University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Weight Analysis for Surveillance Pods (WASP)

Approvals

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1. Problem or Need

Within the aerospace industry, the knowledge of the weight and center of gravity (CG) of a body is paramount to the design of any product that will take flight through the air. Without a robust understanding of these measurements, the body's ability to successfully achieve safe flight is not guaranteed. Some risks associated with inaccurate weight and CG values include difficulties with the aircraft controls, reduced maneuverability, and erroneous feedback responses from on-board computers, ultimately heightening possibility of failures. It then falls on the mass properties engineering team to provide these essential calculations. While weight and center of gravity can be computed analytically, physical measurements are also necessary as irregularities during manufacturing could cause discrepancies between the model and final product. With that, accurate measurements of weight and CG are essential in assuring attachment allowables will not be exceeded in flight.

The Sierra Nevada Corporation (SNC) ISR (Intelligence, Surveillance, and Reconnaissance), Aviation and Security (IAS) division utilizes pod systems that mount onto an aircraft. SNC needs accurate weight measurements of their pod systems as well as an efficient and effective way to measure the CG location in the X and Z coordinate directions. The current method utilized by SNC results in the precarious suspension of these pods from a forklift with tow straps. This method is inefficient, unsafe for the pods and personnel, and does not deliver the accuracy and precision required. Weight Analysis for Surveillance Pods (WASP) seeks to upgrade and standardize the mass properties measurement methods for SNC pods to increase safety, efficiency, and effectiveness.

2. Previous Work

In the aerospace industry, there are two main categories of methods used to obtain the weight and balance of an object. The first and most common method is the static method. This method involves supporting the object at multiple points using force sensors [1] and performing moment calculations to determine the weight and axis-specific CG components. In order to calculate the CG of all three axes, the object or measuring tool must be rotated so that components of each axis can be aligned with the earth's gravity [2]. A project team at the University of Idaho used this method in the design and construction of a tool capable of measuring the CG of objects up to 75 lbs in weight [3]. Members of the Department of Industrial Engineering at the University of Bologna also developed a technique in which the object is statically suspended in two points and inclinometers are used to make angle measurements. Similar to the force measurements, the angle measurements can be used to back-calculate the CG components [4]. The second method is called the dynamical method, and it exploits the dynamical properties of the object itself to back-calculate the CG components. One example of this method is called the Trifilar Torsional Pendulum, which suspends the object by a cable at three separate points. The pendulum is then perturbed and the resulting period of oscillation about each cable can be used to calculate all three CG components, as well as the full moment of inertia tensor [5]. While this method can produce a great deal of information, many objects (including a surveillance pod), are not suitable to being suspended by cables due to their size and weight. After reviewing past work in the experimental mass properties determination realm, it is evident that further work is needed for this project to scale up the size and weight capacity of previously developed devices.

3. Specific Objectives

In order to determine the specific objectives for WASP, the requirements given by the Sierra Nevada Corporation as well as the available resources to create the required tool were used. Table 1 describes the success criteria for the functionality of the tool with respect to six key project elements: Structural Integrity, Mounting and Interfacing, Measurement Accuracy, User Interface, Test Operation, and Transportation. The specific objectives range in expected capability from Level 1 to Level 3. The project will be considered successful if, at minimum, Level 1 objectives are achieved for all project elements. Level 1 objectives reflect the "Threshold" expectations for the capabilities of WASP per given requirements from the Sierra Nevada Corporation. Level 2 aims to reflect the "Objective" capabilities of WASP, and Level 3 objectives reflect "Target" capabilities of the tool to which the team will design WASP. It is intended that the evaluation for meeting the success criterion is verified by demonstration, inspection, or analysis testing. Demonstration testing will involve verifying intended performance capabilities in a partial and/or full run-through of the tool's measurement method. Analysis testing will employ using some computation to determine if a specific numerical requirement is met. Inspection testing will utilize a qualitative check of a requirement. 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 pod onto its frame, perform measurements of pod weight characteristics, and output an excel workbook summary of the pod's weight and center of gravity location.

Table 1: WASP Specific Objectives [6]

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.	The tool will support pod weight up to 2000 lbs in suspension with a safety factor of 2.0.	
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 transportable by truck bed between hangars.		The tool will have dissassembly capability to a stowed/transport configuration that reduces the volume by a factor of TBD*.
	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.	

*awaiting customer decision on dimensions of transportation vehicle used for this tool.

