University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)

Weight Analysis for Surveillance Pods (WASP)

1 Information

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Contents

Table of Acronyms

Table 1: Table of Acronyms

Acronym	Definition
CAD	Computer-Aided Design
CDD	Conceptual Design Document
CONOPS	Concept of Operations
COTS	Consumer Off-The-Shelf
CG	Center of Gravity
CU	University of Colorado (Boulder)
DAQ	Data Acquisition System
DR	Design Requirement
FR	Functional Requirement
GUI	Graphical User Interface
IAS	ISR, Aviation, & Security
ISR	Intelligence, Surveillance, & Reconnaissance
NIST	National Institute of Standards and Technology
SNC	Sierra Nevada Corporation
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.
ISR Pod/Pod	The physical object being measured by WASP, given by SNC.
Measurement Set	One recorded value for each sensor (load and inclination) in the flat and tilted configurations.
Test	The execution of a full procedure which starts after set-up and concludes when weight and CG values are output.
Tool	Equivalent to WASP.
User Procedure	Instructions document that describes transportation, maneuvering, and testing process for test engineers.
WASP	All elements of the final product/deliverable.

2 Problem Description

2.1 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.

2.2 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 aircrafts, 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 straps, performing force gauge measurements, and hand-processing these data. This process has been identified as both ineffective and a safety hazard to working engineers.

WASP aims to streamline the process of finding the weight and CG of the pods to be increase efficiency as well as protect the safety of the engineers and ISR pods themselves. In order to do this, the team looks to design a maneuverable structure that is capable of securely holding the pod, collecting 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 be certain safe care of the pods.

2.3 Specific Objectives

The specific objectives for WASP are outlined in Table 3 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 will be designing to the "Target" objectives. These levels are applied to six project elements 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 the table. The deliverables for this project include a tool composed of a structural frame, measurement devices, and a data processing unit. In summary, WASP shall successfully load the ISR pod onto its frame, perform measurements of pod weight characteristics, and output an Excel-compatible summary file of the pod's weight and CG location. Figure 1 depicts the pod-fixed coordinate frame, for which X, Y, and Z coordinate directions are defined.

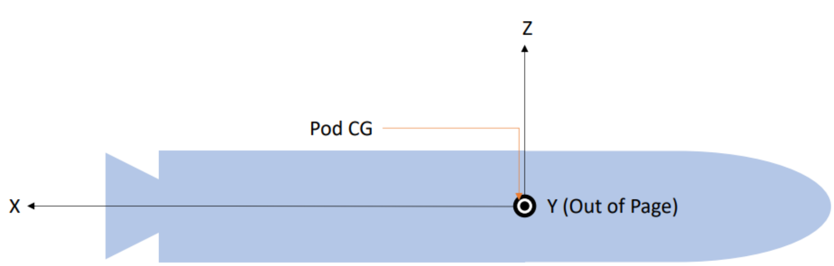


Figure 1: ISR Pod Coordinate Frame

Table 3: WASP Specific Objectives [1]

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. [1]	The tool will support pod weight up to 2000 lbs in suspension with a safety factor of 2.0. [1]	
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.	
	The test engineers will be able to successfully perform the test with the guide of an engineer familiar with tool and the test operation document.	The test engineers will be able to successfully perform the test by following procedure documented in test operation document.	
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.	

2.4 Concept of Operations

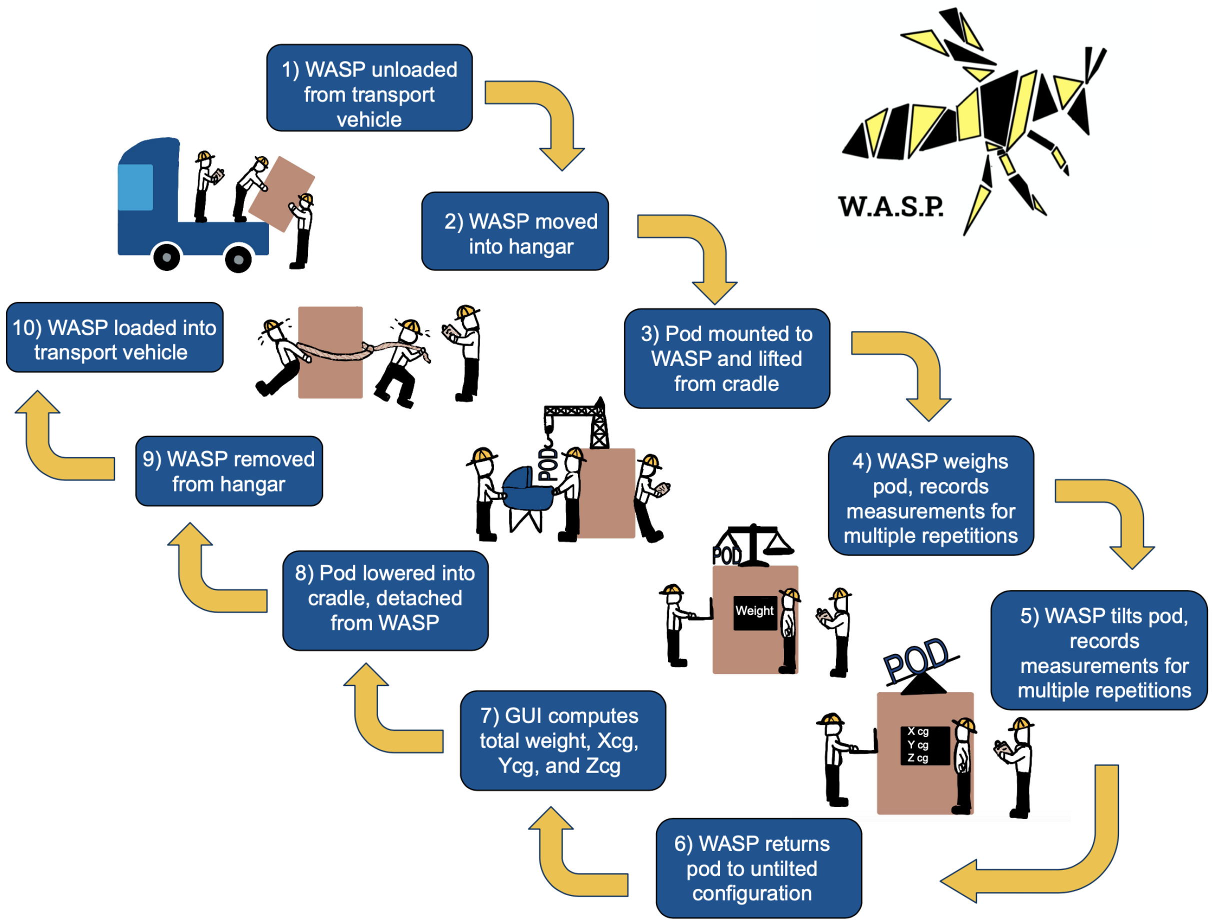


Figure 2: Concept of Operations

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 forklift slots aboard WASP. 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 multiple measurement sets at a flat and angled 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.

2.5 Functional Block Diagram

Figure 3 provides a high level overview of the systems necessary for the WASP to perform the required tasks. To begin, the operator will turn on the power supply, which will power the load cells and other electronics. The ISR pod is mounted onto WASP via the pod's lugs. Once the pod is successfully separated from its cradle and lifted to the expected flat orientation, measurements from the load cells will be captured by the UI via the Data Acquisition (DAQ) device. Next, the testbed and pod will rotate about the Y-axis to the tilted orientation, and record measurements again. The operators can then repeat these steps to collect up to five repetitions of measurement sets. Finally, the UI will utilize averaging to compute the total weight, X, Y, Z CG of the pod. The frame of WASP will have a device that will allow the tool to be transported within the testing area as well as a mechanism to lock the device in place.

