is that it requires the use of additional machinery (forklift) to maneuver WASP. The pros and cons can be observed in Table 30.

Figure 115: Forklift Slots

Table 30: Pros and Cons - Forklift Slots

Pros	**Cons**
Inexpensive	Requires additional machinery
No frame redesign needed	
Can remain completely static	
Simple implementation	

Axle and Wheels/Tires

The next maneuverability design involves the use of a wheel and axle system, seen in Figure 116. This would require the addition of an axle system to the base of the frame with a mechanism for turning. Tires would be mounted to the end of these axles and would allow for two engineers to push WASP around an aircraft hangar. The addition of a braking or locking design would also be required. Designing this system would create additional complex tasks for the team, but could support high loads, and could potentially allow for even more robust maneuvering and locking capabilities. The pros and cons are seen in Table 31.

Figure 116: Wheel and Axle

Table 31: Pros and Cons - Axle and Wheels/Tires

Pros	Cons
Can support high loads	Requires additional complex designs
Can be moved translationally by two engineers	Difficult to turn
	Needs additional locking/braking
	Expensive

Motorized Wheels

The final maneuverability design involves the use of motorized wheels, see Figure 117. This design would have motorized wheels mounted to the frame/base of WASP that could be operated by the use of a remote controller. This design would require no labor from engineers and has the option for precisely controlled maneuvering of WASP. The wheels, however, would require the additional design of a braking/locking system to keep WASP and the ISR pod static. The pros and cons of this design alternative are listed in Table 32.

Figure 117: Motorized Wheels

Table 32: Pros and Cons - Motorized Wheels

Pros	Cons
Easy to maneuver	Very expensive
Precise maneuvering ability	Requires additional braking/locking design
Can support large loads	Requires the involvement of the E&S team for software and wiring design
	Has more moving parts that could fail

Trade Metrics

Because WASP must be highly maneuverable when not loaded with ISR pods and completely static during measurements, a high-fidelity maneuvering mechanism with powerful locking must be employed. Therefore, the metrics of cost, maneuverability, ability to remain static, and complexity were used to compare the alternatives discussed in Section 4.4. These metrics are defined and explained in Tables 33 and 34.

Table 33: Considerations and Weights for Maneuverability Mechanism Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Cost	20%	**Budget**	Once again, component cost is very important in this project due to the large number of expensive parts required to meet the loading and accuracy requirements.
Maneuverability	25%	**FR 4, DR 4.1, DR 4.2, DR 4.2.1**	WASP must be maneuverable about an aircraft hangar and must therefore adhere to the force limits in Table XVIII of [9]. Since various design requirements are entirely dependant on maneuverability, this is weighted higher than cost or complexity.
Ability to Remain Static	35%	**FR 4, DR 4.2.1**	WASP *must not* move during testing, as this would pose a danger while loaded with 2000 lbs. The frame will be designed to handle high loads under static conditions only, so structural failure could result from unwanted movement, especially with the device is loaded with high-weight pods. Also, load measurements can be skewed by movement, which would cause further accuracy and repeatability deficiencies.
Complexity	20%	**Time and Resources**	A complex system will require additional funds and engineering time. If too complex, the maneuverability system may be impossible for the team to complete within the given time frame and budget.

Table 34: Maneuverability Metric Rankings

Metric	1	2	3	4	5
Cost	7+ high-cost off the shelf components	5-6 high-cost off the shelf components	3-4 high-cost off the shelf components	1-2 high-cost off the shelf components	Zero high-cost off the shelf components
Maneuverability	Requires use of heavy machinery	Maneuverable by 3 engineers	Maneuverable by 2 engineers	Maneuverable by 1 engineer	Maneuverable through built in motors
Ability to Remain Static	A locking mechanism must be designed	N/A	Locking mechanism built in	N/A	Locking mechanism unneccessary
Complexity	Requires dedicated electronics and software as well as additions to frame	Requires major additions to frame	N/A	Requires minor additions to frame	Built into frame

Trade Study Results

The maneuverability trade was completed in Table 35. Based on this, the forklift slot design is a clear winner. Caster wheels are a fairly close second, and both options will be considered for the baseline design selection in Section 6.

Table 35: Maneuverability Trade Evaluation

Metric	Weight	Caster Wheels	Tire & Axle	Forklift Slots	Motorized Wheels
Cost	0.2	3	2	5	1
Maneuverability	0.25	3	3	1	5
Ability to Remain Static	0.35	3	1	5	1
Complexity	0.2	4	2	5	1
Total	1.0	3.2	1.9	4	2.0

Caster Wheels

Cost: 3 - High capacity locking caster wheels cost around $100 each. At least 4 would be necessary.

Maneuverability: 3 - Due to the expected weight and size of WASP, it is expected that two engineers would be needed to maneuver WASP while it is rolling on caster wheels.

Ability to Remain Static: 3 - Caster wheels can be purchased with a built in locking brake.

Complexity: 4 - Integrating caster wheels into the design of WASP would require minimal additions to the frame. A simple option would be plates mounted to the bottom of WASP with holes to attach the caster wheels to.

Forklift Slots

Cost: 5 - This design would not require any high-cost components.

Maneuverability: 1 - A forklift would be needed to maneuver WASP.

Ability to Remain Static: 5 - No locking mechanism would be needed to remain static during testing.

Complexity: 5 - The slots would be integrated into the frame itself; there would be no added complexity.

Tire & Axle

Cost: 2 - Implementing a tire & axle system would require more than 4 high-capacity components (multiple axles, bearings, and tires).

Maneuverability: 3 - It is estimated that 2 engineers would be needed to maneuver WASP on wheels.

Ability to Remain Static: 1 - A separate braking system would be needed to ensure WASP remains static during testing.

Complexity: 2 - Mounting bearings for the axles and implementing a braking system would require major additions to the frame.

Motorized Wheels

Cost: 1 - Motorized wheels would require multiple high-cost components (motors, axles, wheels, electronics)

Maneuverability: 5 - WASP could be maneuvered remotely with no human effort.

Ability to Remain Static: 1 - A separate locking mechanism would need to be designed and implemented.

Complexity: 1 - Both major additions to the frame as well as electronics and software would be needed.

Electronics and Software

A.5 Sensor to Computer Interface

In order to output meaningful measurements about the ISR pod weight and CG, it is necessary for sensors on WASP to transmit data to a UI to perform calculations. There is more than one way to achieve this interface between the WASP sensors and the computerized UI tool. This section presents the design alternatives that were investigated as possible solutions for this interface.

Hardwired Connection

The first design alternative for the interface between WASP sensors and the UI is simply a hardwired connection. In this design, the analog signal from the sensors are digitized by a DAQ, then the digital signal is sent through a physical connection to a computer to perform the required calculations. This option is the most simple in terms of components and implementation, but also provides restrictions on how the test can be performed, and may interfere with other WASP systems, such as the tilting and lifting mechanisms. A table of the pros and cons can be found below in Table 36.

Table 36: Pros and Cons - Hardwired Connection

Pros	Cons
Few components (wires, DAQ, power line)	Greater safety hazard (tripping over cords)
Easier verification of correct set up	Signal attenuation over long wire distances
	More difficult integration with WASP structure

Wireless Connection (Radio Frequency)

The second interface design alternative is a wireless connection. This design would utilize microprocessors connected to the DAQ and the computer running the UI, both fitted with a radio-frequency (RF) transmitter and receiver respectively, to wirelessly transmit the digital data between the two. This design increases the complexity of the interface, but allows for more flexibility and the potential for improved functionality over the hardwired connection. Some pros and cons for this design have been listed in Table 37.

Table 37: Pros and Cons - Wireless Connection (RF)

Pros	**Cons**
Improved user experience - more streamlined process, less user interaction at the sensor connections	To achieve required data reliability, extra complexity is necessary
Easily integratable consumer off-the-shelf (COTS) boards for Arduino/microcontrollers	Possibly restricted by customer
Lower cost for additional components	Many components (signal conditioning, DAQ, error checking, filtering)

Wireless Connection (Bluetooth)

This final interface design alternative is very similar to the previous wireless option. However, instead of utilizing RF modules to transmit the digital data, this design would employ Bluetooth modules. While this alternative is a similar design concept, the use of Bluetooth would slightly change various aspects of the design, including cost and implementation. Some pros and cons of this design alternative are tabulated below in Table 38.

Table 38: Pros and Cons - Wireless Connection (Bluetooth)

Pros	**Cons**
Improved user experience - more streamlined process, less user interaction at the sensor connections	Possibly restricted by customer
	Resources state might need to create an app to obtain data transfer
	Many components (signal conditioning, DAQ, error checking, filtering)

Trade Metrics

A trade study on the three design alternatives proposed for the interface between the WASP sensors and the computerized UI is needed to identify the best way to send data from the sensors to the computer. Again, the designs alternative considered are hardwired connection, wireless connection (RF), and wireless connection (Bluetooth).

Five metrics were selected for this trade study, listed in Table 39. Also included in this table are the weights assigned to each metric, which were arrived at qualitatively as the importance of each metric was weighed against the others. This table also includes a list of the requirements that motivated the selection of each metric, and a short explanation for the selection of each metric. Table 40 then defines how the rankings of each of these metrics will be defined for the eventual trade study.

Table 39: Considerations and Weights for Interface Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Connection to WASP structure	10%	**Resources and compatibility**	This metric is important for the integration of E&S into WASP. Interface must not increase complexity or impact other systems.
Dependability (of data delivery)	20%	**DR 1.1, DR 2.1**	Since this tool is a deliverable and not maintained by our team, maintenance is very limited. Dependability of the system to deliver correct data is essential.
Complexity	35%	**Time and resources**	Will impact work-hours required for success and training required for use by SNC engineers.
Cost	15%	**Budget**	Budget will need to allow for expensive components (focused on materials for the frame and sensors). Therefore, a limited budget here is essential for the success of other components
Test set-up	20%	**DR 6.1.1, DR 6.2**	Overall test set-up time and maneuverability of this tool is important for limiting test time and increasing functionality. This metric measures any added complexity and difficulty by the E&S interface to WASP testing and transportation procedures.

Table 40: Interface Metric Rankings

Metric	1	2	3	4	5
Connection to Wasp structure	Integration requires a change in structural design and/or negatively impacts other WASP systems.	Integration requires multiple (5-10) mounting locations to avoid interfering with other WASP systems.	Integration requires several (3-5) mounting locations on WASP frame.	Integration requires few (1-2) components mounted to WASP frame.	Does not require any integration with WASP frame.
Dependability (of data delivery)	Prone to disruptions in communications, level of error causes failure of data communication to computer.	N/A	Additional software or hardware elements to combat the occurrence of disruptions in the communications link ensures dependability of data delivery. Random error may still occur.	N/A	Interface does not introduce any decrease of dependability of data delivery, other than expected line loss and degradation of electrical components over time.
Complexity	Interface consists of DAQ, wiring, and microcontroller + additional modules with supporting software.	N/A	Interface consists of DAQ, wiring, and microcontroller + additional modules.	N/A	Interface consists of DAQ and wiring.
Cost	> $90	$80 – $95	$65 – $80	$50 – $65	< $50
Test set-up	Hardware impacts necessary test configuration (with respect to WASP, test computers, and engineers) and increases difficulty of transportation procedures.	N/A	Hardware impacts necessary test configuration (with respect to WASP, test computers, and engineers).	N/A	Hardware does not impact test configuration (with respect to WASP, test computers, and engineers).

Trade Study Results

Based on the results of this trade study, it is evident that a hardwired connection is the recommended interface design alternative. While this design presents unfavorable challenges by way of physical restrictions in integrating with WASP structure and test operation, its simplicity, dependability, and lighter financial load outweigh those negatives.

