University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

GAINS (General Atomics Inertial Navigation System)

Approvals

	Name	Affiliation	Approved	Date
Customer	General Atomics - Electromagnetics	Sponsor		
Course Coordinator(s)	Dr. Wingate/Prof. Muldrow	CU/AES		

II. Personnel

A. Project Customers

Name	Blake Tellefsen
Address	7304 S Joliet St. Ste 200, Centennial, CO 80112
Email	Blake.Tellefsen@ga.com

Name	Zachary Koch
Address	7304 S Joliet St. Ste 200, Centennial, CO 80112
Email	Zachary.Koch@ga.com

B. Team Members

Name	Addison Woodard (PM)	**Name**	Alfredo Restrepo
Email	Addison.Woodard@colorado.edu	**Email**	Alfredo.RestrepoJr@colorado.edu
Name	Cannon Palmer	**Name**	Jason Popich
Email	Cannon.Palmer@colorado.edu	**Email**	Jason.Popich@colorado.edu
Name	Bennett Grow	**Name**	Kaylie Rick
Email	Andrew.Grow@colorado.edu	**Email**	Kaylie.Rick@colorado.edu
Name	Tucker Peyok	**Name**	Brian Trybus
Email	Tucker.Peyok@colorado.edu	**Email**	Brian.Trybus@colorado.edu
Name	Ross White	**Name**	Alexander Pichler
Email	Ross.White@colorado.edu	**Email**	Alexander.Pichler@colorado.edu
Name	Ben McHugh	**Name**	Derek Popich
Email	Benjamin.McHugh@colorado.edu	**Email**	Derek.Popich@colorado.edu

III. Problem or Need

Typical CubeSats in Low Earth Orbit (LEO) to Medium Earth Orbit (MEO) utilize GPS to determine position and velocity. As orbits exceed MEO altitude, the power, size, and weight requirements of a GPS receiver make GPS increasingly difficult and costly to integrate at greater altitudes. Satellites at the higher (35,786 km) Geosynchronous Earth Orbit (GEO) often use ground-based radar or telescopes to track. Recently, advances have been made in GPS receiver technology that allow tracking at GEO, but these solutions typically require even higher power delivery than their lower-altitude counterparts. These existing solutions usually have intermittent observation of the satellite and thus cannot provide real-time position and velocity data to the satellite.

The General Atomics Inertial Navigation System, or Project GAINS, aims to determine the real-time position and velocity of a CubeSat beyond GEO with relatively low power and size while maintaining accuracy with on-board systems. This will likely require an inertial navigation system (INS) with an accelerometer, gyroscope, and magnetometer, but may also utilize star trackers, radio frequency timing, or other systems for measurement and error correction. The emphasis on accomplishing measurement, calculations, and error correction on-board will avoid the problems associated with systems that only have intermittent contact and high power requirements. The GAINS prototype will allow CubeSats to be deployed at higher orbits and beyond the reach of the GPS constellation for extended periods of time and lower costs than using GPS, all while maintaining an accurate solution.

IV. Previous Work

Inertial Navigation Systems (INS) became a focus of development during the second World War. Initially developed for rockets, Robert Goddard and Wernher von Braun were naturally at the head of the charge. Following the end of the war, the MIT Instrumentation Laboratory (now Draper Laboratory) was selected for development of a self-contained guidance system backup for a new intercontinental ballistic missile [1]. More recently, ballistic missile applications rely on a self-contained system while space applications usually rely on a combination of a self-contained on-board system and a ground-based tracking system [1]. INS is also used in surface level ships as well as submarine vehicles [2]. In all cases, the theory of INS is the same and well developed.

Inertial sensors are either strapped down to the housing directly, or rotated freely on a gimbal system. The gimbal approach yields better accuracy, but is more complex, less reliable, and more costly where strapdown INS's are cheaper and easier to manufacture. Until about the year 2000, gimbal INS's were mainly used. In more recent years, however, the improvements in sensors made strapdown INS's more accurate and therefore more common.

As missions aim to travel further, the use of ground-based tracking systems and GPS become less and less available to augment on-board navigation systems. Therefore, the on-board systems are required to be that much more robust, reliable, and accurate. Missions to the moon will last at least a few months, and with fewer reliable ways to update the state as we travel beyond the reach of GPS and Earth based ground stations, sensor drift rates become all-important.

V. Specific Objectives

At the request of General Atomics, team GAINS will design the Inertial Navigation System (INS) onboard a larger CubeSat. The INS will be designed to be integrated with other navigation methods included in the CubeSat itself such as magnetometers, sun sensors or star trackers. The INS will contain, at minimum, various accelerometers and gyroscopes to sense linear and rotational motion. The GAINS Prototype will be designed and manufactured along with a ground station and compatible software to test system capabilities. The table below, Figure 1, shows Level 1 and 2 requirements for specific project elements. Level 1 requirements represent the minimum for project success while level 2 requirements are extensions of the Level 1 goals the team would like to fulfill, but does not need to for project success. It is worth noting that some values are still being determined with General Atomics, and all "To Be Determined" (TBD) values will be filled in over the coming meetings.