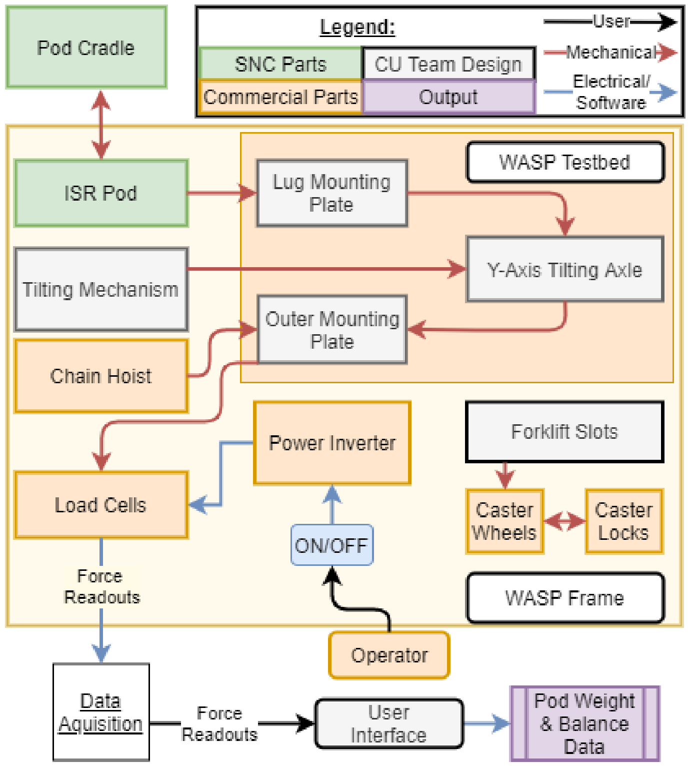


Figure 3: Functional Block Diagram for WASP

2.6 High Level Functional Requirements

The high level functional requirements for WASP were determined from customer requirements as well as aspects that are necessary for the project's success. The functional requirements are stated below in Table 4. Their motivations and Verification and Validation (V&V) methods are described in the "Design Requirements" section along with their flow-downs.

Table 4: 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	Pod Support	WASP shall support all existing ISR pods.
FR4	Form-Factor	WASP shall be free standing, and shall be easily maneuvered around an aircraft hangar by engineers mentioned in FR6.
FR5	Transportation	WASP shall fit into a box truck
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	Interface	WASP shall include a computer based tool to aid in calculations.

3 Design Requirements

Below are the high level functional requirements and design requirements for WASP. Each high level functional requirement (Table 4) prompts design requirements that relate to the customer needs and project objectives. The flow down of these requirements can also be observed below.

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 pod's 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. Sensor calibration shall be National Institute of Standards and Technology (NIST) traceable such that measured values are accurate to within ± 0.1% of the pod's true total weight.

Motivation: Customer specified accuracy requirement.

V&V: Inspection/Testing - Inspection of sensor specifications, NIST-traceable certified, as well as physical testing to verify measurement accuracy.

DR 1.1.4. Sensors shall be removable from the frame.

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.

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. Sensor calibration shall be NIST-traceable such that measured values are accurate to $\pm$0.1% of the pod's true total weight.

Motivation: Customer specified accuracy requirement.

V&V: Inspection/Testing - Inspection of sensor specifications, NIST-traceable certified, as well as physical testing to verify measurement accuracy.

DR 2.1.4. Sensors shall be removable from the frame.

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 capture measurements for CG calculations

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 support 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 up to 2000 lbs without yielding with a safety factor of 2.0.

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 [2].

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 will lift a 2000 lb pod or test item out of its cradle.

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" [2].

V&V: Demonstration - Test items with different known X CG locations will be attached to WASP. If it does not tilt, this requirement will be met.

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 [3] 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.

Motivation: WASP must be transported between hangars at SNC's IAS facilities.

V&V: Demonstration - The final device will be loaded into SNC's box truck to ensure it can be transported.

DR 5.1. WASP shall occupy less than 44"x88"x79" (LxWxH) cubic volume when being transported.

Motivation: These dimensions come directly from SNC's box truck liftgate (L) and roll-up door (WxH) dimensions.

V&V: Inspection - Computer-aided design (CAD) models will be inspected to verify the entire device does not exceed the dimension limits. When the final product is manufactured, its dimensions will be recorded as well.

DR 5.2. WASP shall weigh less than 2000 lbs.

Motivation: 2000 lbs is the maximum weight the SNC box truck liftgate can support.

V&V: Inspection - CAD models will be used to estimate weight based on material density and volume, and the final tool will be weighed after manufacturing is complete.

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 device must not take too long to make measurements and calculations.

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 six minutes.

Motivation: Derived. A minimum of five 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 six minutes. This will also include the time it takes to disconnect and re-attach the pod to the mounting interface.

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 extremely expensive products, and if any of them sustain damage 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 more than 30 degrees about the Y-axis.

Motivation: A 30 degree rotation will allow for Z CG measurements without rotating the pods to an undesirable angle.

V&V: Inspection - The maximum allowable rotation will be measured using an inclinometer.

DR 7.2. 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 7.3. 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 7.3.1. 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.

4 Key Design Options Considered

Structural Components

4.1 Testbed Configuration

To mount the ISR pod onto the frame for testing, a testbed with lug mounts and force transducers must be included in the design. This testbed design will be the method by which weight and inclination of the pod are measured. The weight and inclination measurements will then 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 tolerances.

4.1.1 Direct Connection to Frame

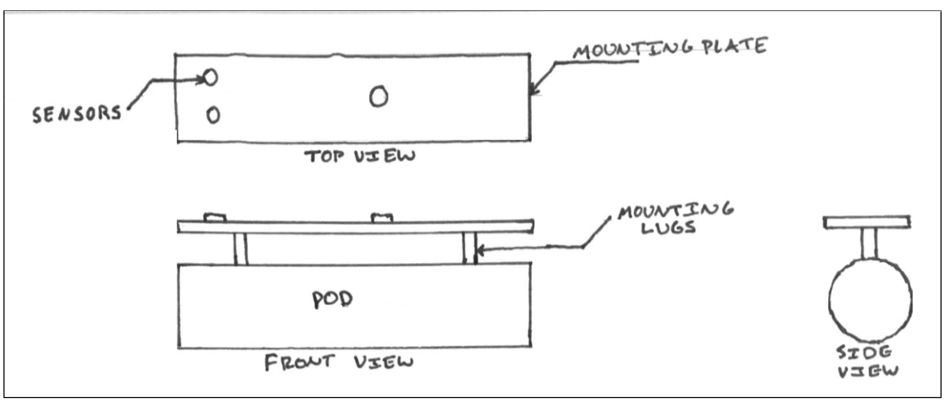


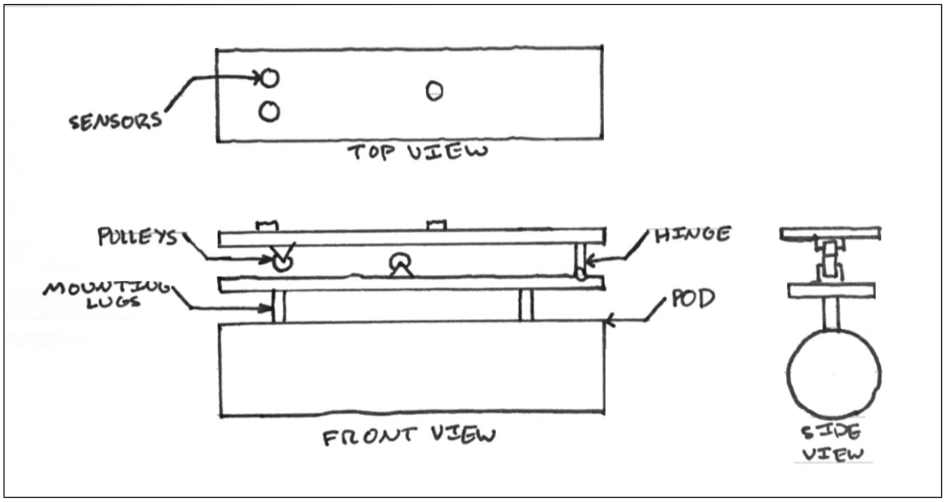
Figure 4: Direct Connection to Frame

The first design option considered for testbed is the direct connection to the frame. In this design alternative, the ISR pod is mounted onto a plate by the lugs included on each pod. This plate is then mounted directly onto 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 5 summarizes some of the pros and cons of the direct connection to frame design option.