Table 41: Interface Trade Evaluation

Metric	Weight	Hardwired Connection	Wireless Connection (RF)	Wireless Connection (Bluetooth)
Connection to Frame	0.1	2	4	4
Dependability	0.2	5	3	3
Complexity	0.35	5	3	3
Cost	0.15	5	3	2
Test Setup	0.2	1	5	5
Total	1.0	3.9	3.5	3.35

Hardwired Connection:

Connection to Frame: 2 - A wired connection would require multiple mounting points to ensure all cables are out of the way of the lifting and tilting mechanism.

Dependability: 5 - A hardwire connection does not introduce any errors to the data.

Complexity: 5 - A wired connection only requires a DAQ system and wires.

Cost: 5 - Initial estimates (not including the DAQ) put the cost of the necessary wires at less than $50 (3 RJ50 at $15 each).

Test Setup: 1 - A wired connection limits the test configuration, as the test computer must be set up close enough for the wires to physically reach.

Wireless Connection (RF):

Connection to Frame: 4 - This interface configuration requires only a microprocessor with an RF module attached to the frame. Much less complexity in terms of physical integration.

Dependability: 3 - RF communications necessitate the use of filtering and signal conditioning in order to achieve dependable data.

Complexity: 3 - This design option requires a DAQ, microcontrollers both on WASP and at the test computer, RF modules, and additional wiring.

Cost: 3 - An initial cost estimate for two Arduino UNOs, the RF modules, and cables results in a cost of $71.

Test Setup: 5 - Wireless communication allows complete freedom of the test setup configuration, with respect to the WASP, test computers, and engineers.

Wireless Connection (Bluetooth):

Connection to Frame: 4 - This interface configuration requires only a microprocessor with a bluetooth module attached to the frame.

Dependability: 3 - Bluetooth communications necessitate the use of filtering and signal conditioning in order to achieve dependable data.

Complexity: 3 - This design option requires a DAQ, microcontrollers both on WASP and at the test computer, bluetooth modules, and additional wiring.

Cost: 2 - The initial cost estimate for two Arduino UNOs, bluetooth modules, and cables is approximately $85.

Test Setup: 5 - Wireless communication allows complete freedom of the test setup configuration, with respect to the WASP, test computers, and engineers.

A.6 User Interface Software

As the final component in the data acquisition stream, a computer-based software program will perform the required analyses to ultimately output the weight and CG location values of the ISR pod. The measurement sets collected from the on-frame sensors will be recorded and processed by various algorithms that altogether comprise the User Interface. Design requirements of the UI are specified in FR8. This section introduces the design alternatives considered for the UI platform.

Microsoft Excel

Microsoft Excel provides two main options for a user interface. First, the workbook environment itself could be constructed as an auto-populating form that is nested with formulae that compute the weight and CG location values. Second, more user-friendly userforms could be developed from scripts written in Microsoft Visual Basic for Applications (VBA) language to import data and manipulate it appropriately to obtain weight and CG location values. Developing an Excel tool is the preferred method by the customer, since SNC engineers primarily work with data in the form of Excel workbooks. Table 42 below summarizes the pros and cons for using Excel to create the UI.

Table 42: Pros and Cons - Microsoft Excel

Pros	**Cons**
Customer-preferred platform	Graphics must be created from scratch
Correct results filetype	Direct data import requires external programming [19]

MathWorks MATLAB

A MATLAB-based UI would require back-end scripting in MATLAB's unique coding language. MATLAB has a graphical user interface toolbox that provides a variety of input box and userform options [18]. MATLAB is particularly powerful in processing large sets of data, which would be useful for this project as repetitions of measurement sets from the on-frame sensors are collected. Table 43 below summarizes some key pros and cons of this option.

Table 43: Pros and Cons - MathWorks MATLAB

Pros	**Cons**
All team members proficient in this language	Graphics must be created from scratch
Capable of direct data import	

NI LabView

National Instruments (NI) LabView software is a high-level graphical design platform created specifically for controlling experimental variables and visualizing data from such experiments. The platform utilizes a graphics construction toolbox that allows a developer to customize the display to include control devices, such as dials and switches, and results figures, such as graphs and tables. LabView interfaces particularly well with NI DAQs and sensors. Table 44 below summarizes additional pros and cons.

Table 44: Pros and Cons - National Instruments LabView

Pros	**Cons**
Pre-built results visualizations	SNC does not have currently have license
Can read data from sensor input	No team members have experience with development
Experienced developers on PAB (Trudy, Bobby)	

Trade Metrics

With the above considerations in mind, five meaningful metrics were established: NI 9237 DAQ Compatibililty, Team Previous Experience, SNC Previous Experience, Customer Usage, and Computation Capabilities. These metrics consider both the risks and rewards on the development side, as well as such on the final product side. Table 45 further summarizes the metrics, their relative weighting, and rationale for their consideration in more detail.

Table 45: Considerations and Weights for User Interface Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Team Previous Experience	30%	**Time and Resources**	The skill-level of the UI developers with the selected UI platform and coding language will dictate the time required to create the UI. Given the tight schedule of this project, it is crucial that UI development is as time-efficient as possible to enable developers to support the other complex elements of WASP.
SNC Previous Experience	20%	**FR 8**	It is necessary that the SNC customer is able to run the UI program, likely enabled by having access to licenses for the chosen software. Additionally, the customer's functional experience with the chosen platform could impact successful execution of UI.
Customer Usage	15%	**Customer Satisfaction**	Since the mission of this project is to streamline the mass properties evaluation process for the pods, it is important that the UI further simplifies the test process and alleviates any frustrations of the data acquisition and processing aspects of the original method.
Data Import and Capabilities	35%	**FR 8, DR 8.1**	The UI platform will be capturing final measurement data and running computations to determine the weight and CG location of the pod; therefore, its success is vital to the success of the project as a whole. To meet DR8.1, the software must be evaluated on its data import abilities (autonomous versus manual).

It was determined that DAQ Compatability deserves the most weight since it is imperative that our selected DAQ, the NI 9237, be able to collect and transmit data to the UI. Any inability to collect and use the sensor measurement data would result in a complete test failure and is therefore mission critical. Next, due to time-limited nature of this project, the ability for the team to develop such UI in the minimum amount of time is highly beneficial. Therefore, the metric rankings vary from none to multiple team members being proficient in the specified coding language as a factor that directly relates to the development time required. As mentioned above, the SNC Previous Experience metric encapsulates the availability and familiarity of the UI platform software to the SNC customer, ranging from no access and no familiarity to access and familiarity to the point that the platform is the preferred platform. At the same weight of as the SNC Previous Experience metric, the customer usage category works to establish the relationship between the functionality of the UI and the overall success of the test. Lastly, we also describe the computational capabilities of the UI platforms. Specific metric characterizations are below in Table 46.

Table 46: UI Metric Rankings

Metric	1	2	3	4	5
NI 9237 DAQ Compatibility	UI platform is not compatible with NI 9237 DAQ or any COTS or student-developed DAQ options.	n/a	UI platform is not compatible with NI 9237 DAQ, but is compatible with other COTS and/or student-developed DAQ options.	UI platform is compatible with NI 9237 DAQ, but requires add-on software toolboxes.	UI platform is compatible with NI 9237 DAQ.
Team Previous Experience	No team members have experience with UI platform.	n/a	1-2 team members have experience with UI platform.	n/a	4+ team members have experience with UI platform.
SNC Previous Experience	SNC engineer does not have any ability with this UI platform. SNC engineer does not have access to UI platform.	SNC engineer has no previous experience using UI platform and will need additional training before able to use. SNC does not have access to UI platform.	SNC engineer has no previous experience using UI platform and will not need additional training before able to use. SNC has access to this UI platform.	SNC engineer has experience with UI platform. SNC has access to this UI platform.	SNC engineer has experience with UI platform and prefers this UI platform. SNC currently uses this software.
Customer Usage	UI has noticeable lack of functionality that impedes test process.	n/a	UI has acceptable functionality that facilitates the test process.	n/a	UI has exceptional functionality that upgrades the test process.
Computational Capabilities	UI platform cannot run necessary computations to obtain weight and CG.	n/a	UI platform can facilitate necessary computations to obtain weight and CG, but requires manual inputs.	n/a	UI platform can autonomously run necessary computations to obtain weight and CG.

Trade Study Results

Table 47 shows the UI trade evaluation matrix for each of the design alternatives. Per the scoring algorithm, the highest-ranked UI platform is MATLAB. Earlier in the semester when these trade studies were performed, there was concern that the unfamiliarity of both the WASP team and the PAB experts with MATLAB's Data Acquisition Toolbox raised question in feasibility of using MATLAB for data acquisition for the user interface. However, driven by the customer's interest in using a software for which they already have licenses, the Data Acquisition Toolbox was further explored and MATLAB was deemed acceptable regarding capabilities of communication with the NI DAQ components.

Table 47: User Interface Trade Evaluation

Metric	Weight	Microsoft Excel	MATLAB	NI Labview
NI 9237 DAQ Compatibility	0.4	1	4	5
Team Previous Experience	0.3	3	5	3
SNC Previous Experience	0.1	5	3	1
Customer Usage	0.1	3	3	5
Computational Capabilities	0.1	5	5	5
Total	1.0	2.6	4.2	4.0

Microsoft Excel

NI 9237 DAQ Compatibility: 1 - Excel is not directly compatible with the NI 9237 DAQ Module.

Team Previous Experience: 3 - There are two team members on the WASP team that have experience coding in Excel Visual Basic for Applications (VBA), with some experience in developing user interfaces in Excel.

SNC Previous Experience: 5 - SNC engineers indicated that they currently use Excel for this testing procedure and most often use Excel for data-related files.

Customer Usage: 3 - Excel has appropriate features for user interface, but is not particularly powerful for userform options and customization.

Computational Capabilities: 5 - Excel can autonomously run computations via programming through VBA scripts.

MATLAB

NI 9237 DAQ Compatibility: 4 - MATLAB is compatible with NI DAQ modules through the Data Acquisition Toolbox Add-on. Functionality may be limited in comparison with LabView's customizations.

Team Previous Experience: 5 - All ten WASP team members and all PAB members have experience coding in MATLAB. Some members have experience with user interface development in MATLAB.

SNC Previous Experience: 3 - SNC has available licenses for MATLAB for this testing procedure. SNC engineers generally have some/limited experience working in MATLAB.

Customer Usage: 3 - MATLAB has appropriate user-interfacing tools, but is not particularly powerful for userform options and customizations.

Computational Capabilities: 5 - MATLAB can autonomously run computations via script programming.

NI Labview

NI 9237 DAQ Compatibility: 5 - Labview is specifically created to interface with NI modules and other equipment. Functionality is extensive as far as DAQ programming via Labview tool.

Team Previous Experience: 1 - While the WASP team has minimal experience with NI Labview through CU, none of the team members have previous experience programming an NI Labview GUI.

SNC Previous Experience: 1 - SNC team has no previous experience with NI Labview as well as does not possess the licenses for it.

Customer Usage: 5 - Labview is specifically designed to facilitate the development of user interfaces, with pre-made graphic tools like dials, plots, sliders, etc. that help communicate with the user.

Computational Capabilities: 5 - Labview can autonomously run computations to compute weight and CG.

A.7 Force Measurement Device

All proposed designs require some form of sensor that can be used to determine the weight and center of gravity location of the pods. This is in accordance with DR 1.1 and 2.1. This can be done measuring force, loads (tension or compression), or strain. The proposed sensor options are mentioned below along with the pros and cons of each option.

Tension Load Cells

The first sensor option is using tension load cells. Tensile load cells would be connected from the frame to the test bed in some manner, and measure the load applied at the point where they are connected. These load cells return force values that are essential for calculating the weight of the pod as well as the moments of the pod. These moments would then be used to calculate center of gravity location. This option is compatible with most of the structural design options listed above and would not be complex to implement. Pros and cons of this choice can be seen in Table 48.

