COSMIC Capstone Challenge - Track 3

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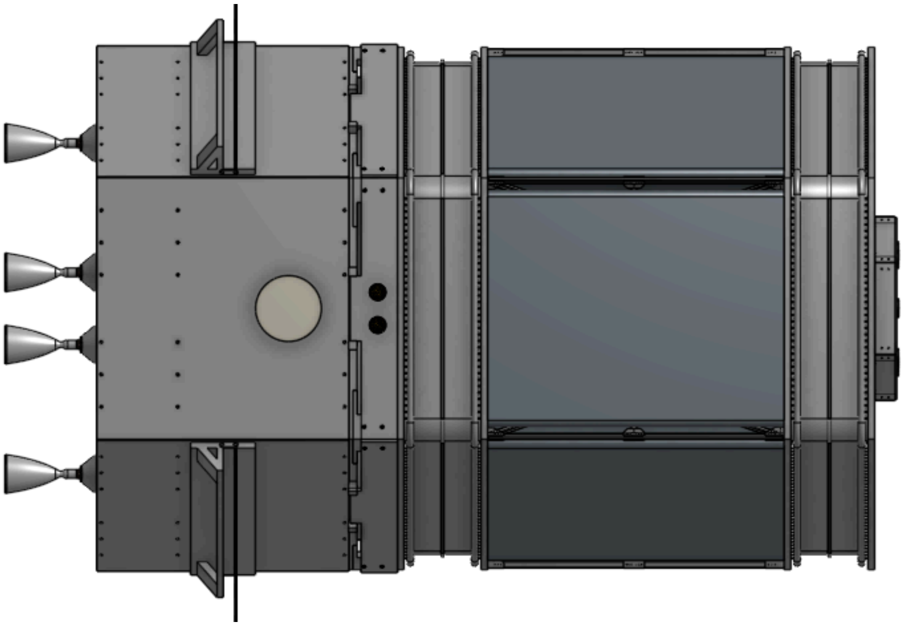


1. Executive Summary

The Spacecraft Platform for Autonomous Repair, Refuel, and Orbital Work, or SPARROW, is a modular, fully autonomous spacecraft designed to be a servicing satellite in Low Earth Orbit (LEO). The goal of SPARROW is to address the rapid growth of satellites in LEO by extending lifetimes and upgrading existing satellites like Starlink and Kuiper. As the number of satellites increases, it becomes increasingly difficult and inefficient to repair depleted satellites, providing SPARROW with a pathway to be a solution for on-orbit servicing.

SPARROW will operate from a dedicated orbital range of 500 - 650 km in altitude with an inclination range of 50° - 71.6°, with a parking orbit of 800 km altitude and 61.1° inclination. The spacecraft will perform all servicing functions, including diagnostics, communications, repairs, refueling, etc., in this regime. These capabilities are made possible through the modular architecture of the spacecraft, as well as the use of two robotic arms that can autonomously perform the functions required by the client.

The system as a whole places a heavy emphasis on autonomy and eliminating any human-in-the-loop interventions. This enables rapid response to client needs and any anomalies encountered along the mission. SPARROW's propulsion system provides 4000 m/s of delta-V, allowing for multiple clients to be serviced in one mission. The power subsystem will be able to provide 7 kW of continuous power, aiding in the autonomous capabilities and servicing functions of the spacecraft. The thermal and structural subsystems are then engineered to ensure modularity and nominal system operations from launch to end-of-life procedures.

SPARROW represents an innovative advancement towards the solution of an overcrowded LEO regime. The goals of the spacecraft align with national and commercial efforts to preserve Earth's orbit for future space operations. SPARROW provides the ability to reduce reliance on replacement launches, lower operating costs, and mitigate the risk of increasing orbital debris. Ultimately, this spacecraft is a critical step towards a fully functional, on-orbit servicing architecture.

2. Introduction and Motivation

2.1. Background

The Space Pirates satellite, SPARROW, is designed to fulfill part of the In-Space Servicing, Assembly, and Manufacturing (ISAM) needs of the United States. The White House released a national strategy for the United States to stimulate national ISAM capabilities in April 2022 [25]. In December of the same year, the U.S. government released the National ISAM Implementation Plan, providing an interagency plan to guide the government activities to fulfill the United States' ISAM needs [26]. These initiatives underline the importance of developing sustainable space infrastructure via the ability to repair, refuel, and upgrade satellites in orbit [27].