Table 5: Pros and Cons - Indirect Testbed

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

4.1.2 Indirect Connection to 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 the figure above, 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.

Table 6: Pros and Cons - Direct Testbed

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

4.1.3 Hybrid Connection to Frame

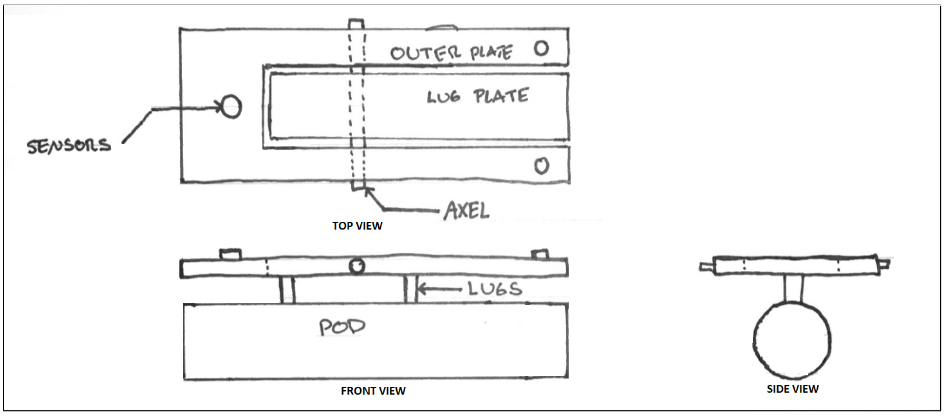


Figure 5: Hybrid Connection to Frame

The hybrid design attempts 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 7: 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	

4.2 Lifting Mechanism

In most design concepts, the ISR pods must be lifted out of a cradle and suspended in order to measure weight and CG. Thus, a reliable, safe, and robust mechanism must be developed to lift these large pods in the very likely case that lifting is required. A chain hoist, hydraulic system, and pulley system were all considered. Their functionality as well as benefits and weaknesses are described below.

4.2.1 Chain Hoist

The chain hoist (Figure 6) 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 small force over a long distance to large force over a short distance [4]. Figure 7 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 6: Generic Chain Hoist

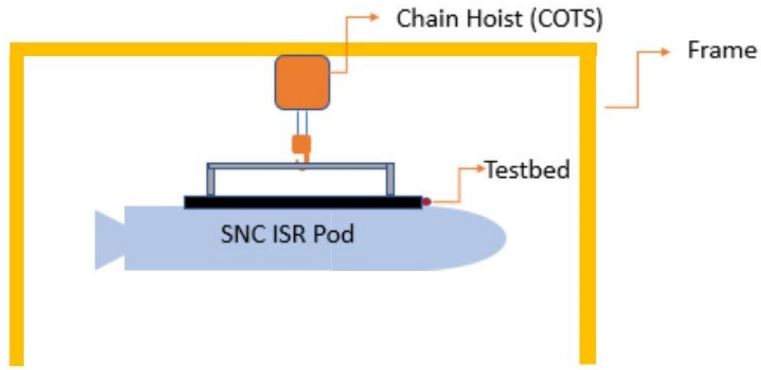


Figure 7: Chain Hoist Lifting Mechanism on WASP

The benefits and drawbacks associated with using a chain hoist are shown in Table 8. 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 8: 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	

4.2.2 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 8 illustrates this concept.

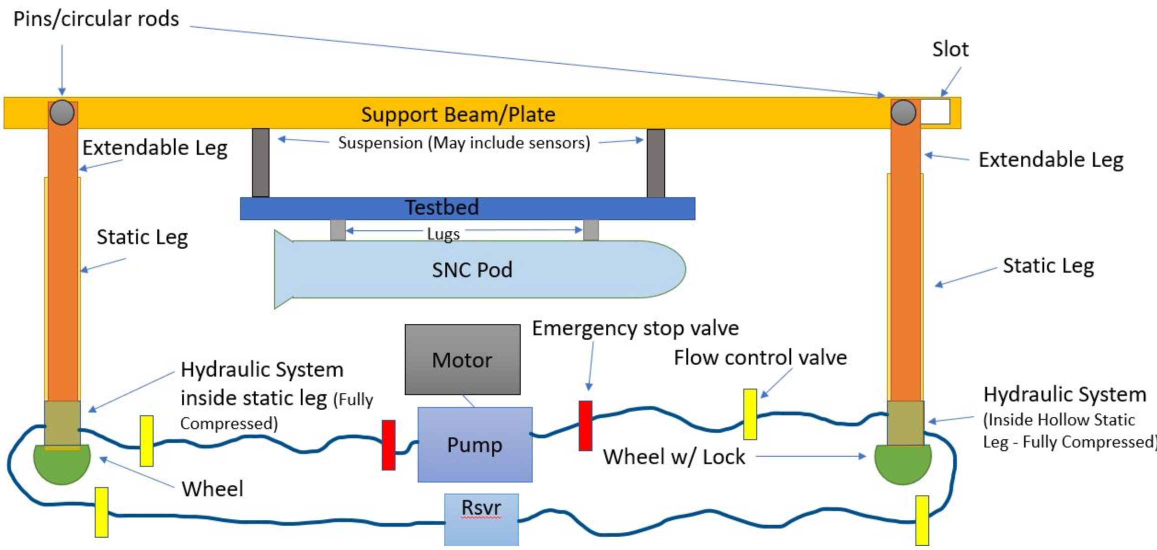


Figure 8: Hydraulic Lifting Mechanism on WASP

A hydraulic system offers the best choice for smooth, easy lifting. However, such a method would be extremely costly relative to the other methods presented. Furthermore, with this team's current experience with hydraulics and the number of components, the chance of failure is relatively high. The pros and cons of using hydraulics are summarized in Table 9.

Table 9: 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

4.2.3 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 9 portrays how this system may be employed for WASP.

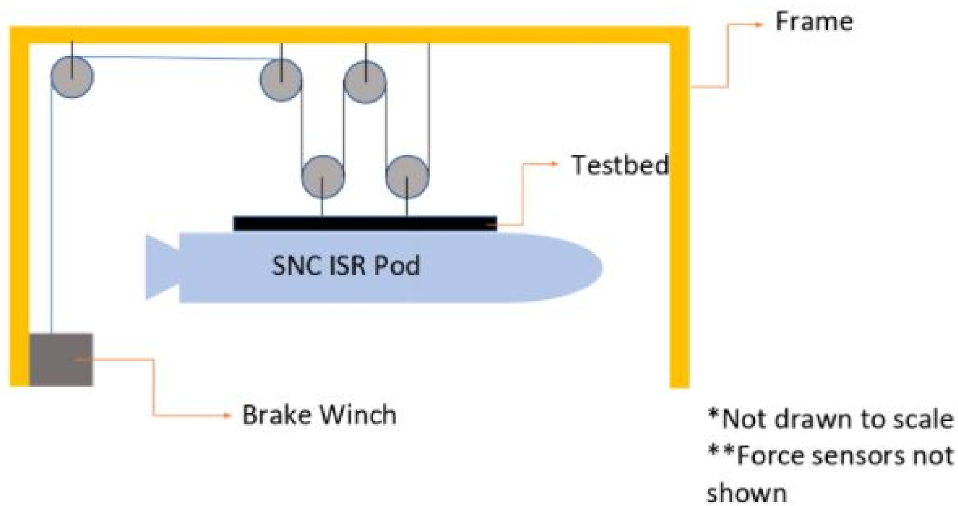


Figure 9: Pulley Lifting Mechanism on WASP

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 that the cost of various pulleys and cables would add up and it would require more integration design. A full list of advantages and disadvantages for a pulley system are given in Table 10.

Table 10: 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

4.3 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 gives 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 [5].