4. High Level Functional Requirements

In order to provide a metric of success for the project, WASP shall adhere to the following functional requirements, Function Block Diagram (FBD), and Concept of Operations (CONOPS):

Table 2: High Level Functional Requirements

Number	Name	Requirement Description
FR1	Weight Accuracy	WASP shall measure the weight of each pod within ± 0.1%.
FR2	CG Accuracy	WASP shall measure the X and Z CG of each pod within ± 0.1".
FR3	Pod Mounting	WASP shall support pods of weights up to 1000 lbs and be capable of being attached to pods with specific lug spacing (as detailed in MIL-STD 8591 [7]).
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 or flatbed pickup truck.
FR6	Operation	WASP shall complete test procedure in no more than 1 hour with no more than three engineers to operate and move.
FR7	Maneuverability	WASP shall not maneuver the pods in any manner that may cause damage to them.
FR8	Interface	WASP shall include a computer based tool to aide in calculations.

4.1 Functional Block Diagram (FBD)

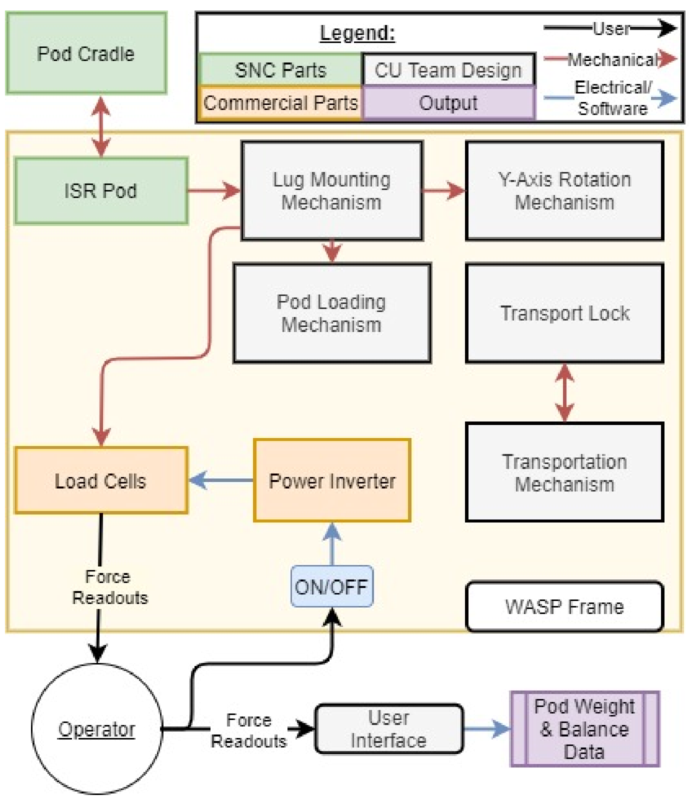

Figure 1: Functional Block Diagram for WASP

Figure 1 gives a high level overview of the systems necessary for the WASP to perform the required tasks. The operator will turn on the power supply, which will power the load cells. The pod is mounted onto WASP via the pod's lugs. Once the pod is successfully separated from its cradle, the operators can record measurements from the load cells and input them to the GUI. Next, they will rotate the pod about the Y-axis and record measurements again. Once the operators have taken the desired number of measurements at each configuration, the GUI shall compute the total weight, X CG, and Z CG of the pod. Included in the frame of WASP shall be a mechanism with which to transport the device within the testing area, as well as a mechanism to lock the device in place.

4.2 Concept of Operations (CONOPS)

A breakdown of the complete mission can be seen in Figure 2 as the concept of operations. The CONOPS demonstrates the breakdown of the mission objectives into chronological steps. WASP must be transported and unloaded from the desired vehicle. Then, WASP must have the capabilities to be moved around within the hangar. The pod will be mounted to WASP and separated from the pod cradle. Next, WASP weighs the pod and records measurements for multiple repetitions. Recorded measurements will be transferred to the GUI which will calculate the total weight as well as the locations of the X CG and the Z CG. The process is then reversed with the pod being lowered and detached, and WASP being removed from the hangar.