Figure 118: Tension Load Cell

Table 48: Pros and Cons - Tension Load Cells

Pros	Cons
Returns correct measurements for calculations	Very expensive
No frame redesign is needed to connect them to the frame	
Measurements from these sensors are accurate and precise	

Compression Load Cells

The second sensor option is using compression load cells. These load cells would be located in the legs of the frame which would support the full weight of the frame and the pod for the compatible design alternatives. Similar to the tension load cells, these load cells return the force values needed to execute our calculations. However, implementing this design would require some structural design changes as well as using sensors with greater load capacities. The pros and cons are demonstrated in Table 49.

Figure 119: Compression Load Cell

Table 49: Pros and Cons - Compression Load Cells

Pros	Cons
Returns correct measurements for calculations	Expensive
Readily Available	Requires frame redesign

Compression Load Cells with Designed Adaptations

Similar to the previous option, this design option utilizes compression load cells. The difference being is that the team would design a system that would use the compression load cells in a tension manner by means of pistons or other engineering. This design would return the correct measurements needed, however it requires intensive engineering design for the adaptation system. The motivation behind this method is an attempt to decrease the overall costs of the sensors. The pros and cons can be seen summarized in Table 50.

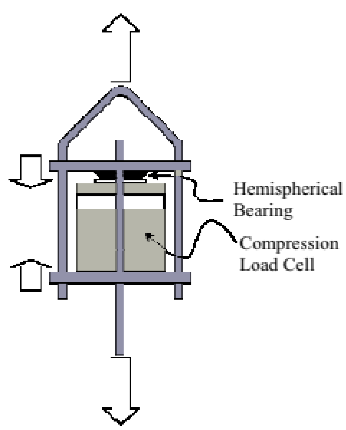


Figure 120: Compression Load Cell with Adaptor Diagram

Table 50: Pros and Cons - Compression Load Cells with Designed Adaptations

Pros	Cons
Returns correct measurements for calculations	Required construction of adapter
Compatible with most designs	Complex

Force Sensors

Another design option is the use of force sensors. The force sensor design would be similar to that of the compression load cells in where the sensors are located in the legs of WASP. The sensors would then measure the force applied to each of these legs. This would return the measurements needed to complete the desired calculations, however it would require some redesign to the frame. Force sensors while relatively affordable, are not that accurate or reliable. The pros and cons can be seen weighted in Table 51.

Figure 121: Force Sensors

Table 51: Pros and Cons - Force Sensors

Pros	Cons
Affordable	Not compatible with most structural designs
Returns desired measurements	Inaccurate
	Unreliable

Strain Gauges

The final sensor design option uses strain gauges. This design would result in a bar with known material properties and dimensions connecting the frame to the test bed in some manner. Strain gauges would lie on this bar and measure the strain on the material. These calculations would then have to be converted into the force values needed. This design is compatible with most of the structural designs presented previously. The pros and cons are listed in Table 52.

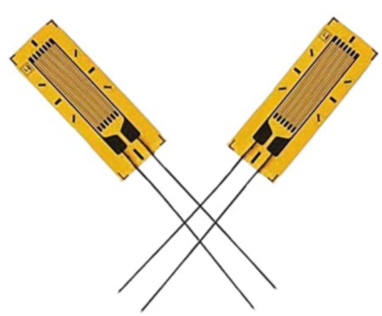


Figure 122: Strain Gauges

Table 52: Pros and Cons - Strain Gauges

Pros	Cons
Affordable	Need specific material properties
Compatible with most of the designs	Introduces error through calculations

Trade Metrics

Analyzing the pros and cons of each option as well as WASP's functional and design requirements, five trade study metrics were devised. The fist metric, connection to frame was determined due to resource limitations as well as redesign complexity. Since WASP has very specific accuracy requirements, the second metric is built around this specification. WASP deals with very heavy loads and it is essential that no additional forces or torques are put in place on the sensors for the sensors' own safety and accuracy. This is the driving reasoning for the third metric. The fourth metric is primarily a budget concern. The final metric is not only a software concern, but also a hardware concern. If additional measurement conversions are needed to solve our CG equations, that could impact the software and/or the structural design to account for these conversions. If additional software conversions need to be implemented, then this section will be rated lower. If additional structural design components need to be added to obtain the correct measurements, then this section will be rated lowest.

Table 53: Considerations and Weights for Sensor Type Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Connection to Frame	25%	**Resources and Compatibility**	The sensor type chosen must be compatible with the frame, lifting, and tilting baseline design selection. The ability of the sensor to connect to the frame should not require frame redesign or significant additional resources. This is weighted relatively high because without compatibility, the sensor will not perform.
Accuracy and Precision	20% or 35%	**FR1, DR 1.1, FR2, DR 2.1**	Directly from the customer requirements. The sensor should be able to have accurate and precise measurements in order to complete the mission. This has two weightings as there were two trade studies performed, one prioritizing cost and the other prioritizing accuracy and precision.
Static Ability	10%	**Sensor Safety**	The sensors should not be connected in a way that allows for static instability of the pod or in a way that would cause any damage to the sensors. This is weighted at only ten percent because it is an aspect that can be designed around.
Cost	20% or 35%	**Budget**	Budget is a consideration because multiple high performing sensors are expensive and will take up much of the budget. This, as well as accuracy and precision, has two weights based on the priority of the trade study.
Correct Measurements	10%	**FR1, DR 1.1, FR2, DR 2.1**	The sensors need to take measurements that can be used to calculate weight and center of gravity. Without the correct measurements or the ability to obtain them, the mission can not be completed.

Table 54: Sensor Type Metric Rankings

Metric	1	2	3	4	5
Connection to Frame	Need frame redesign to implement sensor	N/A	Some design additions or alterations to the frame required for implementation	N/A	Can be connected to the frame easily with minimal hardware involved
Accuracy and Precision	accuracy and precision both are worse than (0.X%)	accurate or precise where one is (0.X%) and one is >(0.X%)	accurate or precise where both are within (0.X%)	accurate and precise where one is (0.X%) and the other is (0.0X%)	high accuracy and precision both at or better than (0.0X%)
Static Ability	Not Static	N/A	N/A	N/A	Static
Cost (per sensor)	>$1000	$750 - $1000	$500 - $750	$100 - $500	<$100
Correct Measurements	Requires some form of additional hardware to return correct values	N/A	Requires some form of software conversion to return proper measurements	N/A	Gives exactly the right measurements with no conversions

Trade Study Results

There were two trades conducted on the sensor type, one prioritizing accuracy and one prioritizing cost. When accuracy and precision are prioritized tension load cells are the clear option. However, when cost is prioritized, strain gauges are the option. Based on the scope of the project, accuracy and precision were determined to be more important than cost. The final recommendation on sensor type is for tension load cells.

Table 55: Sensor Type Trade Evaluation - Prioritize Cost

Metric	Weight	Tension Load Cell	Compression Load Cell	Compression Load Cell w/ Adapter	Force Sensors	Strain Gauges
Connection to Frame	0.25	5	1	3	3	3
Accuracy & Precision	0.2	5	4	3	1	4
Static Ability	0.1	5	5	5	5	1
Cost	0.35	1	2	2	2	5
Correct Measurements	0.1	5	5	1	5	3
Total	1.0	3.6	2.75	2.65	2.65	3.7

Table 56: Sensor Type Trade Evaluation - Prioritize Accuracy

Metric	Weight	Tension Load Cell	Compression Load Cell	Compression Load Cell w/ Adapter	Force Sensors	Strain Gauges
Connection to Frame	0.25	5	1	3	3	3
Accuracy & Precision	0.35	5	4	3	1	4
Static Ability	0.1	5	5	5	5	1
Cost	0.2	1	2	2	2	5
Correct Measurements	0.1	5	5	1	5	3
Total	1.0	4.2	3.05	2.8	2.5	3.55

Tension Load Cell

Connection to Frame: 5 - the nature of the sensor does not require much additional hardware design to be connected to the frame as it is a tension sensor and connect directly with the current frame design.

Accuracy and Precision: 5 - tension load cells are common on the market and are extremely accurate. There is also thorough data for repeatability which can be accounted for in the equations.

Static Ability: 5 - The sensor does not introduce additional instability into the main design.

Cost (per sensor): 1 - Good tension load cells can be worth over one thousand dollars and this accounted for with a low price scoring.

Correct Measurements: 5 - Returns the desired tensile force measurements with no conversions needed for WASP's calculations.

Compression Load Cell

Connection to Frame: 1 - frame redesign is needed to implement this kind of load cell.

Accuracy and Precision: 4 - compression load cells are common on the market and are fairly accurate. There is less repeatability data, and they perform worse than tension load cells.

Static Ability: 5 - The sensor does not introduce additional instability into the main design.

Cost (per sensor): 2 - Good compression load cells can be worth over 750 dollars and this accounted for with a low price scoring.

Correct Measurements: 5 - Returns the desired force measurements with no conversions needed for WASP's calculations.

Compression Load Cell w/ Adapter

Connection to Frame: 3 - Some design alterations are needed to account for the sensor adapter design.

Accuracy and Precision: 3 - compression load cells are common on the market and are fairly accurate. There is less repeatability data, and they perform worse than tension load cells. There also is additional errors introduced with a "home-made" adaptor.

Static Ability: 5 - The sensor does not introduce additional instability into the main design.

Cost (per sensor): 2 - Good compression load cells can be worth over 750 dollars and this accounted for with a low price scoring.

Correct Measurements: 1 - This option requires an adaptor that the team must come up with as another hardware design task.

Force Sensors

Connection to Frame: 3 - Some design alterations are needed to account for the nature of the force sensors.

Accuracy and Precision: 1 - Force sensors have very low accuracy and precision that significantly worse than to the nearest tenths place.

Static Ability: 5 - The sensor does not introduce additional instability into the main design.

Cost (per sensor): 2 - Good force sensors can be worth over $750 and this accounted for with a low price scoring.

Correct Measurements: 5 - This option returns the desired force values needed for the calculations

Strain Gauges

Connection to Frame: 3 - Some design alterations are needed to account for the implementation of strain gauges. A "hanging bar" needs to be designed to hold the strain gauges in place for measurements to be taken.

Accuracy and Precision: 4 - Strain gauges are fairly accurate and precise, but the additional calculations needed for this option introduces additional errors.

Static Ability: 1 - Introducing this "hanging bar" to the frame introduces instability at the connection points.

Cost (per sensor): 5 - Strain gauges are each less than one hundred dollars on average.

Correct Measurements: 3 - Since strain gauges measure strain, software calculations need to be made using material properties of the "hanging bar" to convert strain into force.

Appendix B: Baseline Design Selection

9.11 Baseline Design Overview

After the trade studies were completed, the top compatible designs were integrated together to form an overall design. During the conceptual design process, it became apparent that some design options from certain trades could not be combined with some from other trades. Thus, two compatibility matrices (Figures 123 and 124) were created to review these conflicts. The matrices were used to determine if the highest-ranked alternatives for each trade would be compatible or if secondary options would have to be considered. The approach taken was to first choose a testbed configuration, then narrow down the structural design space to a baseline design, and finally ensure said choices were compatible with the trades performed for electronics, sensors, and software. Visualizations of a WASP design that implements all components of the baseline design are diagrammed in Figures 125, 126, 127, and 128.