2.2. Mission Motivation

Modern society is becoming highly dependent on satellites for basic services. Satellites operated by various entities provide internet, weather data, navigation, defense, communications, and Earth observation that keep society connected, safe, and ever progressing. As the reliance on satellites increases, so does the necessity for more satellites to be launched either to replace broken ones, or to increase the coverage of a satellite constellation, or for many other reasons. This increase in launches is causing space to become more and more crowded as time goes on, with satellites as well as space debris, specifically in low Earth orbit (LEO)

Despite the general advancement of the aerospace industry and space travel, nearly all current orbital satellites lack the means to be serviced, refueled, repositioned, repaired, or disposed of at the end of their lifecycles. This, coupled with the rising launch rates, will lead to a growing population of objects in space as well as debris. Eventually, this could become such a big problem that it would be impossible to launch anything to space and impossible to clean up everything in orbit. In order to combat this, SPARROW was developed.SPARROW is a fully autonomous, modular spacecraft capable of servicing client satellites while in orbit. By having a satellite in orbit capable of servicing other satellites, this can help address the problem of growing space objects by allowing satellites to last longer.

2.3. Mission Objectives

The mission objectives can be categorized into two distinct categories: autonomy and critical servicing functions (CSFs). The most important mission objective is the performance of CSFs, without which SPARROW would serve little purpose other than taking up space. The spacecraft must also be fully autonomous with zero human-in-the-loop interactions, so autonomy is the second most important objective. Within the category of autonomy, there are two targets that, if reached, will ensure that the autonomy objective is satisfied. The spacecraft should autonomously resolve anomalies during servicing operations with a success rate of at least 90%. In this context, anomalies are any off-nominal conditions, such as space debris, eclipses, client satellite issues, etc. The spacecraft might also autonomously coordinate the servicing of multiple satellites in a single mission, where servicing at least two satellites is considered a success. In order for the CSF objective to be satisfied, more conditions must be met. The spacecraft must be able to perform at least two of the four CSFs outlined in this report. The spacecraft should also be capable of injecting client satellites into desired orbits by providing at least 200 m/s of ΔV, and should have a 90% success rate of removing damaged components and space debris from and around client satellites. The spacecraft should also be capable of storing at least 200 Liters of volume worth of replacement parts for client satellites and should be able to perform maintenance using those parts to replace damaged components and upgrade client satellites. Once all of these conditions are met for the CSFs and the autonomy, SPARROW shall be able to perform successful missions.