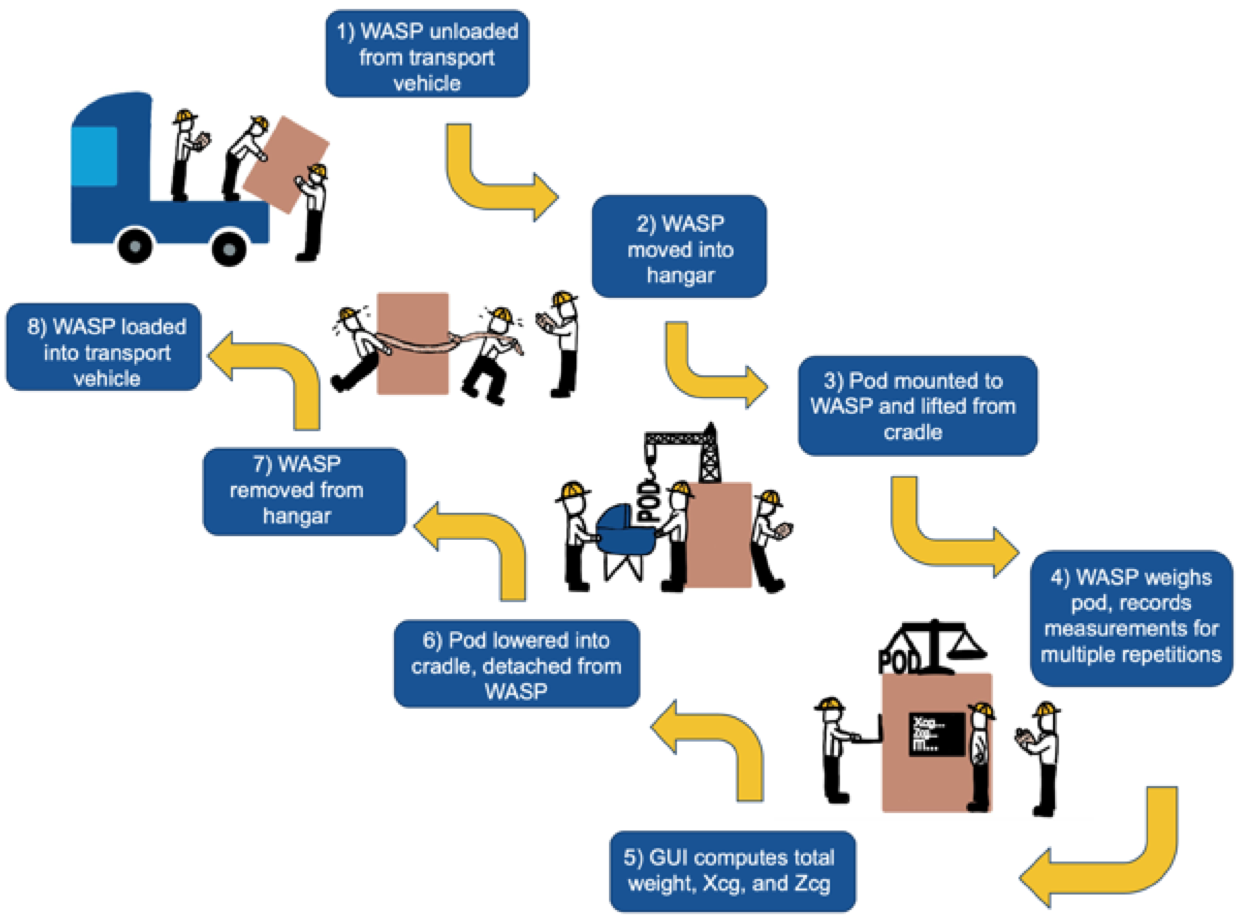

Figure 2: Concept of Operations

5. Critical Project Elements

Tabulated below are the Critical Project Elements (CPEs). These elements are crucial to the success of the design due to technical, logistical, or budgetary constraints.