Structural Design

		Tilting Alternatives				Test Bed Alternatives		
		Mounting Interface w/ Axle	Mounting Interface w/o Axle	Cradle	Paralleogram	Direct	Indirect	Hybrid
Lifting Alternatives	Chain Hoist	compatible	compatible	compatible	compatible	not compatible	compatible	compatible
	Hydraulic System	compatible	compatible	compatible	compatible	compatible	compatible	compatible
	Pulley System	compatible	compatible	compatible	compatible	not compatible	compatible	compatible
Test Bed Alternatives	Direct	compatible	compatible	irrelevant	compatible			
	Indirect	not compatible	compatible	irrelevant	compatible			
	Hybrid	compatible	irrelevant	compatible	compatible			

Legend
Compatible
Not Compatible
Irrelevant

Figure 123: Structural Compatibility Matrix

Figure 123 shows that the testbed trade has the most compatibility restrictions, so it was used as the basis of the baseline design. Looking at the trade evaluation in Figure 15, the hybrid design is a recommended choice due to its exceptional performance in the accuracy and weight metrics. Using the hybrid design as a baseline, and once again referring to the structural compatibility matrix, the next trade that was narrowed down was tilting alternatives.

Looking back to Table 21, the suspended tilting mechanism with an axle is ranked the highest. It is compatible with the hybrid testbed configuration according to Figure 123, and the use of an axle reduces the complexity of the design (which was a higher-ranked metric at 30%). For these reasons, this tilting alternative is the clear choice.

Next, the lifting alternative was chosen based upon the prior selections for the baseline design. Looking at the structural compatibility matrix, all three lifting alternatives considered are compatible with both the hybrid testbed and a tilting mechanism based upon a mounting interface with an axle, so interfacing issues were not a concern. The trade evaluation in Table 21 was then consulted. Due to its relatively low number of required high-cost off-the-shelf components compared to the pulley system, the chain hoist lifting mechanism was selected as the next structural aspect of the baseline design.

Finally, the maneuvering mechanism was selected. It was determined that the maneuvering mechanism was independent of any of the selections in the structural compatibility edmatrix, so only the results of the trade need to be considered. Based on the trade evaluation in Figure 35, forklift slots were the recommended choice. However, the customer had requested that a forklift only be used if absolutely necessary, so mounting interfaces for caster wheels were also included in the baseline design in case the budget allows for the purchase of caster wheels, or if the customer wishes to purchase them at a later time.

The baseline structural design choices are summarized in Table 57.

Table 57: Structural Baseline Selection

Trade	Baseline Selection
Testbed	Hybrid
Lifting Mechanism	Chain Hoist
Tilting Mechanism	Mounting Interface w/ Axle
Maneuvering	Forklift Slots w/ Caster Wheel Mounting

Electronic, Sensor, and Software Design

		Tilting Alternatives				Sensor Type Alternatives			
		Mounting Interface w/ Axle	Mounting Interface w/o Axle	Cradle	Paralleogram	Tension Load Cell	Compression Load Cell	Force Sensor	Strain Gauge
Lifting Alternatives	Chain Hoist	compatible	compatible	compatible	compatible	compatible	compatible**	not compatible	compatible
	Hydraulic System	compatible	compatible	compatible	compatible	compatible	compatible	compatible	compatible
	Pulley System	compatible	compatible	compatible	compatible	compatible	compatible**	not compatible	compatible
Sensor Type Alternatives	Tension Load Cells	compatible	compatible	not compatible	compatible				
	Comp Load Cells	compatible**	compatible	compatible	compatible**				
	Force Sensor	not compatible	not compatible	compatible	not compatible				
	Strain Gauge	compatible	compatible	not compatible	compatible				

Legend
Compatible
Not Compatible
Irrelavant

** compression to tension adapter device needed

Figure 124: Electrical-Structural Compatibility Matrix

Once the structure was finalized (conceptually), the electronic components were selected. The sensor type was used as the basis for the electronics baseline design. The sensor type is the key electronics design element of the project because it affects how the pods are measured. After picking the tension load cell for functionality, looking at Table 124 verified its compatibility with the selected structural design choices. Shown in Table 55, and 56, the tension load cell had the best or second best evaluation. Although the cost of these sensors were concerning to the team, this sensor type was compatible and the best choice, and thus was selected.

The next design choice dealt with how the sensors interface with SNC hardware. Shown in Table 41, the highest ranking option was the hardwired connection. This was due to the simplicity, affordability and reliability for data transfer. Although wireless connection would have provided faster hardware interfacing, this was not required by the customer. Designing for wireless connection added complexity and more expenses for more robust functionality. Because of these additional issues, the hardwired connection was selected as the baseline option.

The final design alternative selected was the user interface. From Table 47 the MATLAB interface was ranked the highest. Although the preference of the customer was Excel, WASP is being designed to perform autonomous calculations. MATLAB has a option to produce a UI that is separate from the application. This user interface will be easy to use for the engineers. Data collection will be faster and more tests can be run in a shorter amount of time. An Excel sheet will be provided as well for redundancy.

Table 58 shows a summary of the electronic baseline choices.

Table 58: Electronics Baseline Selection

Trade	Baseline Selection
Sensor Type	Tension Load Cell
Accuracy Enhancement	NIST-Traceable after Purchase
Interface	Hard-wired
User Interface	MATLAB (pending customer answer), Excel

Overall Baseline Design Concept

The final baseline design concept is shown in Figures 125, 126, and 127, which incorporate all of the design selections made through the trade studies. The design is primarily comprised of two major subsystems: the electronics/software, and the structure. The functionality and interfacing between these subsystems will be discussed further.