Subsystem	Project Element	Level 1 (Minmum)	Level 2 (Goal)
Electronics	Power consumption	<1W not including downlink capability	<1W including downlink capability
Software	Inertial position accuracy	TBD m to 1σ over 1 month	TBD m to 1σ over 1 month
	Inertial velocity accuracy	TBD m/s to 1σ	
	Downlink capability	Real time understanding of GAINS prototype in User Interface	User interface will present position and velocity in a meaningful manner
Mechanical	Size	< 3 x 10 x 10 cm	
	Weight	< 0.5 kg	
	Lifespan	3 year mission capability	5 year mission capability

Fig. 1 Project GAINS Specific Objectives (Levels 1 and 2)

VI. High Level Functional Requirements

To ensure the best final product possible is delivered to General Atomics, the team will ensure the GAINS prototype adheres to the Functional Requirements (FR) contained below in Table 1, and the Concept of Operations (CONOPS) diagram in Figure 2.

A. Functional Requirements

No.	Functional Requirement	Rationale
FR1	The GAINS team shall operate within the budget and time constraints of the course.	The project must work within set course logistical and financial constraints.
FR2	The GAINS prototype shall withstand testing environments.	All components must be designed to withstand the necessary testing environments.
FR3	The GAINS prototype shall operate within power consumption constraints.	The final deliverable must draw minimal power from the parent CubeSat.
FR4	The GAINS prototype shall fit within a CubeSat.	The final deliverable will be a component for CubeSats.
FR5	The GAINS prototype shall accurately track position and velocity after leaving a known state.	The final deliverable must have a real time estimate of its position and velocity at all times.
FR6	The GAINS prototype shall be able to take measurements that allow for trajectory calculations.	Inertial state computations are to be completed on-board the final deliverable.
FR7	The GAINS prototype shall be capable of two-way communication.	Uplink and downlink capability with the ground station is critical to a meaningful user understanding of data.
FR8	The GAINS system shall present the real time data received from the GAINS prototype in a meaningful way.	The ground station operator must be able to easily view the final deliverable status and state at all times.

Table 1 GAINS Functional Requirements

B. CONOPS

The Concept of Operations (CONOPS) diagram in Figure 2 below details the phases of the GAINS system throughout a sample mission. To begin, the INS is integrated in a larger CubeSat and launched into orbit. Once it has reached the required orbit, the GAINS system will be powered on and begin establishing communication with the Ground Station. The INS system will receive an initial position from a reliable source (namely, GPS) before beginning to sense inertial forces and rotations to determine the position and velocity. This cycle of sensing, computing position and velocity, and storing the last known CubeSat state vector will continue throughout the mission and will be visible to the ground station user. The ground station user will have access to the GAINS user interface (UI) in order to contact the INS system and visually see the state vector data updating. Though more specific iterations of the GAINS project CONOPS are expected, the initial figure below outlines the concept of the mission.