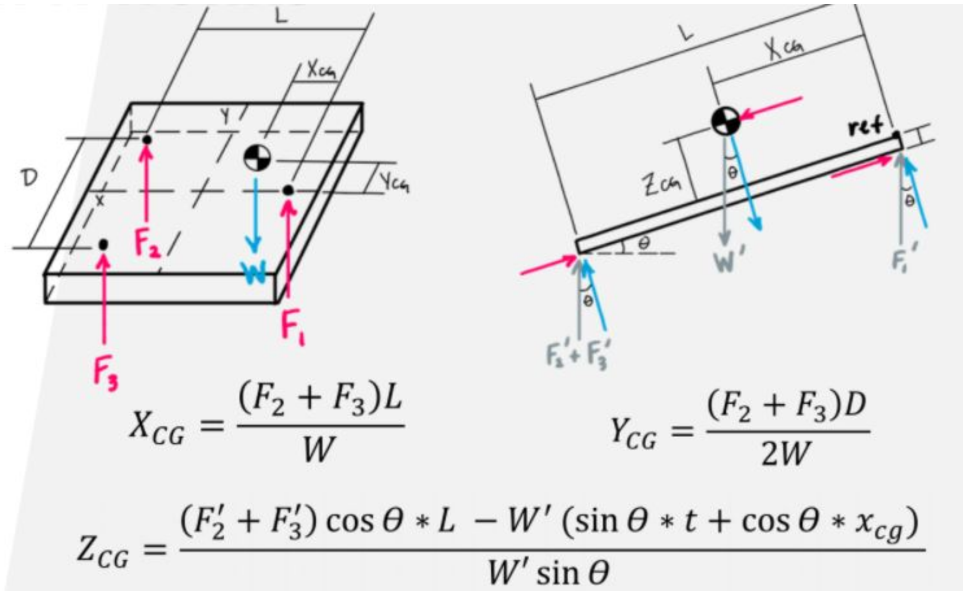
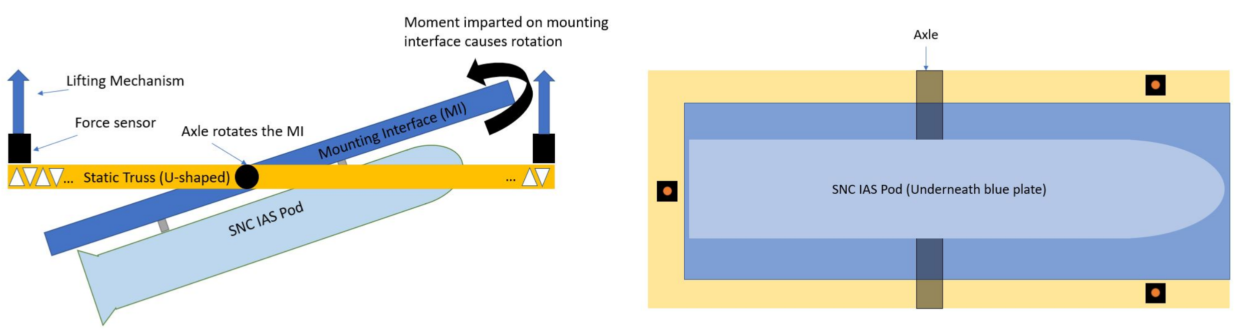


Figure 10: Generic CG Determination Equations Using Load Sensors [5]

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 are 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 are some compatibility issues between specific design alternatives that may influence the baseline design selection. This is discussed in more detail in Section 6.

4.3.1 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, while the internal one is a ISR pod mounting interface that rotates with the pod. When a moment is applied to the inner plate, the system rotates, as shown in Figure 11.



Front View

Top View

Figure 11: 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 11.

Table 11: 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	

4.3.2 Suspended Mounting Interface with No Axle

The second mechanism considered for tilting the pods involves a testbed suspended from cables or chains from which the force measuring system would be connected, pictured in Figure 12. Tilting the testbed would be achieved by lowering the chain/cable on one side of the testbed.

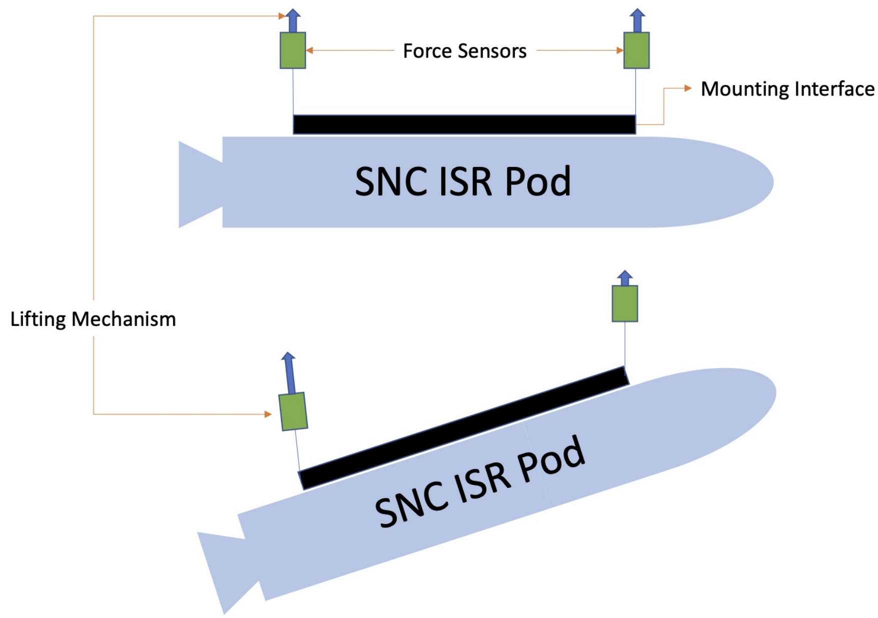


Figure 12: Suspended Testbed Tilting Mechanism

This design would be simple and economical 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 12.

Table 12: 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	

4.3.3 Cradle Platform Tilts Pod from Below

This system involves rolling the cradle and ISR pod onto a platform and rotating the entire platform into the air, shown in Figure 13.

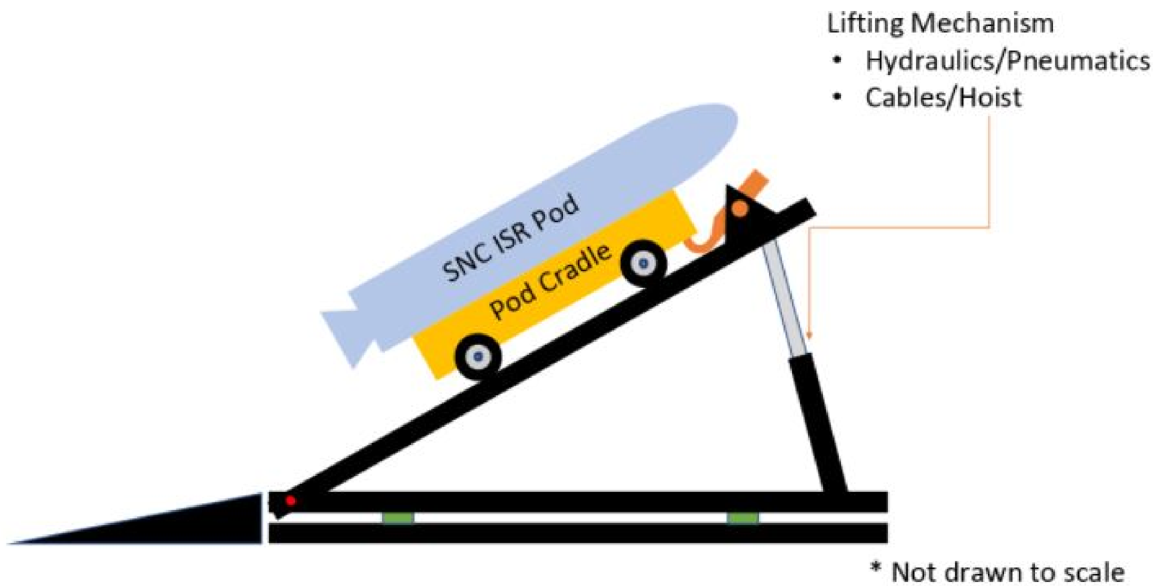


Figure 13: Cradle Platform Tilting Mechanism

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. The pros and cons are displayed in Table 13.

Table 13: 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

4.3.4 Parallel Plate Suspension

This design 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 14. As the upper plate is tilted, the lower plate also tilts while keeping the force sensors perpendicular to the ground.