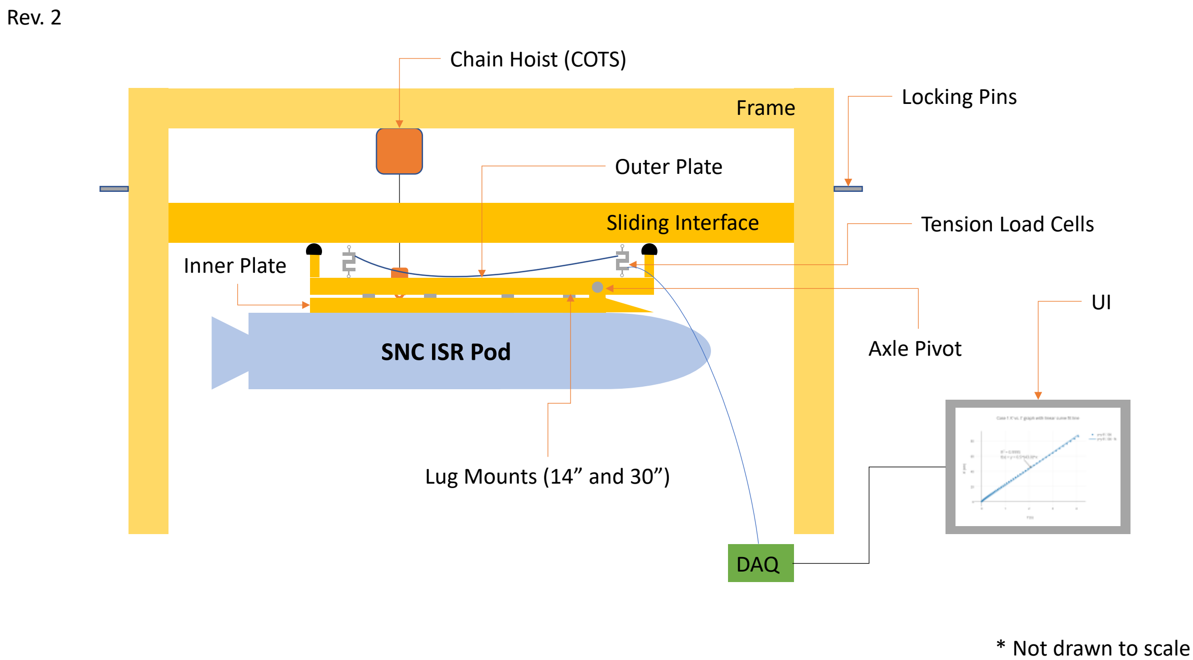


Figure 125: Baseline Design Concept Drawing Lowered

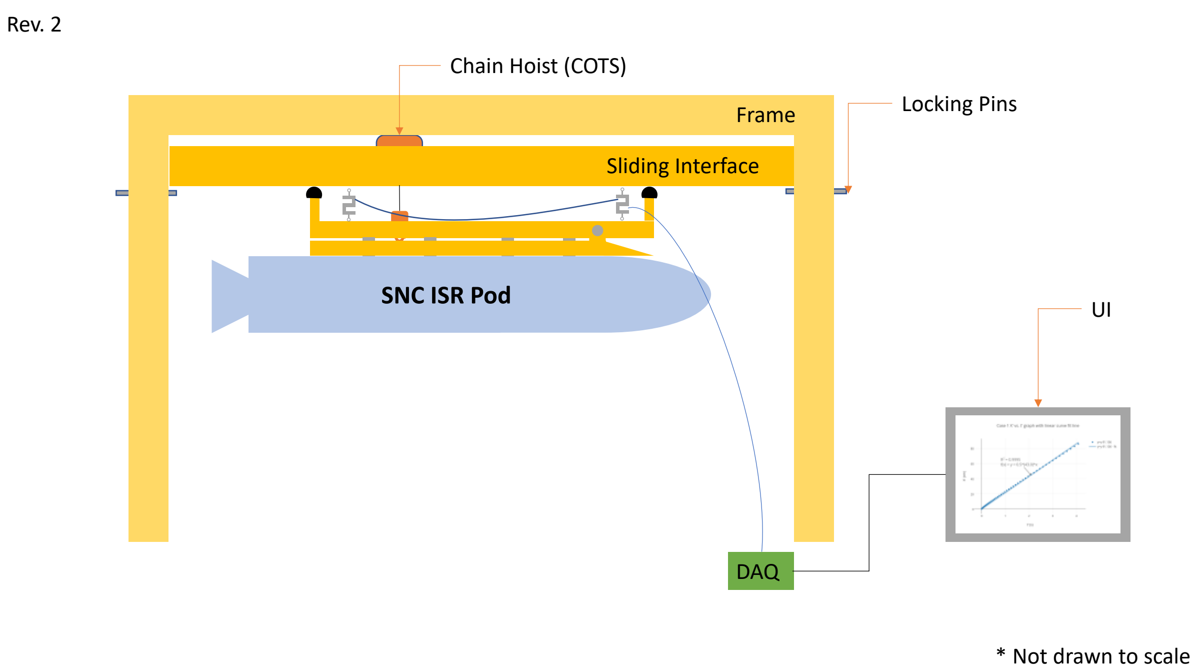


Figure 126: Baseline Design Concept Drawing Lifted

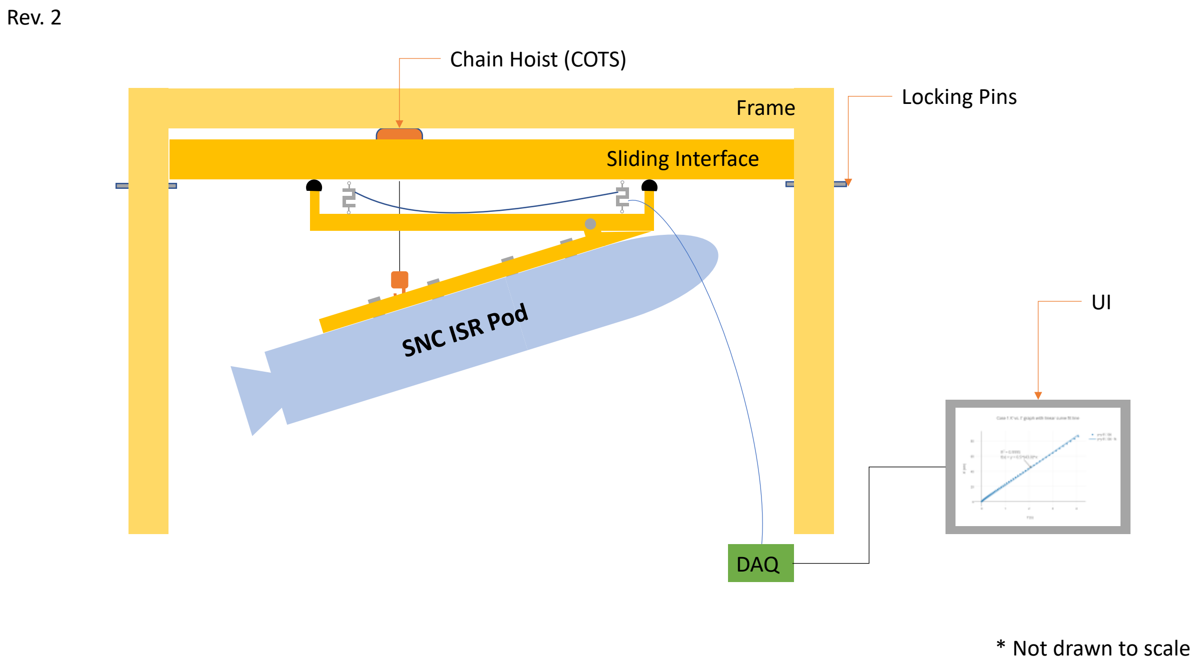


Figure 127: Baseline Design Concept Drawing Tilted

The structure is encased by the frame, which is comprised of four legs and a series of beams on the top. From the top of the frame, the COTS chain hoist is attached to raise and lower the testbed assembly. Because the chain hoist connects to the testbed at only one point, balancing the pod and testbed became an immediate concern. To mitigate this problem, a sliding interface was added, which serves to keep the testbed oriented consistently relative to the frame by sliding up and down the four legs of the frame. The sliding interface also provides a connection point for the three tension load cells that will be in line with gravity. A series of bumpers separate the testbed from the sliding interface to ensure the load cells are not loaded in compression during lifting. Once the sliding interface and testbed are raised to the desired height for measurement, the sliding interface is pinned to the frame via the four legs. Once the sliding interface is safely pinned to the frame, the chain hoist can be disconnected from the testbed and level measurements can be taken. To tilt the pod, the chain hoist is then reconnected to the inner testbed, and pins connecting the inner and outer testbeds are removed. The inner testbed is tilted using the chain hoist until a hard stop between the testbeds is engaged. Then, the chain hoist is removed and the tilted measurements are recorded. The same process in reverse can be used to lower and unload the pod. To transport WASP, forklift slots will be added to the top of the frame, and locking caster wheels may be added to the bottom of each leg.

The testbed structure is shown in more detail in Figure 128. The axle connecting the inner and outer testbeds is placed at the far end of the pod to ensure that the CG of the pod is always behind the axle. This allows the chain hoist to tilt and untilt the pod from one point and always be in tension. The pod is connected to the inner testbed using either 14 in. or 30 in. lugs as specified by SNC. The load cells connect the outer testbed and sliding interface at three points. These are the only connections between the testbed assembly and the rest of the structure, which is necessary to ensure that all of the pod weight is transferred through the load cells and not some other structural component.

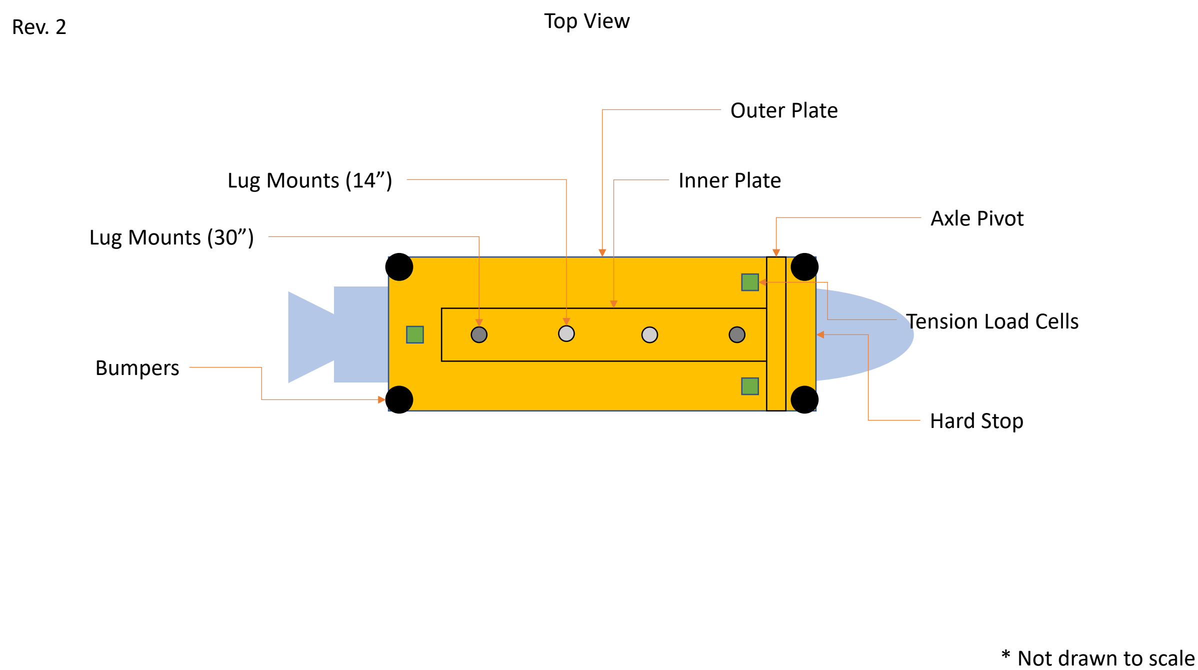


Figure 128: Baseline Design Concept Testbed Top View

The load cells are just one of the electronics and software subsystem components that must be integrated into the final design. This subsystem also features a data-acquisition system, or DAQ, and a computer to run the WASP GUI. Each load cell will be wired into a separate channel on the DAQ, which will filter the signal and convert the analog voltage signal into a digital force value. These force values will be passed to the computer via a USB port to Matlab. A digital inclinometer reading will be passed manually to the GUI via a user. Matlab will then perform the weight and CG calculations and report them to the user. The DAQ location shown in the previous drawings are not shown accurately. All DAQ hardware will be 5-10 ft away from the WASP frame to protect the hardware.

A summary of the baseline design features and common terminology to be used throughout the project is displayed in Table 59.

Table 59: Baseline Design Components

Component	Description
Frame	Outer structure for WASP, comprised of four legs and the frame top which houses the chain hoist.
Sliding Interface	Slides up and down the four legs, and connects to the outer testbed via the three load cells. Primarily for balancing the pod/testbed during transient states.
Outer Testbed	Testbed part that always remains parallel to the ground and connects to the three load cells. Connects to the inner testbed via an axle.
Inner Testbed	Testbed part that connects to the pod via the lug mounts and can tilt the pod via the axle.
Hard Stop	Structural component that maintains a rigid angle between the inner and outer testbeds. Allows for the chain hoist to be removed during tilted measurements.
E&S Subsystem	All electronics and software components, including the load cells, DAQ, GUI, and any additional electronic hardware added later on in the design.

Budget Details

	Unit Cost	QTY	Project Cost	Purpose
Raw Materials			**$ 2,381.41**	
S6x17.25 A36 I-Beam	$ 1,440.95	1	$ 1,440.95	Frame
3"x.120" A36 Square Tube	$ 303.00	1	$ 303.00	Legs, legs support
2"x2"x.25" A36 Angle (4' length)	$ 27.76	1	$ 27.76	Leg cleats
2"x2"x.25" A36 Angle (1' length)	$ 10.22	1	$ 10.22	Leg cleats
1"x1"x.125" A36 Angle (4' length)	$ 19.28	1	$ 19.28	Sliding plates
Chrome-Plated 1045 Carbon Steel Shaft, 1" Diameter (18" length)	$ 31.85	1	$ 31.85	Tilting mechanism shaft
Chrome-Plated 1045 Carbon Steel Shaft, 1" Diameter (18" length)	$ 21.93	1	$ 21.93	Tilting mechanism shaft
104[illegible] Carbon Steel Rod, .875" Diameter (3' length)	$ 18.92	1	$ 18.92	Force sensor attachment
A36 Steel Plate, 2'x'2x'3/8"	$ 83.68	1	$ 83.68	Sliding Interface plate, lug attachment plate
8020 extrusions, 1" square, 2' long	$ 7.79	1	$ 7.79	Bumper bars for FS attachments
14 GA. Steel Sheet, 4'x4'	$ 72.55	1	$ 72.55	Forklift slots
1"x1.5"12" 6061 Bar	$ 13.42	1	$ 13.42	Hard stop top and bottom
1.5"x2"x13" 6061 Bar	$ 27.20	1	$ 27.20	Tilting mechanism block, inner pin housing
2"x2.5"x12" 6061 Bar	$ 44.08	1	$ 44.08	Outer pin houses
2"x2"x10" 6061 Bar	$ 28.36	1	$ 28.36	Force sensor attachment - sliding
.75"x1"x17" A36 Bar	$ 8.79	1	$ 8.79	100, 1000 lb lug pins
.75"x1.5"x13" A36 Bar	$ 9.97	1	$ 9.97	TP lug mount
1"x1.5"x12" A36 Bar	$ 23.24	1	$ 23.24	2000 lb lug pins
1"x1.5"x6" A36 Bar	$ 13.48	1	$ 13.48	2000 lb lug pins
2"x3"x9" A36 Bar	$ 36.89	1	$ 36.89	2000 lb lug mounts
2"x2"x13" A36 Bar	$ 24.94	1	$ 24.94	100, 1000 lb lug mounts, FS attachment - testbed
1.5"x2"x6" A36 Bar	$ 20.86	1	$ 20.86	
.75"x2"x12" A36 Bar	$ 19.45	1	$ 19.45	Shackle mounts
6"x6"x1/4" Polyethylene Plate	$ 5.00	2	$ 10.00	Sliding interface
12"x12"x1/8" Polyethylene Plate	$ 8.39	2	$ 16.78	Sliding interface
3"x36"x3/8" Polyethylene Plate	$ 23.01	2	$ 46.02	Sliding interface