Table 3: Critical Project Elements

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

6. Team Skills and Interests

Table 4: Team Skills and Interests

Team Member	Skills/Interests	CPEs
Maddie Dube	Programming (MATLAB, Python), Technical Writing, Machining/Shop Experience, some Graphic Design. Interested in: Structural Design, Electronics, Software, Machining	E1, E2, E4, E5
Adam Elsayed	CAD Modeling (Solidworks), Programming (MATLAB). Interested in: Finite Element Analysis, Machining, Integration and Testing.	E1, E2, E3, E5
Samuel Felice	FEM (COMSOL, ANSYS), CAD (SolidWorks, Inventor), Programming (MATLAB, C++, Python), Mathematics, Theoretical Modeling. Interested in: Machining, Test Engineering, Documentation & Technical Writing	E1, E2, E4
Foster Greer	Programming (MATLAB, Python), Technical writing. Interested in: CAD Modeling, Finite Element Analysis, Testing	E1, E2, E3, E5
Ansh Jerath	Programing (MATLAB), Systems Engineering, Technical Writing, Limited Excel Experience Interested in: Structural Analysis, Testing, Systems Engineering	E1, E2, E5
Aidan Kirby	Programming (MATLAB, C++, Python), Technical Writing, ANSYS, some Machining/Shop Experience, Interested in: CAD Modeling, Testing/Validation	E1, E2, E4, E5
Emma Markovich	FEA (Patran/Nastan, Creo Parametric), Excel-based User Interface (VBA), Root-Cause Analysis (Lean Six Sigma) Interested in: Stress Analysis, UI Development, Testing	E1, E2, E4
Bailey Roker	CAD Modeling (Autodesk/Solidworks), Programming (MATLAB, C++, Python), Electronic Design (Altium), Mathematica, Interested in: Hardware/Software Interfacing, Testing and Integration	E1, E2, E3
Parker Simmons	Programming (MATLAB), Data Analysis (Tableau, Excel), some CAD (Solidworks, Creo Parametric) Interested in: Finite Element Analysis, machining, Failure Analysis	E1, E2, E5
Matthew Zola	Systems engineering, CAD Modeling (Solidworks), GD&T, Machining, Programming (MATLAB, Python) Interested in: Structural design and analysis	E1, E2, E5

7. Resources

Table 5: Resources

Critical Project Elements	Resource/Source
Frame Design	Static and Dynamic Loading Assistance: Making a tool that measures weight and CG for a multi-million dollar pod must be efficient, effective, and reliable. To meet these requirements, the frame must control all static and dynamic loading through feasible approaches. Interfacing Assistance: Having correct hardware and software interfacing is critical to project success. All static and dynamic loading must be captured correctly. Material Choice Assistance: Finding the correct material to use for the frame within the limits of the budget is an important choice for the design of the frame. Making sure the material can withstand 1000 lb pods, does not interfere with electronic integration, and is viable for easy transportation is mission critical.
Mounting Interface	Lug Interface Blueprints: This is essential to meeting deliverable requirements. Without the blueprints, safety, measurements, and applicability will be severed. Steel CG Simulator: As discussed with SNC, using a steel mass simulator to replicate the pods for testing will provide valuable information for interfacing.
Accuracy	SNC hardware/electronics catalog: Characterization verification: Verifying the characterization of the sensors is accurate and precise is important for calibration. This will require a large amount of mass sampling. True value verification (NIST): Calibrating the sensors to measure at least a 1000lb pod accurately and precisely will need meticulous measuring. This will be an extremely difficult feat and will take a lot of time to develop. Measurement verification: Matching the CG and weight measurements of the pod to the true values will require a lot of testing, calibration, and characterization of the sensors
Ease of Use	Documentation for re-calibration: This will resolve faulty data and can be a quick process before measuring the pods. Certified factor of safety: Since the deliverable is ground equipment, the factor of safety can be higher, which will ensure the odds of damage to the pods is manageable. Personnel instruction: Putting engineers in the correct place to minimize exposure to danger while maximizing testing efficiency will be important for the deliverable.
Safety	SNC facilities: The facility will need to be large enough to fit in the Steel CG Simulator and all measurement tools. If the facility is not practical for testing, damage to the pods or employee injuries will be more likely. Fail-safe Redundancy: While going through testing, having fail-safe mechanisms for different stages of the test will help reduce risk to the pods and the engineers. This will be a vital point to address for the frame.

8. References

[1] Brad Hill. *Measuring the Weight and Center of Gravity Using Load Cells: for presentation at the 65th annual conference of Society of Allied Weight Engineers, Valencia, California Beach, May 20-24, 2006.* Boeing Integrated Defense Systems, May 2006.

[2] Richard Boynton. *Measuring weight and all three axes of the center of gravity of a rocket motor without having to re-position the motor: for presentation at the 61st annual conference of Society of Allied Weight Engineers, Virginia Beach, Virginia, May 20-22, 2002.* Space Electronics, LLC, May 2002.

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

[4] Dario Modenini, Giacomo Curzi, and Paolo Tortora. Experimental verification of a simple method for accurate center of gravity determination of small satellite platforms. *International Journal of Aerospace Engineering*, Apr 2018.

[5] Liang Tang and Wen-Bin Shangguan. An improved pendulum method for the determination of the center of gravity and inertia tensor for irregular-shaped bodies. *Measurement*, 44(10):1849–1859, 2011.

[6] 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.

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