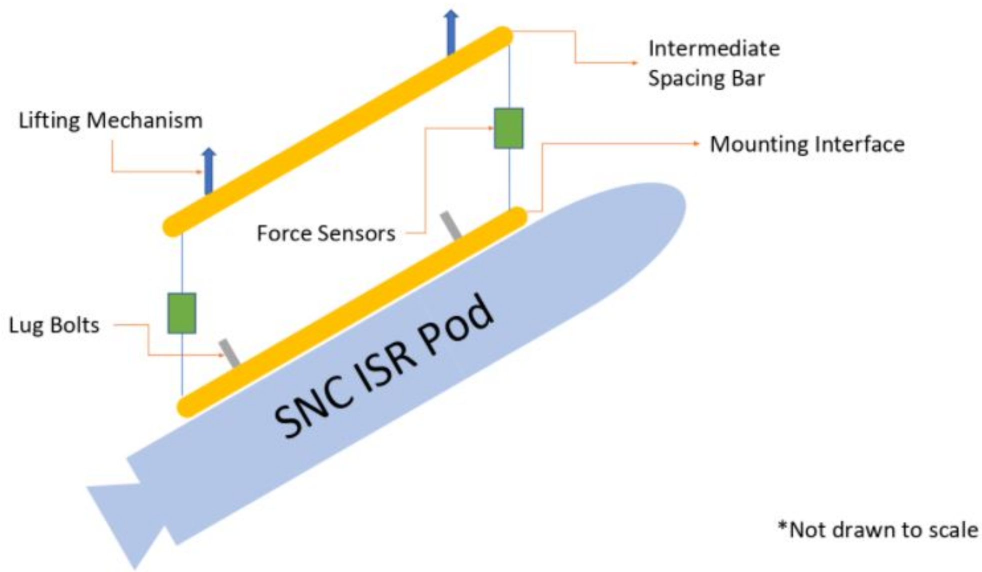


Figure 14: Parallel Plate Tilting Mechanism

This design would simplify the CG calculation relative to the suspended plate design, while remaining relatively 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 14.

Table 14: 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	

4.4 Maneuverability Mechanism

4.4.1 Caster Wheels

The first maneuvering design involves the use of caster wheels, seen in Figure 15. The caster wheels would mount directly to the legs/base of the frame to allow for easy maneuvering around the aircraft hangar. These wheels also allow for turning of WASP without additional design or materials. Caster wheels are readily available, can support large loads, and have locking abilities. They would provide a simple way for a few engineers to maneuver WASP. The pros and cons of using caster wheels can be seen listed in Table 15.

Figure 15: Caster Wheels

Table 15: Pros and Cons - Caster Wheels

Pros	**Cons**
Relatively Affordable	Locks may not hold WASP completely static
Readily Available	Wheels are not the most reliable
High load Bearing Ability	
Turning Ability	

4.4.2 Forklift Slots

The second maneuvering design would be the addition of forklift slots into the base of the frame, as shown in Figure 16. An engineer would then be able to lift and maneuver WASP by use of a forklift. Implementing this design would require little redesign to the frame and would not be complex to manufacture. The frame also would remain completely static whilst the forklift is separated, eliminating the rist of measurement errors due to translational movement during the test procedure. The downside of this design is that it requires the use of heavy machinery. The pros and cons can be observed in Table 16.

Figure 16: Forklift Slots

Table 16: Pros and Cons - Forklift Slots

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

4.4.3 Axle and Wheels/Tires

The next maneuverability design involves the use of a wheel and axle system, seen in Figure 17. 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. The pros and cons are seen in Table 17.

Figure 17: Wheel and Axle

Table 17: 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

4.4.4 Motorized Wheels

The final maneuverability design invokes the use of motorized wheels, see Figure 18. 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 precise 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 18.

Figure 18: Motorized Wheels

Table 18: 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

Electronics, Sensors, and Software

4.5 Sensor Type

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.

4.5.1 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 19.

Figure 19: Tension Load Cell

Table 19: 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	

4.5.2 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 20.

Figure 20: Compression Load Cell

Table 20: Pros and Cons - Compression Load Cells

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

4.5.3 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 21.

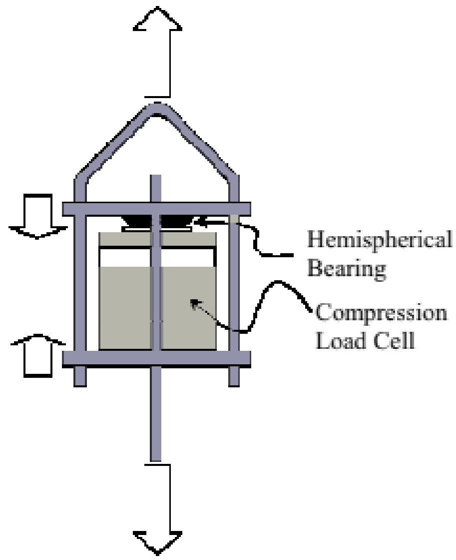


Figure 21: Compression-Tension Adapted Load Cell[6]

Table 21: 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

4.5.4 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 22.

Figure 22: Force Sensors

Table 22: Pros and Cons - Force Sensors

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

4.5.5 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 23.

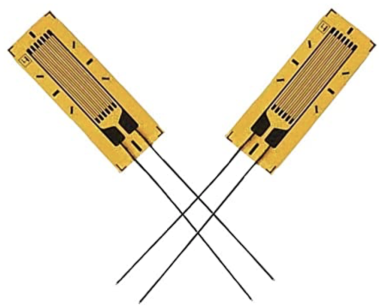


Figure 23: Strain Gauges

Table 23: Pros and Cons - Strain Gauges

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

4.6 Accuracy Enhancement

Design options to enhance accuracy were explored to improve success of meeting design requirements for weight and CG accuracy. This is referenced under FR1 and FR2 in the design requirements section. This trade study discusses the different ways to use NIST-Traceable Certification to calibrate sensors. The source of calibration for accuracy enhancement is suggested by the customer. To have a NIST-Traceable sensor means to characterize the sensor carefully, so all sources of errors are documented and contained within a tolerance. The design options are given below.

4.6.1 Pre-NIST Traceable

This option purchases the sensors with NIST-Traceable Certification. This type of sensor meets the project accuracy requirements including the effects of temperature changes from the environment. While the sensor accuracy benefits from such certification, it comes at a high price. Completing the project with these sensors is feasible with additional funding. The pros and cons are discussed in Table 24.

Table 24: Pros and Cons - Pre-NIST Traceable

Pros	Cons
Comes calibrated with reduced sensor deviation	Expensive
Consistent accuracy with temperature/ environmental changes	

4.6.2 Post-NIST Traceable

In this option, the team purchases sensors without additional calibrations. These sensors will be sent to a company to provide NIST-Traceable Certification. This option gives the team calibrated sensors with detailed error analysis at a lower cost. The sensors also have a different threshold for environmental sensitivity. Details on whether the NIST-Traceable Certification improves environmental sensitivity is not clear, so future testing will be needed. The Pros and Cons are shown in Table 25.

Table 25: Pros and Cons - Post-NIST Traceable

Pros	**Cons**
Sensors are cheaper to calibrate after purchasing them	Less accurate with temperature/ environmental changes
Can obtain NIST-Traceable accuracy	

4.6.3 Non-NIST Traceable

The final option is meant to account for the worst case scenario of the project. This option does not meet the accuracy requirements of the customer. On the other hand, the cost of the sensors is the cheapest option. This allows the team to allocate funding to other parts of the project in support of successes in other DRs and FRs. When the deliverable is given to the customer, the customer can use internal funds to buy more accurate sensors to meet their accuracy requirements. The pros and cons are shown in Table 26.

Table 26: Pros and Cons - Non-NIST Traceable

Pros	**Cons**
Cheapest option	No accuracy enhancements made
Can be replaced by SNC	Meeting accuracy requirements will be difficult

4.7 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.

4.7.1 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 27.

Table 27: 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

4.7.2 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 28.

Table 28: 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)

4.7.3 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 29.

Table 29: 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)

4.8 User Interface

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.

4.8.1 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 30 below summarizes the pros and cons for using Excel to create the UI.