Figure 129: Budget - Raw Materials Breakdown

	Unit Cost	QTY	Project Cost	Purpose
Hardware			$ 1,978.54	
Chain Hoist (2 ton x 10' option)	$ 391.00	1	$ 391.00	
Trolley (2 ton option)	$ 246.00	1	$ 246.00	
Testbed Hoist Ring	$ 35.47	1	$ 35.47	
Tilting Mechanism Bearings	$ 39.74	2	$ 79.48	
Ball Joint Linkages	$ 21.43	6	$ 128.58	
Swivel Leveling Mount - 1/2"-13	$ 10.03	4	$ 40.12	Leveling feet
Threaded Rod, 1/2-13x4'	$ 20.67	1	$ 20.67	Hard stops
Steel Quick-Release Pin 3/4"x5-1/2"	$ 5.36	2	$ 10.72	Testbed shear pins (level)
Steel Quick-Release Pin 3/4"x2-1/2"	$ 4.30	2	$ 8.60	Testbed shear pins (tilted, inner)
Steel Quick-Release Pin 1"x5-1/2"	$ 8.32	12	$ 99.84	Sliding interface shear pins
Steel Quick-Release Pin 3/16"x1-3/16"	$ 1.64	2	$ 3.28	Lug shear pins
Steel Quick-Release Pin 1/4"x4"	$ 1.80	4	$ 7.20	TP lug pins
10-24 FHS, .75" long (50 pack)	$ 8.56	1	$ 8.56	Sliding interface plastic
10-24 Hex Nut (100 pack)	$ 3.77	1	$ 3.77	Sliding interface plastic
#10 Washer (100 pack)	$ 2.40	1	$ 2.40	Sliding interface plastic
1/4-20 Hex Bolt, 3.75" long (25 pack)	$ 13.32	1	$ 13.32	Cleat to leg
1/4" Washer (100 pack)	$ 3.47	1	$ 3.47	Cleat to leg
1/4-20 Hex Nut (100 pack)	$ 3.98	1	$ 3.98	Cleat to leg, cleat to cleat
1/4-20 Hex Bolt, 1.375" long (25 pack)	$ 12.32	1	$ 12.32	Cleat to cleat
5/16-18 Hex Nut (100 pack)	$ 5.63	1	$ 5.63	Sliding cleat
5/16-18 Hex Bolt, 1.125" long (10 pack)	$ 4.93	1	$ 4.93	Outer pin housing
5/16-18 Hex Bolt, 1.5" long (50 pack)	$ 11.89	1	$ 11.89	Sliding cleat
5/16-18 Hex Bolt, 2.5" long (25 pack)	$ 8.92	1	$ 8.92	Tilting axle
5/16-18 LP SHCS, .75" long (25 pack)	$ 6.60	1	$ 6.60	Inner pin housing
5/16" Washer (100 pack)	$ 5.27	1	$ 5.27	Sliding cleat, outer pin housing
3/8-16 Hex Bolt, 1.25" long (25 pack)	$ 8.42	1	$ 8.42	Tilting bearing
3/8" Washer (100 pack)	$ 5.27	1	$ 5.27	Tilting bearing, sensor block, lug mount
3/8-16 Hex Bolt, 2.75" long (10 pack)	$ 6.04	1	$ 6.04	Sensor block
3/8-16 FHS, 1" long (25 pack)	$ 8.66	1	$ 8.66	Lug mount plate
3/8-16 LP SHCS, 1.25" long (25 pack)	$ 11.74	1	$ 11.74	Lug mount plate
3/8-16 FHS, 1.125" long (5 pack)	$ 10.48	2	$ 20.96	2000 lb lug mount plate
1/2"-13 Hex Nut (50 pack)	$ 8.97	1	$ 8.97	Leveling feet
Welding Gas	$ 65.85	1	$ 65.85	
Gas Welding Rod (5lbs)	$ 34.45	1	$ 34.45	
1/2 in. Galvanized Anchor Shackle	$ 5.98	3	$ 17.94	
2' Wire Rope Sling	$ 37.17	1	$ 37.17	
3/8" Hex Nut (100 pack)	$ 7.01	3	$ 21.03	
3/8"-16 Hex Bolt, 4.75" long (5 pack)	$ 10.34	1	$ 10.34	
Double Sided Tape	$ 7.97	1	$ 7.97	Sliding plates
Fastenal Bolts	$ 3.74	1	$ 3.74	
5/8" Shackles (2)	$ 18.77	1	$ 18.77	
Lifting Straps	$ 22.64	1	$ 22.64	
Carabiners	$ 31.90	1	$ 31.90	
Lifting Straps	$ 22.94	1	$ 22.94	
Caster Wheels + Fastners	$ 380.22	1	$ 380.22	
Tape and Hooks	$ 13.72	1	$ 13.72	
Sand and Hooks	$ 24.32	1	$ 24.32	
Sand Bags	$ 16.99	1	$ 16.99	
Laser Pointers	$ 16.47	1	$ 16.47	

Figure 130: Budget - Hardware Breakdown

	Unit Cost		QTY	Project Cost		Purpose
Electronics				$	-	
Cables	$	85.00	0	$	-	Load cells to DAQ
DSUB-37 Connectors	$	4.36	0	$	-	Load cell cables to NI 9237 connection
DSUB-37 Backshell	$	6.34	0	$	-	Protective housing for connector
Other Expenses				$	342.42	
Hoist Zone Shipping	$	59.00	1	$	59.00	
McMaster Shipping (Fasteners)	$	68.23	1	$	68.23	
McMaster Shipping (Metal)	$	20.67	1	$	20.67	
Metals Supermarket Handling	$	45.00	1	$	45.00	
McMaster Shipping (Hardstops)	$	30.44	1	$	30.44	
McMaster Shipping (Angle)	$	9.39	1	$	9.39	
McMaster Shipping (Shaft)	$	9.39	1	$	9.39	
McMaster Shipping (Plastic)	$	10.64	1	$	10.64	
McMaster Shipping (Steel)	$	40.77	1	$	40.77	
Angle Grinder Wheels	$	15.94	1	$	15.94	
Safety Signs	$	32.95	1	$	32.95	
Omega 500 lbf Load Cell - LC103B-500	$	208.00	3	$	-	
Omega 1000 lbf Load Cell - LC103B-1K	$	208.00	3	$	-	
NI-9237 Bridge Input Module	$	1,655.00	1	$	-	
NI cDAQ-9171	$	333.00	1	$	-	
Clinotronic Plus Inclinometer	$	2,000.00	1	$	-	
Manufacturing Labor	$	-	1000 hours	$	-	

Figure 131: Budget - Electronics Breakdown

	Unit Cost		QTY	Project Cost	
Other Expenses				**$**	**342.42**
Hoist Zone Shipping	$	59.00	1	$	59.00
McMaster Shipping (Fasteners)	$	68.23	1	$	68.23
McMaster Shipping (Metal)	$	20.67	1	$	20.67
Metals Supermarket Handling	$	45.00	1	$	45.00
McMaster Shipping (Hardstops)	$	30.44	1	$	30.44
McMaster Shipping (Angle)	$	9.39	1	$	9.39
McMaster Shipping (Shaft)	$	9.39	1	$	9.39
McMaster Shipping (Plastic)	$	10.64	1	$	10.64
McMaster Shipping (Steel)	$	40.77	1	$	40.77
Angle Grinder Wheels	$	15.94	1	$	15.94
Safety Signs	$	32.95	1	$	32.95
Omega 500 lbf Load Cell - LC103B-500	$	208.00	3	$	-
Omega 1000 lbf Load Cell - LC103B-1K	$	208.00	3	$	-
NI-9237 Bridge Input Module	$	1,655.00	1	$	-
NI cDAQ-9171	$	333.00	1	$	-
Clinotronic Plus Inclinometer	$	2,000.00	1	$	-
Manufacturing Labor	$	-	1000 hours	$	-

Figure 132: Budget - Other Expenses Breakdown

9.12 Appendix C: Risk Descriptions and Mitigation

9.13 Risk Identification

9.13.1 Technical Risks

Figure 133 and 134 summarizes the pre- and post-mitigation risk evaluations respectively.

		Impact Level			
		Low	Mild	Medium	High
Likelihood Level	High			14	13
	Medium		12, 15, 17	4, 5, 8, 9, 10, 11	1, 2, 6, 7, 16
	Low		18		3

Figure 133: Technical Risk Matrix - Pre-Mitigation

		Impact Level			
		Low	Mild	Medium	High
Likelihood Level	High				
	Medium	12	14		
	Low	11,15,17,18	7,8,10,13	4,5,9,16	1,2,3,6

Figure 134: Technical Risk Matrix - Post-Mitigation

Risk 1: Structural Component Failure

Structural component failure may include, but is not limited to, the following: manufacturing or alignment imperfections that cause components to be overloaded or loaded in unintended ways, material imperfections that weaken the integrity of a component (both manufactured and COTS), plastic deformation (yielding) of any component such that loads are not distributed as intended, failure of any interface between components (welds, clamps, joints, axles, bolts, pins, etc.), and any use of the equipment that is not intended/beyond the structural limits of the design.

If any of these risks occur, they could cause permanent damage to the structure. This includes any deformation that would prevent WASP from meeting the measurement accuracy requirements, or damage to components that cannot be replaced without rebuilding the entire frame. In more severe cases, structural component failure could lead to damaging a SNC pod (costing millions of dollars), or complete structural failure which poses a threat to the safety of all engineers working around the equipment.

In order to mitigate the risk of structural component failure, the team has agreed to take the following measures to reduce the consequence, likelihood, or both for this particular risk.

1. Design each component to a safety factor of 2.0 or grater to reduce the likelihood of component failure.
2. Utilize FEA modeling and BOTE calculations in designing components to ensure the calculated safety factors are accurate.
3. Additional testing of components with the lowest safety factors, such as the 2000 lb class lug mount, to quantify failure load.

4. Inclusion of a detailed procedure description as a project deliverable to prevent the hardware from being accidentally misused.

5. Potential addition of a crash-pad for early testing on SNC pods to reduce the damage incurred by a pod should the structure fail.

Risk 2: Structural Interface with Pods

The pod interfacing risk includes any inability for WASP to rigidly attach to pods using the lug configurations up to 2000 lbs specified in MIL-STD 8591 or the SNC TP lug mount. This includes alignment errors that prevent the lug pin from being fully inserted through the lug and lug mount, sizing errors with the lug pin that allow the pod to move relative to the testbed during pod tilting, attachment bias that could degrade the accuracy of measurements if a pod is connected differently between measurements, and the inability of engineers to align the pod directly under the lug mounts to attain a rigid connection when attaching a pod.

This risk could render WASP completely useless because it would not be possible to safely attach pods in order to obtain weight and CG measurements. The spacing and tolerancing for different lug configurations is strictly determined by the aircraft to which the pods attach. If WASP cannot meet these tolerancing requirements, it will not be able to interface with the pods at all.

In order to mitigate this risk, the following actions have been or will be taken:

1. Close interaction with SNC during the design of all lug mounts.

2. Physical verification of the lug mount design through connection of all available lugs to the appropriate lug mount.

3. Modularized lug mount design that allows for a redesign of small, inexpensive components should the first design not function as intended.

4. Rotation of the lug mounts to allow pin insertion in the Y-direction. This provides engineers margin to insert the pins whilst maintaining a rigid connection in the X and Z-directions for tilting.

Risk 3: WASP Structural Fatigue

The final structural risk considered was the fatigue of WASP's structure from bearing the load of pods that vary in weight up to 2000lbs. This risk includes all components of the WASP structure that are taking extensive loads that could be subject to fatigue over time. Since the rate of loading and unloading is at most 10/month, the team was primarily concerned with low cycle fatigue, which is only common if a structure is plastically deforming on each load cycle.

This risk can cause catastrophic failure to WASP and harm engineers using it. If fatigue occurs, failure of any part could cause the entire frame to fall apart. This puts the user, pod, and the rest of WASP in danger of serious harm. While not every fatigue issue will cause complete failure, even slight fatigue in structural beams of WASP can cause the CG to change. Thus causing the accuracy of the whole system to be off.

To help mitigate the risk of structural component fatigue, specific design choices have been or will be made to minimize the likelihood. These can be seen tabulated below:

1. Designing the structure with all component safety factors being sufficiently high to avoid the plastic region.

Risk 4: Electronic Component Damage

Electronic component damage includes the internal or external damage to the load cells, inclinometer, DAQ bridge module, compact DAQ module, or any connectors that disturbs or disrupts the electronic unit functionality. Damage can be caused by physical sources, such as dropping the equipment, overloading the load cells, or fatigue over time. Damage can also be caused by electrical/internal sources, such as electrical shorts, or over-voltage/over-current due to incorrect pin placement.

The impact of such risk varies with the severity of the damage. For the load cells, damage could occur that alters the calibration/accuracy of the sensors or damage that entirely internally breaks the load cells so outputs are not useful. Moreover, a load cell could fail structurally, in which case the risk would parallel that of the structural component failure (Risk 1). For the inclinometer, damage could result in reduced accuracy or miscalibration of the instrument, as well as complete failure if the instrument if severely damaged. For the DAQ system, any damage would likely disrupt the data acquisition process and disallow the load cell data to be transferred to the computer. Overall, damage to electrical components would hinder accurate data collection and therefore impact the ability for WASP to obtain useful weight and CG measurements.