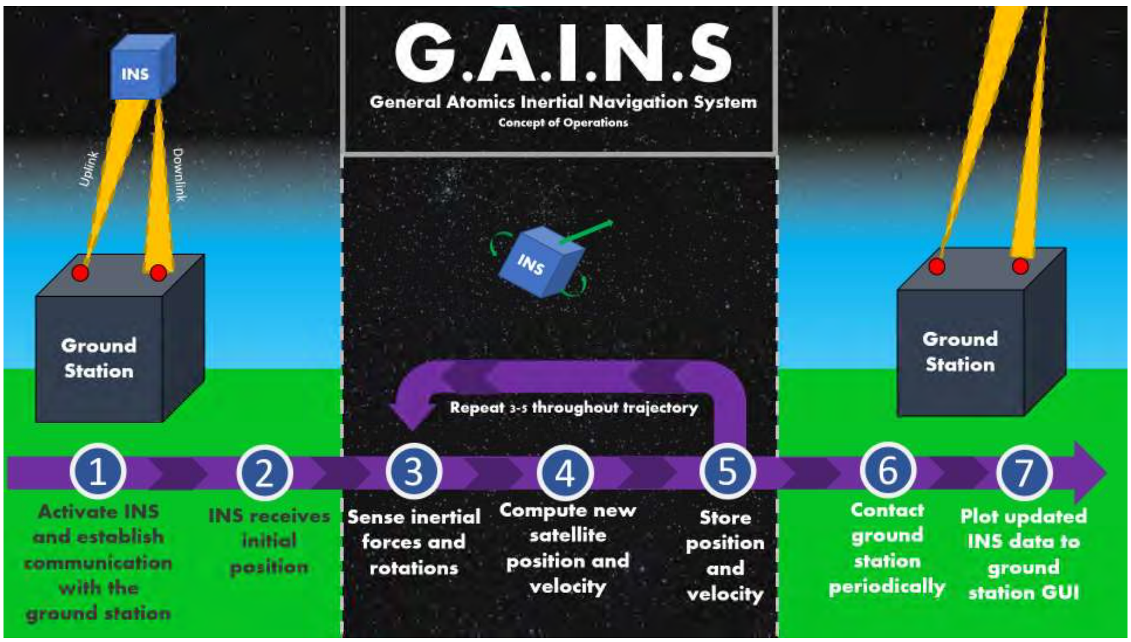

Fig. 2 Project GAINS Concept of Operations Diagram

VII. Critical Project Elements

The GAINS project Critical Project Elements are the essential aspects of the project which must be performed in order to meet project objectives due to technical, logistic, financial, or testing/validation constraints. The elements below will be the guiding light for the team as the GAINS project progresses and develops.

No.	Constraint	Rationale
E1	Sensors (Technical - Essential)	The overarching goal of the project is to determine inertial position and velocity without GPS. This will be done with a sensor or group of sensors. These could be but are not limited to accelerometers, gyroscopes, or sun-senors.
E2	Ground Station (Technical - Essential, Logistical)	The in-orbit hardware must have uplink and downlink capabilities. In order to receive inertial position/velocity and verify these capabilities, a ground station with a User Interface (UI) is needed. This includes antennas and any software needed to package and receive the telemetry.
E3	Accuracy (Technical - Essential, Validation)	The GAINS system should have no more than a TBD meters and a TBD meters/second total error month to month. A peak error of no more than TBD kilometers and TBD meters/second is required. These errors will be crucial for the project success as they are the basis of INS measurements and navigation.
E4	Hardware Testing (Technical - Essential, Financial)	A hardware test setup and procedure must be designed and integrated to test the inertial navigation system and verify requirements. This includes (at minimum) a measurable power source, a mechanical test stand that can withstand movement loads and accelerations, and components to aid with user-interface and data processing.
E5	Functionality (Technical - Logistical, Validation)	The GAINS system should be easy to use. This will include a GUI with a real time status, and power on/off switches.
E6	Position and Velocity Determination (Technical - Essential, Validation)	The GAINS project requires real time position and velocity computation on board the spacecraft. In order to do this, a microprocessor is needed to perform the necessary calculations.
E7	Orbit Simulation Software (Technical - Essential)	A software package will be developed to test sensor accuracy over time. Time permitting, this may also be displayed as simulation.

Table 2 GAINS Critical Project Elements

VIII. Sub-System Breakdown and Interdependencies

A. Sub-System Outline

In order to adequately fulfill the Functional and Specific requirements laid out in Table 1 and Figure 1, the GAINS project will be comprised of a number of interdependent sub-systems, detailed in the following list.

- **Central Processing Unit (CPU)**:
  The CPU will be the brain of the GAINS prototype. It will include the following subsystems to fulfill its required functionality:

- **Command and Data Handling (C&DH)**:
  The command and Data Handling system will be the central hub for data exchange. This includes receiving measurements from the sensor suite and relaying it to the software for further use, as well as relaying the software output to the CubeSat bus for transmission to the ground station and eventual display on the GUI. The C&DH system will furthermore receive any commands sent from the ground segment that pertain to the INS.

- **Software**:
  The Software will perform on-orbit, real-time calculations with the data provided by the C&DH to meet the objective of velocity and position determination. It will also be responsible for parsing the resulting data sets and outputting them back to the C&DH system.

- **Power Distribution**:
  Since the GAINS prototype does not have its own power source, the system will draw power from the CubeSat it is integrated in. This limits the scope of the GAINS Power subsystem to a role of power distribution to the individual components that require it, namely the CPU and the sensor suite.

- **Ground segment**:
  The ground segment will be separate from the GAINS prototype and visualize the downlinked data and on-orbit calculations to the ground segment operator in a meaningful way, such as a graphical user interface (GUI). It will also give some control over the INS such as, but not limited to, an on/off switch.

- **Sensor Suite**:
  The sensor suite will contain all necessary instrumentation to accurately determine the attitude, position, and velocity over time in order to allow the CPU to perform necessary calculations. This will include an at this time undetermined number of accelerometers, gyroscopes and possibly other kind of sensors, which will feed their measurements to the C&DH system in the CPU for further processing.

- **Structural Elements**:
  This will be the physical structure enclosing the GAINS prototype, providing structural rigidity and allowing for the integration of its individual subsystem components in the greater CubeSat.