Table 30: 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 [7]

4.8.2 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 [8]. 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 31 below summarizes some key pros and cons of this option.

Table 31: 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	

4.8.3 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 32 below summarizes additional pros and cons.

Table 32: 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)	

5 Trade Study Processes and Results

Structures

5.1 Testbed Configuration

Three design alternatives were proposed for the testbed configuration. Five metrics were used to determine the most promising configuration, including the degrees of separation between the sensors and lugs, testbed weight, design complexity, measurement accuracy, and system stability. These are described in more detail in Table 33. The ranks associated with each metric are defined in Table 34.

5.1.1 Trade Metrics

Table 33: 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 the load sensors as close to 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 really 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 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.

Table 34: 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

5.1.2 Trade Study Results

Below (Table 35) are the results of the testbed trade study. According to the chosen metrics, the hybrid configuration is the most likely to lead to project success, given that the tilting mechanism and sensor type are compatible with it.

Table 35: 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

5.2 Lifting Mechanism

One of the most important mechanical aspects of WASP is the ability to lift heavy ISR pods to make accurate measurements. The following trade was completed to ensure a safe, reliable, and effective lifting method that fits 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 36 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 to support the necessary loads.

5.2.1 Trade Metrics

Table 36: 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 rather than 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 [3]).
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. 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 37 features the metric ranks for the lifting mechanism trade.

Table 37: 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	55-75	35-55	<35	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

5.2.2 Trade Study Results

Table 38 holds the lifting trade evaluation. The chain hoist appears to be the most practical method for lifting pods in this project considering all requirements as well as budgetary and time constraints.

Table 38: 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

5.3 Tilting Mechanism

As discussed before, WASP must tilt an ISR pod to determine the Z CG. The tilting must be precise, safe, and simple in order to satisfy all requirements. To encapsulate these considerations, four metrics (cost, design complexity, CG calculation accuracy/complexity, and stability) were created. Table 39 describes the reasoning for using these four metrics. Table 40 shows the ranks associated with each tilting trade metric.

5.3.1 Trade Metrics

Table 39: 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 should be 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 will allow 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 40: 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 point of contact with the frame	N/A	Tilting mechanism is connected directly to the frame

5.3.2 Trade Study Results

The trade evaluation for tilting is in Table 41. According to this study, the concept of rotating the suspended mounting interface using an axle is the most advantageous design alternative moving forward.

Table 41: 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

5.4 Maneuverability Mechanism

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 42 and 43.

5.4.1 Trade Metrics

Table 42: 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 [3]. 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 43: 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

5.4.2 Trade Study Results

The maneuverability trade was completed in Table 44. 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 44: 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

Electronics, Sensors, and Software

5.5 Sensor Type

WASP requires accurate sensors that can determine the weight and CG of the ISR pods within customer specified tolerances. The various sensor types were evaluated using the metrics: connection to frame, accuracy and precision, static ability, cost, and correct measurements. These can be seen described in Tables 45 and 46.

5.5.1 Trade Metrics

Table 45: 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 46: 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

5.5.2 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 47: 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 48: 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

5.6 Accuracy Enhancement

This trade is a study on methods for improving the accuracy of the sensors. Using NIST-Traceable certification, the sensors used by WASP are evaluated and calibrated to achieve the design accuracy requirements. This study explores different implementations of the NIST-Traceable certification which is shown in the tables below.

5.6.1 Trade Metrics

Table 49: Considerations and Weights for Accuracy Enhancement Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Accuracy	30%	**FR 1, DR 1.1, DR 1.1.3, FR 2, DR 2.1, DR 2.1.3**	The purpose of this trade study is to enhance accuracy so success of customer accuracy demands increases. Accuracy is assumed to be measured in a controlled environment (i.e lab, clean room, temperature controlled facility)
Precision	30%	**FR 1, DR 1.1.2, FR 2, DR 2.1.2**	Accuracy and precision are important to mission success. Having consistent measurements that are accurate is crucial to producing a functional deliverable.
Environmental	15%	**FR 1, FR 2**	Since WASP will define accuracy as a measurement taken in a controlled environment, understanding changes in bias and error due to the environment is important. The test will take at most an hour to complete. This does not include testing preparation or hardware being disassembled. Because Colorado has sporadic weather changes, having sensors that mitigate error due to temperature sensitivity is needed.
Cost	25%	**Budget**	This metric defines additional expenses needed while purchasing the sensors. Using the initial budget given, the sensor calibrations to achieve customer accuracy demands are very expensive.

Table 50: Accuracy Enhancement Metric Rankings

Metric	1	2	3	4	5
Accuracy	Sensor meets an accuracy worse than 1%	Sensor meets an accuracy of 1%	Sensor meets an accuracy of 0.1%	Sensor meets an accuracy of 0.01%	Sensor meets an accuracy better than 0.01%
Precision	Sensor has consistent accuracy for 1 test	Sensor has consistent accuracy for 2 test	Sensor has consistent accuracy for 3 test	Sensor has consistent accuracy for 4 test	Sensor has consistent accuracy for 5 test
Environmenta	Sensor is affected by 0.5 °C change in temperature	N/A	Sensor is affected by 5 °C change in temperature	N/A	Sensor is affected by 10 °C change in temperature
Cost	Sensor requires pre NIST-Traceable calibration services during purchase	N/A	Sensor requires NIST-Traceable calibration services after purchase	N/A	Sensor requires no NIST-Traceable calibration services

5.6.2 Trade Study Results

Looking at the evaluation table below,the results of the accuracy enhancement trade study reveals obtaining NIST-Traceable Certification after purchasing the sensors is the best option.

Table 51: Accuracy Trade Evaluation

Metric	Weight	Pre-NIST Traceable	Non-NIST Traceable to NIST-Traceable	Not NIST Traceable
Accuracy	0.3	4	4	2
Precision	0.3	5	5	3
Environmental	0.15	5	3	3
Cost	0.25	1	3	5
Total	1.0	3.7	3.9	3.2

5.7 Interface

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).

5.7.1 Trade Metrics

Five metrics were selected for this trade study, listed in Table 52. 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 53 then defines how the rankings of each of these metrics will be defined for the eventual trade study.

Table 52: 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 53: 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).

5.7.2 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 54: 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

5.8 User Interface

WASP requires a user interface that reliably imports data, performs necessary calculations to obtain weight and CG location values, and outputs such results to an Excel-compatible file, per DR8.3. Additionally, since this tool is human-operated, an SNC engineer with access to SNC licensed software must be able to successful run and utilize the UI in its intended manner. Moreover, the software will need to be compatible with the DAQ use for signal conditioning, which in the current state of the project is likely to be NI 9237 both for its availability and capabilities. Finally, in the interest of customer satisfaction, the UI should be designed to improve the ease of use of the tool and elevate its functional efficiency, consistent with the Ease of Use critical project element.

5.8.1 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 55 further summarizes the metrics, their relative weighting, and rationale for their consideration in more detail.

Table 55: Considerations and Weights for User Interface Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
NI 9237 DAQ Importability	40%	**FR 1, FR 2, FR 8, DR 8.1**	The UI platform will need to capture final measurement data from the sensors, which will be processed through a signal-conditioning electronics unit. The available and recommended DAQ for load cells is NI 9237. However, compatible software options are very limited. While there exists other DAQ options, including COTS and student-developed units, using department available hardware is in the best interest of the project at this time. It is critical that the UI software is compatible with the DAQ, or the measurement data from the sensors will be useless and the functional requirements will not be met.
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	10%	**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	10%	**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.
Computation Capabilities	10%	**FR1, FR2, FR 8**	To satisfy FR1 and FR2, the UI platform will be 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. However, this category earns a low weight because the equations for weight and CG location are not particularly computationally heavy, and it is predicted that many UI platforms would meet the criteria.

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 56.

Table 56: 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 or PAB members have experience with UI platform.	No team members and 1 PAB member have experience with UI platform.	1-3 team members or 1+ PAB members have experience with UI platform.	1-3 team members and 1+ PAB members have experience with UI platform.	4+ team members and 2+ PAB 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.
Computation 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 .