To help mitigate the risk of electronic component failure, the following techniques will be employed:

1. Provide detailed electronic component installation and removal guides.
2. Apply additional safety factor on pod weights allowable to use particular load cells sets (to protect against overloading).
3. Establish safe location away from heavy objects for DAQ system to be placed during testing.
4. Recommend best storage practices for the components.

Risk 5: Sensor Error Greater than Reported

This risk captures the issues that stem from the deviance of the load cells and inclinometer from the manufacturer's reported error value. Specifically, the data sheet provided for the Omega LC103B series is not particularly convincing and seems to be missing key error specifications. The data sheet currently reports the accuracy of the load cells to $\pm 0.02\%$ FSO. While the data sheet provided for the Wyler Clinotronic plus is more credible and offers key error specifications, there is still a risk that the specific instrument WASP uses will deviate from the reported accuracy of $\pm 0.025°$.

If the manufacturer's provided data has overpredicted the accuracy capabilities of the load cells and/or inclinometer, the weight and CG accuracy will be impacted. This could results in a failure of DR 1.1 and DR 2.1.

While it is unlikely that this risk comes to fruition, the team plans to verify the accuracy of the load cells using the MTS machine. See Section 5.1.2 for more details.

Risk 6: E&S Communication Interruption

Electronics and software communication failure includes but is not limited to: load cell signal failure due to sensor-cable connection failure, load cell signal failure due to broken wires within cable, load cell signal failure due to improper pin connections (input/output), load cell signal failure due to DAQ module-cable connection failure, measurement signal failure due to DAQ module due to signal processing mishap (ADC, filtering, etc.), measurement signal communication failure between DAQ module and cDAQ module, measurement signal communication failure in cable connecting cDAQ and computer, measurement signal communication corruption at USB connector to computer, measurement data import to Matlab failure, measurement data processing failure due to code bug.

The result of a communication interrupt during data collection, load cell data may fail to arrive whatsoever which would force WASP to fail FR 1 and FR 2 (weight and CG measurement capability).

To mitigate the likelihood of any of the aforementioned communication failures occurring, the WASP team plans to employ the following methods and tests:

1. Provide detailed diagrams of connection interfaces in operation guide.
2. E&S Functional Test (see Section 5.1.4)
3. Measurement Accuracy Test (see Section 5.1.6)

Risk 7: Operator Misuse of User Interface

The user interface is set up to lead the operator through a series of procedures, recording data at necessary steps. Therefore, it is possible for software to record data at an incorrect time (improper WASP configuration) caused by operator misuse of on-screen interface. For example, load cell data for WASP in flat configuration could be erroneously recorded as tilted configuration data if user improperly selects this option on GUI.

The impact of improper load cell data collection is that the integrity and accuracy of weight and CG measurements. Likely, WASP will fail DR 1.1 and DR 2.1.

In efforts to mitigate the project risk associated with operator error with the software interface, the following techniques will be employed:

1. Build in "re-do", "go back", "repeat" functions into the UI that allows measurements to be redone if operator error occurs (without losing all previous data).
2. Provide written instructions on how to properly use the UI.
3. Provide on-screen prompts/diagrams as another layer of protection against misuse.

Risk 8: Incorrect Model for WASP Accuracy Capabilities

This risk considered the implications if the error simulation developed is not a correct model for WASP's true accuracy capabilities. Such issue could arise if the simulation has failed to consider all relevant errors or if true errors differ that the simulation of them.

The impact of this risk is that WASP may fail to meet DR 1.1 and DR 2.1, the weight and CG accuracy requirements.

The mitigation strategy for this risk is as follows:

1. Have error simulation methods reviewed by CU faculty experts.
2. Have CG equations reviewed by SNC engineers.
3. Use test results to appropriately adjust weight and CG determination equations and parameters in the software to reduce error.

Risk 9: Manufacturing Beam-Beam Connections

While manufacturing the WASP structure, an important series of steps during the subassembly phase will be to connect the structural beams together. This will be done by welding the interfaces between the beams. As with any welding process, poor welding would negatively impact the structural integrity of this connection.

The impact of this risk is that poor beam-beam connections, where the strength of the connection is far less than initial weld analysis estimates due to imperfect welding, could result in catastrophic failure of WASP. This risk poses a threat to the personnel performing tests, the SNC pods, and WASP itself.

To mitigate this risk, the manufacturing team will take the following steps:

1. Performing detailed weld analysis to ensure welding will be strong enough at each connection point.
2. Increasing the area and length of the welds to increase the strength of the connection.
3. Quality checks throughout the manufacturing process to ensure welding is performed to a satisfactory level.

Risk 10: Manufacturing Beam-Leg Connections

Another important manufacturing step during the subassembly portion of building the WASP structure will be attaching the legs to the structural beams. Again, welding will be used to make this connection, and poor welding will still negatively impact the strength of this joint.

The impact that this risk could take is that a poor connection between the beam and legs could again result in catastrophic structural failure of WASP. This risk poses a threat to the personnel performing tests, the SNC pods, and the structure of WASP.

To mitigate the likelihood and impact of this risk, the team will employ the following techniques:

1. Add cleats to the connections to provide additional strength to the joint.
2. Perform detailed weld analysis to ensure welding will be strong enough at each connection point.
3. Increase the area and length of the welds to increase the strength of the connection.
4. Perform quality checks throughout the manufacturing process to ensure welding is performed to a satisfactory level.

Risk 11: Manufacturing Chain Hoist Attachment

The attachment point between the chain hoist and the testbed is a particularly high-load component which must be looked at in more detail. During lifting, lowering, and tilting, this hoist ring will need to withstand the entire load of the pod, as well as the testbed and sliding interface weights. Any issues with attachment of this component will reduce the structural integrity of WASP.

There would be a severe impact due to failure at this attachment. Significant damage to the pods and WASP as well as safety hazards would result from this chain hoist attachment failing.

To mitigate this risk the team will:

1. Add welds around the connection point to increase the fidelity of the attachment.
2. Perform detailed bolt engagement and tensile strength analysis to fully understand the expected strength of the attachment.

Risk 12: Manufacturing Lug Attachments

The attachment interface between the SNC ISR pods and WASP is a manufactured component of particular importance. Due to the nature of their design, they will be among the most difficult components to manufacture.

If the lug interface attachments are not strong enough, or if they fail due to poor manufacturing, the team would risk damage to the SNC ISR pods, as well as to the WASP structure and threaten the safety of the testing personnel. If the lug flanges are not manufactured with the right tolerances or any error occurs, SNC will not be able to mount the pods to WASP, resulting in a failure to perform tests.

To mitigate this risk the team will:

1. Design for additional tolerance on on the lug mount flanges to allow for manufacturing error.
2. Over-design bolts to ensure they are not at risk of failing.
3. Utilize bolt engagement equations to ensure the strength of the lug attachments is satisfactory.
4. Design the lug mounts to be replaceable.

Risk 13: Manufacturing Load Cell Placement

During the final assembly phase of manufacturing, one important step will be lining up the major subassemblies (the sliding interface and the testbed) to correctly attach the load cell mounts. The vertical alignment of these mounts is critical, and also difficult to do, which poses a major risk if not properly completed.

The impact of this misalignment would be to cause a drop in the accuracy that WASP can provide. If the load cells are not measuring loads in the vertical direction, but are instead oriented at some angle with respect to the vertical direction, WASP will be unable to provide accurate weight and CG measurements.

To mitigate the likelihood of this risk, the team did/will do the following:

1. Developed a manufacturing procedure to reduce misalignment (building subassembly frames first and physically lining them up as they will be attached, multiple steps of physical measurements to ensure good alignment before permanently attaching them).

2. Built adjustability into these mounts (slotted bolt holes) to further correct any misalignment that may occur.

3. Looking into analytical ways to handle misalignment. If the angle of misalignment can be measured well enough, WASP can recover some of the accuracy lost.

Risk 14: Manufacturing Misalignment from Welding

It is understood that during the assembly of the WASP structure, welding structural components together may lead to misalignment and parts that are not perfectly straight. In particular, the team is concerned that the WASP legs, once welded, will not be aligned well with the vertical axis.

If significant misalignment occurs, the could be issues with the sliding interface binding to the legs and being unable to move. If this misalignment is bad enough, it may even introduce additional loads on the legs which could lead to total structural failure in an extreme case.

To mitigate this risk the team will:

1. Utilize a specific assembly procedure when attaching the legs (using the other assembled frame components to line them up correctly) to aid in alignment.

2. Use cleats on the leg connections so that they may be oriented correctly before attaching.

3. Test sliding interface before permanently welding legs.

Risk 15: Manufacturing Test Bed Pin House Alignment

During manufacturing, it will be necessary to correctly align the test bed pin housings as they are attached to the inner and outer test bed. This is to ensure that the pins are able to keep the testbed in the level configuration when desired.

If the pin housings are misaligned, it may be impossible to keep the testbed in the level configuration, or at the very least it may be difficult to insert the pins to do so.

The team will mitigate this risk by:

1. Employing manufacturing procedures that prevent this case. Only after the testbed subassemblies are constructed will the pin housings be lined up and attached.

2. Increasing the tolerance designed into the pin houses and the diameter of the pins to ensure that minor misalignments due to manufacturing due not cause the pin to bind.

Risk 16: Manufacturing Axle Housing Alignment

Similar to the pin housings, the axle housing will need to be aligned before being attached during the final assembly portion of the manufacturing procedure.

If there is misalignment between the axle and the housing, it may be that the axle is not able to interface with the axle bearings (as a worst case scenario). Even if it can connect, WASP may still experience binding, or an inability of the testbed to fully rotate if the alignment is off. Lastly, there may be increased frictional load on the components due to poor alignment.

The team will mitigate the likelihood and impact of this risk by using the following:

1. Manufacturing procedures to prevent misalignment, involving making adjustments while constructing and drilling the holes after the testbed subassemblies are already completed.

2. Lubricating the axle to reduce friction.

Risk 17: Manufacturing Leg Length

Since the WASP legs are some of the longest structural members, any inaccuracy in the length to which they are cut or the way they are connected will have a large impact on the structure of WASP. Cutting the legs to incorrect lengths or attaching them asymmetrically may introduce an additional unintended tilt to WASP.

This tilt could effect measurment accuracy, as the load cells are expected to be in line with gravity. The team will mitigate this risk by using the following steps:

1. Manufacturing procedures to prevent this case from happening (see Risk 10)
2. Measuring the structure tilt/floor tilt with an inclinometer and accounting for it in the calculations.
3. Adding adjustable feet which can be used to level WASP once it is in place

Risk 18: Manufacturing Schedule

WASP is a beast of a structure. It was initially estimated that 1000 person-hours would be required to complete the manufacturing process. Testing is directly dependant on the completion of manufacturing, so there is risk that the project will not be delivered on time, or that the team will have to cut back on testing to fit the semester-end.

The impact of a lengthy manufacturing schedule would be that the team would not be able to test the full structure, or there would be a delay in the delivery of WASP to SNC.

The team will mitigate this risk by:

1. Completing a manufacturing precedence diagram, to better understand the timeline of tasks for manufacturing WASP.
2. Scheduling and planning with Matt Rhode, the machine shop manager.

9.13.2 Logistical Risks

The rapid nature of this project requires that key deadlines are met and the team is staying on schedule (see Section 7.3 for more details on schedule). This year, the team has been placed in a unique position to deal with logistical challenges resulting from COVID-19 public health safety guidelines and restrictions. On-time delivery is non-negotiable, so this section discusses potential challenges to staying on schedule. Figure 135 summarizes the pre/post mitigation risk evaluations.