B. Functional Block Diagram
The following preliminary FBD visualizes the aforementioned sub-system interactions and inter-dependencies of the GAINS project.

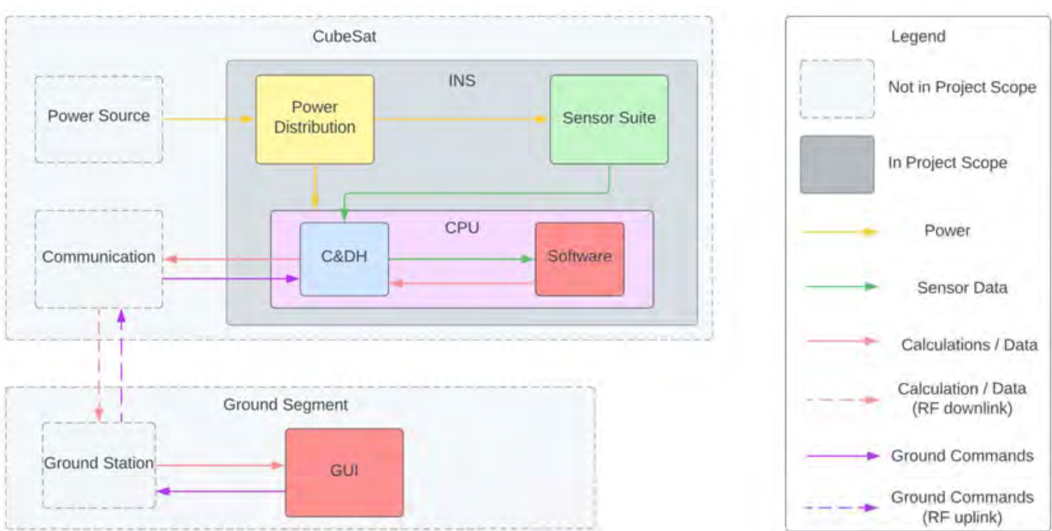

Fig. 3 Project GAINS Subsystem Overview FBD

IX. Team Skills and Interests

Critical Project Elements	Team member(s) and associated skills/interests
Sensors	Alex Pichler (Hardware Acquisition and Integration) Jason Popich (Hardware Acquisition and Integration) Addison Woodard (Integration and Verification)
Ground Station	Derek Popich (Ground Segment Hardware)
Accuracy	Tucker Peyok (Computation, Verfication) Ross White (Cost Analysis) Addison Woodard (Error Flow Down/Computation Verification)
Hardware Testing	Bennett Grow (Manufacturing and Test Verification) Ben McHugh (Manufacture and Assembly) Tucker Peyok (Testing and Machining) Alex Pichler (Manufacture and Assembly) Alfredo Restrepo (Test Planning and Verification) Kaylie Rick (Test Planning, Testing, and Machining) Brian Trybus (Machining) Ross White (Manufacturing and Machining)
Functionality	Cannon Palmer (GUI Creation) Ben McHugh (GUI Creation) Alex Pichler (C&DH) Derek Popich (GUI Creation) Kaylie Rick (GUI Creation)
Position and Velocity Determination	Bennett Grow (Low-Level Programming, Computation) Ben McHugh (Attitude Computation) Cannon Palmer (Low-Level Programming) Tucker Peyok (Low-Level Programming) Alex Pichler (C&DH, Data Parsing) Jason Popich (Low-Level Programming, Computation) Alfredo Restrepo (Low-Level Programming, Computation) Kaylie Rick (Computation) Brian Trybus (Low-Level Programming) Ross White (Low-Level Programming) Addison Woodard (Attitude Computation)
Orbit Simulation Software	Bennett Grow (Simulation Software) Ben McHugh (Simulation Software) Cannon Palmer (Simulation Software) Tucker Peyok (Simulation Software) Derek Popich (Simulation Verification and Test) Alfredo Restrepo (Simulation Software) Kaylie Rick (Simulation Software and Test) Brian Trybus (Simulation Software) Ross White (Simulation Software) Addison Woodard (Simulation Verification)

X. Resources

Critical Project Elements	**Resource/Source**
Sensors	SMEAD Electronics Lab
Ground Station Display Software	CU Boulder Software Library / SMEAD Electronics Lab
Accuracy	Professor Dale Lawrence
Hardware Testing	TBD
Functionality	TBD
Position and Velocity Determination	Professor Dale Lawrence
Orbital Simulation Software	CU Boulder Software Library

XI. References

[1] Wikimedia Foundation. (2022, July 31). Inertial Navigation System. Wikipedia. Retrieved September 8, 2022, from https://en.wikipedia.org/wiki/InertialnavigationsystemHistory

[2] WRIGLEY, W. (1977). History of inertial navigation. Navigation, 24(1), 1–6. https://doi.org/10.1002/j.2161-4296.1977.tb01262.x