5.8.2 Trade Study Results

Table 57 shows the UI trade evaluation matrix for each of the design alternatives. Per the scoring algorithm, the highest-ranked UI platform is MATLAB. However, after discussion with PAB experts Trudy Schwartz and Bobby Hodgkinson, the recommendation for the UI platform is LabView due to the uncertainty in the interface between MATLAB and NI 9237 DAQ. While MathWorks describes that MATLAB's Data Acquisition Toolbox is compatible with NI DAQs [9], the unfamiliarity of both the team and the PAB experts with such method raises question in feasibility. Since LabView scored close to MATLAB in the trade study and considering the aforementioned hesitation, LabView is the preferred design alternative. Importantly, this choice is dependent on the availability of LabView software on the intended test computer at SNC. Since

SNC does not currently have LabView licenses, they would either need to agree to purchase the software or the project would need to receive approval from National Instruments to develop a LabView UI that exports as an executable-only file that SNC would be able to use.

Table 57: 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
Computation Capabilities	0.1	5	5	5
Total	1.0	2.6	4.2	4.0

6 Selection of Baseline Design

During the conceptual design process, it became apparent that some design options from certain trades cannot be combined with some from other trades. Thus, two compatibility matrices (Figures 24 and 25) 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 a secondary option must 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 WASP design that implements all components of the baseline design are diagrammed in Figures 26, 27, 28, and 29.

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 24: Structural Compatibility Matrix

Figure 24 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 35, 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 38, the suspended tilting mechanism with an axle is ranked the highest. It is compatible with the hybrid testbed configuration, 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 are not a concern. The trade evaluation in Table 38 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 final 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 matrix, so only the results of the trade need to be considered. Based on the trade evaluation in Figure 44, forklift slots are the recommended choice. However, the customer has requested that a forklift only be used if absolutely necessary, so mounting interfaces for caster wheels will also be 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 date.

The baseline structural design choices are summarized in Table 58.

Table 58: 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	not compatible	not compatible				
	Strain Gauge	compatible	compatible	not compatible	compatible				

Legend
Compatible
Not Compatible
Irrelavant

** compression to tension adapter device needed

Figure 25: Electrical-Structural Compatibility Matrix

The Sensor Type is used as the basis for the electronics baseline design. The Sensor Type is the key electronics design element of the project because it effects how the pods are measured. After picking the sensor for functionality, looking at Table 25 verifies its compatibility with different structural designs. Shown in Table 47, and 48, the tension load cell has the best or second best evaluation. Although the cost of these sensors are concerning for the project, this sensor type is compatible with all except one structure design. Using the structures baseline design (Table 24) and Table 25, the tension load cell is compatible with baseline design choices. The tension load cell is chosen as the baseline design.

After selecting the sensor, the accuracy enhancement method is chosen. Looking at Table 51, the best choice was to choose to acquire NIST-Traceable calibrations on the sensors after purchasing them. This method is most cost effective and provides a high level of accuracy. Until further discussion with the customer, this method is chosen as the baseline.

The next baseline design deals with how the sensors interface with SNC hardware. Shown in Table 54, the highest ranking option was the hardwired connection. This was due to the simplicity and reliability for data transfer. This provides the cheapest option of the alternatives as well. Although wireless connection would provide quickest hardware interfacing, this was not required of the customer. Designing for wireless connection added complexity and more expenses for features that making testing easier. Because of these additional issues, the hardwired connection was selected as the baseline option.

The final baseline design selected was the user interface. From Table 57 the MATLAB interface was ranked the highest. The recommended design choice is LabView. Although the preference of the customer is Excel, Excel does not have a Data Acquisition Tool that can communicate with the NI 9237 DAQ, which devalues the choice significantly. LabView is the UI option that is compatible with the NI 9237 DAQ without additional tools. This is mission critical since failure to connect with the DAQ and software means a loss in data. The option to produce an UI that is separate from the application will require special permission from NI. Discussion with the customer to verify the use of LabView is requires, since SNC may need to buy a license to run a LabView UI. Another option is to use the Data Acquisition Toolbox from MATLAB, which is understood to facilitate compatibility with the NI 9237 DAQ. This method is not used frequently in practice, so the team will need to develop test procedure to verify compatibility. Until these issues are addressed, the LabView user interface is the baseline design choice. If WASP cannot accomplish design baseline, data from the sensors will be digitally reported to a physical gauge, and an engineer will record measurements on an Excel sheet for manual calculations.

Table 59 shows a summary of the electronic baseline choices.

Table 59: Electronics Baseline Selection

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

Baseline Design Concept Diagrams

The following diagrams provide a high-level overview of WASP in its completeness, following the baseline design selections. Pictured are three key configurations of WASP during the test process, beginning in the lowered configuration (Figure 26), raising to the lifted configuration (Figure 27), and angled to the tilted configuration (Figure 28). Figure 29 illustrates a top-down view of WASP.