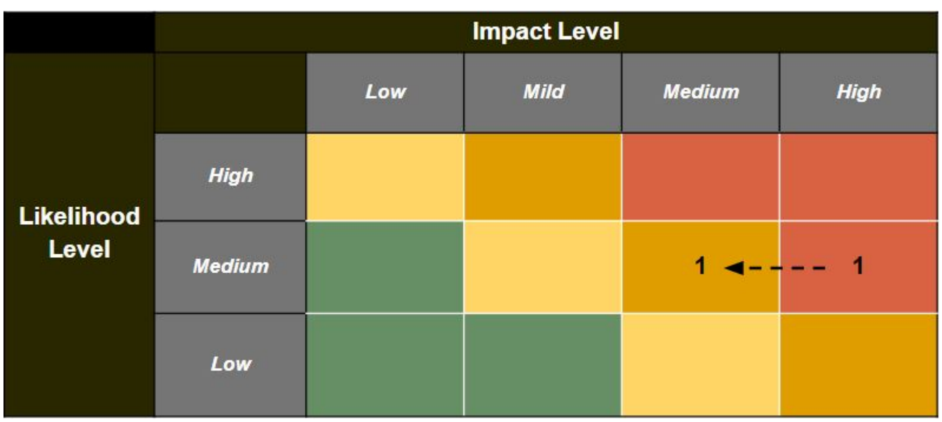


Figure 135: Logistical Risk Matrix

Risk 1: COVID-19 Restrictions

This risk covers all impact from COVID-19 related restrictions that pose an obstacle for the WASP team. First, with respect to facilities, COVID-19 restrictions could impact the availability for the manufacturing shop, PILOT lab, SNC hangar, and other potential testing locations. WASP's structure is large, heavy, and not-easily maneuverable. For this reason, it is extremely difficult to attempt to move WASP to an off-campus location to perform manufacturing or testing. Second, with respect to schedule, COVID-19 restrictions could place human capacity limits on the manufacturing shop. Shop manager Matt Rhode has informed that team that he will need extensive help from WASP team members in order to complete the manufacturing on time. Additionally, COVID-19 restrictions could reduce the hours of operation for the manufacturing shop and testing locations that may delay the team's efforts to complete manufacturing and/or testing.

In the worst case, if CU campus is shut down completely, WASP will not be able to be manufactured and the team would lack a deliverable. In a less severe case where capacity is further restricted or hours of operation are limited, the impact of COVID-19 restrictions is a schedule delay. The team does not have an option to delay the delivery of WASP to the SNC customer since this project is bounded by the end of the school year. For this reason, schedule delays early-on could force the WASP team to forfeit some anticipated testing.

To mitigate the risk of logistical impacts of COVID-19 restrictions, the team has built in significant margin for manufacturing and testing into the work plan. Specifically, manufacturing has a 40% schedule margin (two weeks on five weeks expected), and post-manufacturing testing has a 64% schedule margin (3.5 weeks on expected 5.5 weeks expected). Additionally, the team has met extensively with Matt Rhode to review the manufacturing plan from a scheduling perspective and have received his approval.

9.13.3 Safety Risks

With any system that includes human operation, safety concerns are paramount. This concern is increased exponentially when large and heavy structures make up that system. To ensure safety of the system, human user safety as well as human error considerations must be evaluated as risks. The risks below, will go into a greater detail of what the risk entails, what it effects, and how it can be mitigated. Figure 136 shows the risk matrix of these safety concerns before and after mitigation techniques are implemented.

Figure 136: Safety Risk Matrix

Risk 1: Human User Safety

This risk covers the possibility of the operator/engineers using WASP and becomes injured. This risk includes many human safety concerns: moving WASP throughout the hangar, attaching and detaching the pod to WASP via its lug mounts, using the chain hoist to lift and lower the the pod, and inserting pins in the test bed and sliding interface.

If this risk occurs, injury to the user will occur. This can range anywhere from small injuries to large injuries including death and is therefore an important risk to evaluate.

To help mitigate this risk the following choices have been or will be implemented.

1. Implementing safe distance and user guidelines.
2. Creating an intensive user manual detailing the entire procedure to ensure the user knows what to do before using WASP.

Risk 2: Human User Error

This risk involves the user not completing the test correctly causing failure of WASP. This can include but is not limited to forgetting to correctly pin/unpin sliding interface and test bed, incorrectly attaching the pod via lug mounts, forgetting to add slack to the chain hoist when detaching, and not having correct safety precautions in place.

Not only can this risk effect the structure of WASP which could be rendered useless if the user is not careful (breaking components of WASP), but this risk can also harm the user. If the correct processes are not followed, the user is put in serious danger as WASP could end up injuring the user.

By implementing the following techniques, the risk of user error can be mitigated.

1. Implementing safe distance and user guidelines.
2. Creating an intensive user manual detailing the entire procedure to ensure the user knows what to do before using WASP.

9.13.4 Financial Risks

Due to the budget margin remaining being less than the desired 20% of the total budget, a detailed analysis was performed in order to ensure that the existing margin is sufficient. After speaking with the customer, it was determined that the best course of action would be to break down the anticipated additional costs to the project beyond what is required for the minimum viable product. These additional costs range from manufacturing and integration errors to underestimates in shipping. The purpose of this analysis was to prove that even if all of these financial risks come to fruition, the remaining budget margin (referred to as management reserves by the customer) would be sufficient to cover all expenses. Below is a risk matrix outlining the six financial risks, as well as their mitigation and cost implications.

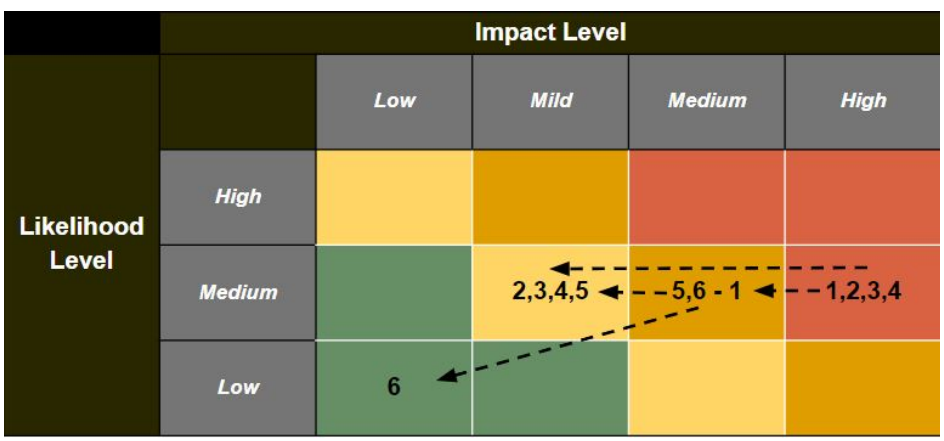


Figure 137: Financial Risk Matrix

Risk 1: I-Beam Manufacturing/Integration Error

If *a manufacturing or integration error occurs during the assembly process of the I-beams,* ***then*** *an additional 10 foot length of beam must be purchased.*

This is one of the major risks due to the fact that the I-beams alone are a significant percentage of the overall budget, and there is not room to purchase extra material. Furthermore, due to the length of some of the beams, if a mistake is made, the entire beam could need to be replaced. Therefore, the team is tentatively allocating \$165 of the management reserves to purchasing an additional 10 length of I-beam should it be necessary. Due to the relatively high cost and high number of beams included in the WASP design, both the impact and likelihood of this risk is being marked as a medium.

This risk is being mitigated by intensive assembly and manufacturing procedures. The manufacturing team has developed extensive instructions on how WASP should be built in order to prevent manufacturing mishaps. Additionally, the team will manufacture the shorter beams first, so that in the event that a mistake occurs, it will be on a shorter beam that is less expensive to replace.

Risk 2: Leg Manufacturing/Integration Error

If *a manufacturing or integration error occurs during the assembly process of the legs,* ***then*** *an additional 8-foot (96-inch) length of square tubing must be purchased.*

This is the second major risk due to the fact that the alignment of the legs is critical to ensure that the sliding interface can move freely without binding. Furthermore, due to the length of some of the beams, if a mistake is made, the entire leg could need to be replaced. Therefore, the team is tentatively allocating \$50 of the management reserves to purchasing an additional 8 length of square tubing should it be necessary. Due to the lower cost associated with this part, the impact is only mild, whereas the likelihood is still a medium.

This risk is being mitigated in the same ways as the I-beam manufacturing, however the strategy of manufacturing the shorter lengths is not possible due to the legs all being the same length. Instead, extra design features have been added to reduce the amount of welds that are being done to the legs, which are the greatest risk to putting the legs out of alignment.

Risk 3: Shipping Charge Underestimate

If *shipping costs exceed the allocated \$500,* ***then*** *additional funding will be required to ensure parts can be ordered and delivered.*

This is a major risk due to the fact that many of the commercial off-the-shelf components in the WASP design are either heavy or very large, which both lead to a high shipping cost. The team is planning to procure the raw materials from a local distributor, which will cut down the shipping costs. There are still a great deal of components that must be ordered from online wholesale suppliers like McMaster Carr. These wholesale suppliers often do not provide shipping estimates until after the order has been placed. Therefore, the team is tentatively allocating an additional \$100 of the management reserves for shipping costs. Similar to the I-beams, the cost impact is marked as a mild due to the relatively high costs and due to the fact that there is already an allocation for shipping in the main budget, the likelihood is marked as medium.

In order to mitigate this risk, local pickup is the preferred method of shipment. This will be used for the raw metals, but it is unavoidable, as mentioned. Fortunately, this risk will go away as soon as the items are ordered, so the team will know early on if it comes to fruition.

Risk 4: Manufacturing Consumables Underestimate

If the manufacturing of WASP requires more consumables than the CU AES machine shop has or is willing to provide, **then** additional funding will be required to purchase said items.

This is a risk that the team is tracking after conversations with CU AES departments machine shop manager. Due to the high amount of machining and labor required to assemble WASP, the team needs to be prepared to purchase additional equipment to replenish the machine shops stock. This may include drills, end mills and welding/grinding equipment. Therefore, the team is tentatively allocating \$200 of the management reserves to manufacturing consumables. The cost impact is marked as a mild due to the relatively high costs, while the likelihood is still medium.

This risk is difficult to mitigate due to the inevitability of running through manufacturing equipment. The team is planning to engage in conversation with the department to get a better idea of what this expense would be, and whether it could be included in the department overhead rather than the WASP budget.

Risk 5: Fasteners Underestimate

If *the WASP team determines that additional fasteners are necessary to complete the design,* ***then*** *additional funding will be required to purchase said fasteners.*

This is one of the least impactful risk due to the fact that fasteners are not only relatively low cost, but the CU AES machine shop also has a limited stock of fasteners. Should it be determined that additional fasteners are needed (due to unexpected manufacturing difficulties or other reasons), the team is tentatively allocating $50 of the management reserves to this. Due to the lower cost, the impact is being marked as mild, and the likelihood is still medium.

This risk is being mitigated in part by the stock of fasteners in the departments machine shop, as well as careful planning to ensure that the existing fasteners will be sufficient for the project.

Risk 6: Electrical Connectors

If *the WASP team determines that additional electrical connectors are necessary to complete the design,* ***then*** *additional funding will be required to purchase said connectors.*

This is also one of the least impactful risks as this has been scored as low impact, low likelihood. The CU AES department has a stock of electrical connectors that we can use for the project. Should we need to purchase additional connectors to interface the load cells to the DAQ, the team has tentatively allocated $50 of the management reserves to this.

This risk is being mitigated in part by the stock of connectors in the departments electronics lab, as well as careful planning to ensure that the existing connectors will be sufficient for the project.

After summing the incurred cost from all six of these risks, the total is $610, which leaves $230 remaining in the budget as an allocated margin. This means that even if all six risks come to fruition, the team will still have $230 for unanticipated expenses. After discussing the results of this financial risk analysis with the customer, it was determined that the overall budget risk is being properly mitigated and is no longer a major concern to the project.