Figure 26: Baseline Design Concept Drawing Lowered

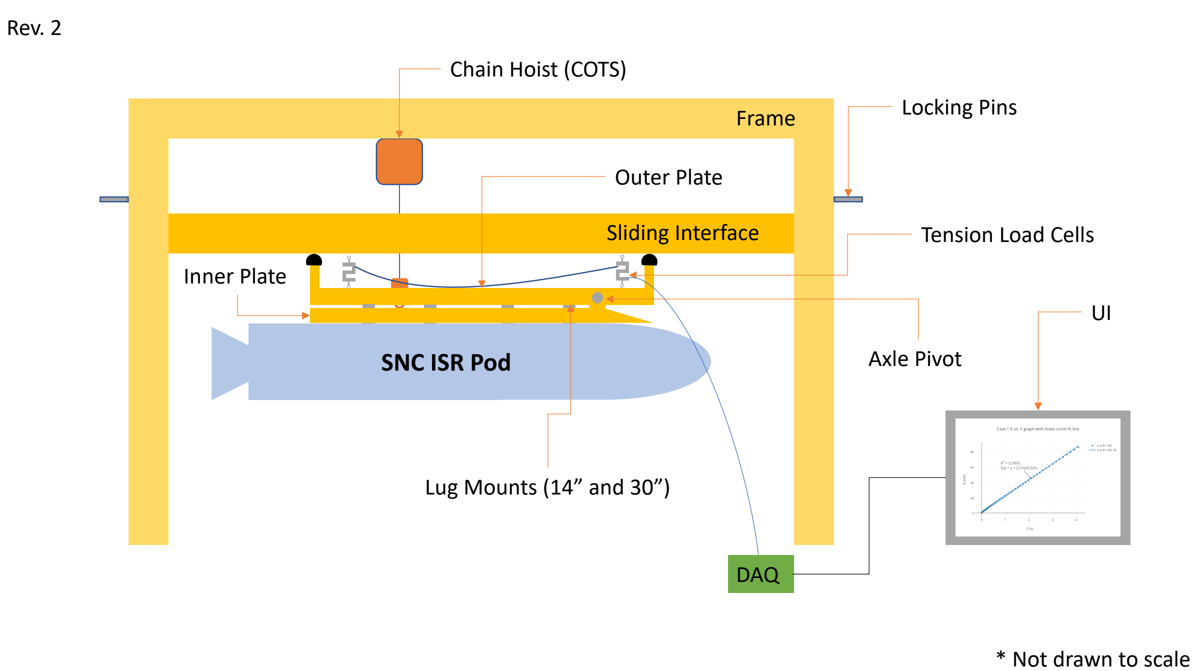


Figure 27: Baseline Design Concept Drawing Lifted

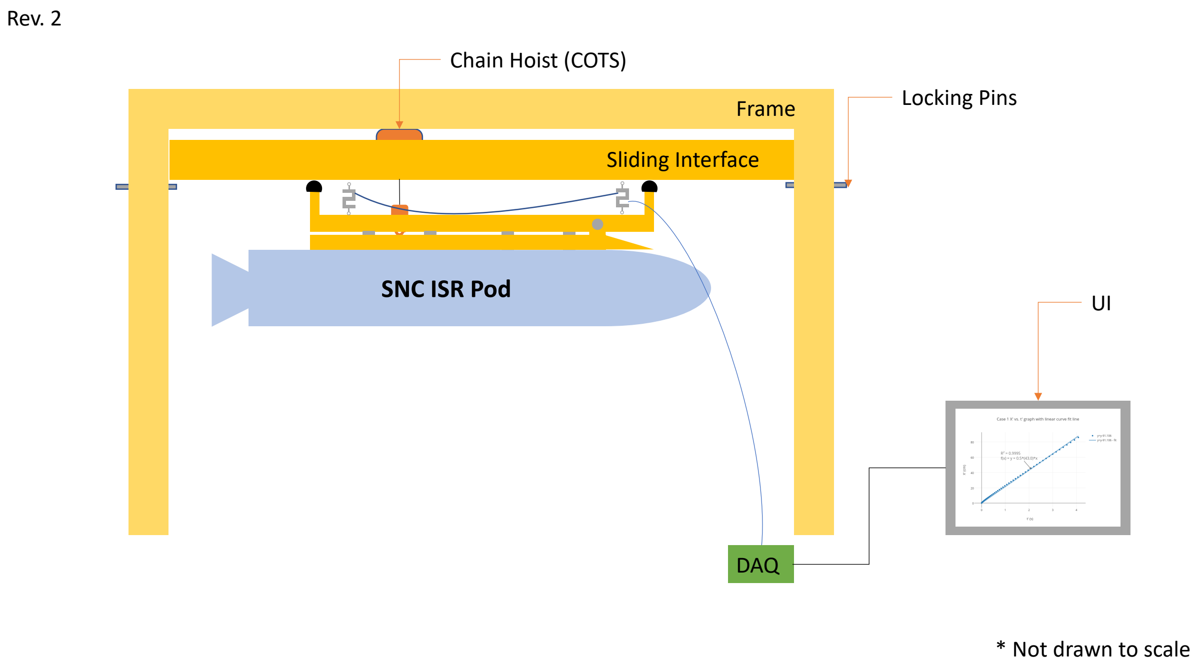


Figure 28: Baseline Design Concept Drawing Tilted

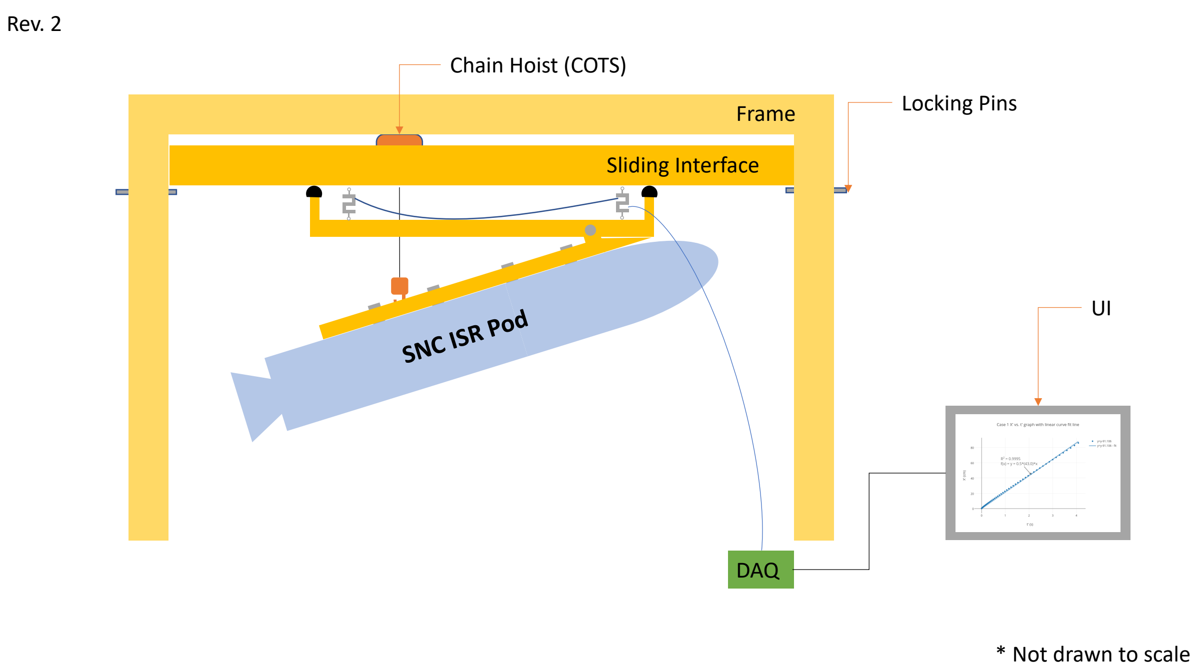
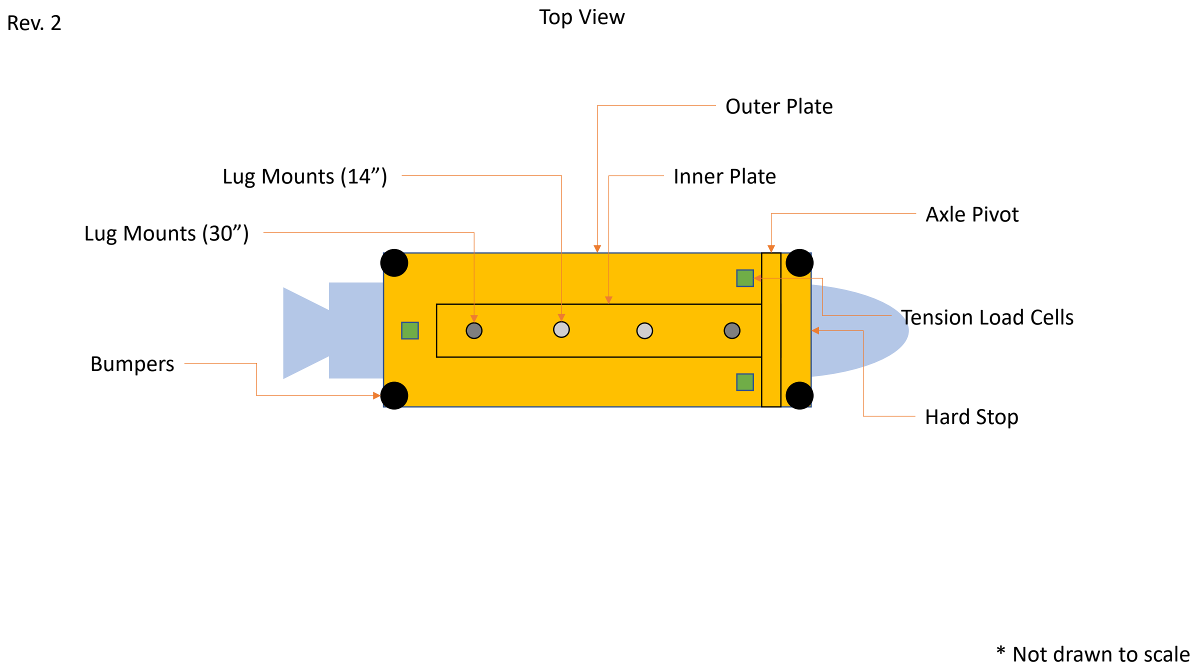


Figure 29: Baseline Design Concept Testbed Top View



8. References

[1] Robert Anderson. Ground support equipment design requirements - international space station. *National Space Development Agency of Japan, National Administration of Aeronautics and Space, Canadian Space Agency*, February 1994.

[2] Mil-std-8591, department of defense design criteria: Standard airborne stores, suspension equipment and aircraft-store interface (carriage phase), Dec 2005.

[3] Mil-std-1472f, department of defense design criteria standard: Human engineering, Aug 1999.

[4] How a manual chain hoist works, November 2015.

[5] Kaleb Cartier, Kendal Gray, and Eric Smead. 3 axis center of gravity measurement device, May 2019.

[6] Brad Hill. Measuring weight and center of gravity using load cells. *65th Annual Conference of Society of Allied Weight Engineers, Inc.*, May 2006.

[7] Philip Treacy. Real time data in excel. *myOnlineTraininghub*, April 2020.

[8] David Sampson. Gui layout toolbox. *MATLAB Central File Exchange*, 2020.

[9] Data acquisition toolbox. *MathWorks, Inc*, 2020.