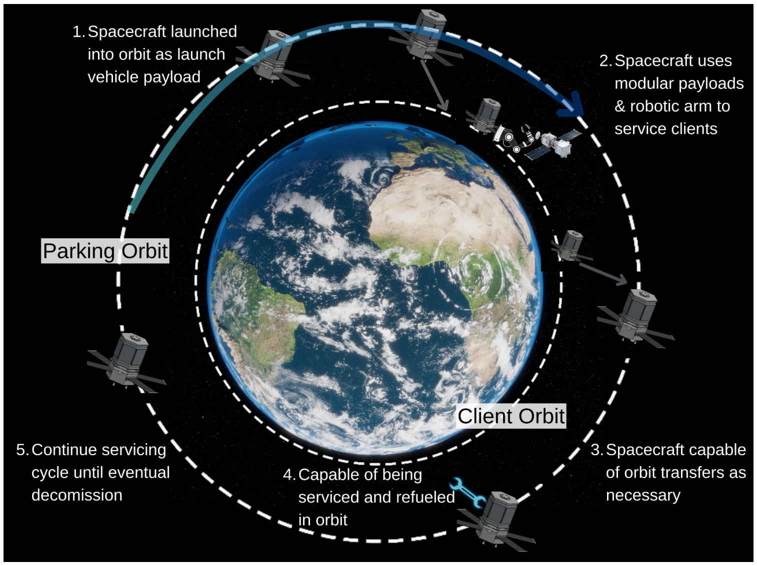


Figure 1: *ConOps*

3. Concept of Operations

3.1. Mission Lifecycle

This graphic depicts the mission lifecycle for SPARROW, or ConOps. There are five main capabilities of SPARROW, which are highlighted in the graphic and are explained as follows: The first capability of the spacecraft is its ability to fit within the launch vehicle and withstand the loads experienced from the launch, as well as being placed into orbit. The second capability highlights the modularity of the spacecraft and its use of modular payloads and the robotic arms to service the client satellites. In order to do this, the third capability must be shown as well; the spacecraft must be capable of orbit transfers to rendezvous with the client satellite. The fourth capability of SPARROW is the ability to be serviced and refueled while in orbit, either servicing itself, or receiving the services of another SPARROW, or other satellite. The fifth and final capability is the continuation of the mission lifecycle. SPARROW must be capable of completing more than one servicing mission to validate the need for an on-orbit servicing spacecraft.

3.2. Functional Flow

The graphic below depicts the functional flow of SPARROW as it completes a mission. This is the base structure for how the spacecraft will complete any mission, taking into account having multiple clients in the same mission, and avoiding space debris. Below is the physical flow diagram, which outlines the subsystem interactions previously mentioned that must take place during a mission. This shows how the average mission should play out from the point of view of SPARROW, and which subsystems will be used to perform the mission. Of note in this diagram is the mention of AI, which is responsible for the autonomy of the spacecraft and is a part of the CDH subsystem. The power and thermal subsystems are also not mentioned in the diagram, but can be assumed to be providing the proper power and temperature control throughout not only the entire mission, but the entire lifespan of the spacecraft as well.

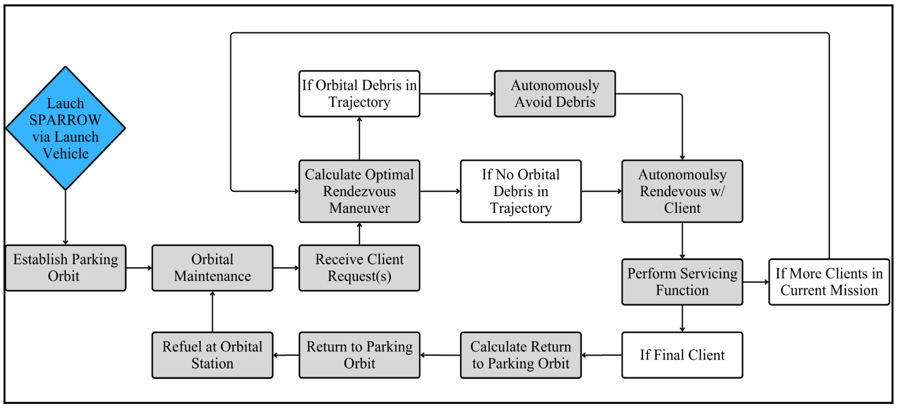


Figure 2: *Functional Flow Diagram*

3.3. Client Servicing

The main payload responsible for client servicing is the UR8-long robotic arm, UR8-L. The UR8-L has a modular end effector, as well as ten degrees of freedom. This, along with the modular payloads carried by SPARROW, as well as the arm track along the spacecraft allow the servicing functions of the robotic arm to be nearly limitless. The main servicing functions that were focused on are as follows: Diagnosis and repair, client refueling, client maneuvering, and data transfer. The diagnosis and repair are done using the different cameras on the outside of the spacecraft, which feed into the onboard computer. From there, the AI can diagnose what is wrong with the satellite, determine the best course of action to service the client, and conduct the appropriate servicing function[s]. Client refueling and client maneuvering are done mainly with the robotic arm. With the UR8-L, client fuel tanks can be refilled or replaced, and by docking with the client using the UR8-L, enough ΔV can be supplied to the client satellite to maneuver into the desired orbit. SPARROW will be designed to act as a data relay or transfer medium for client satellites. If a client satellite's communications system fails, SPARROW will be able to rendezvous with that satellite and transmit data to the desired ground station.

3.4. Autonomy

The SPARROW platform operates without human-in-the-loop intervention, even when scaled up to a constellation of servicing satellites. To adhere to the SPARROW timeline, the platform will employ several specialized AI agents that perform specific tasks, called upon by an AI agent, rather than a general AI. Models can be updated or added via uplink periods as needed after initial SPARROW deployment. The primary "Perception Agent" manages computer vision for rendezvous and defect detection, as illustrated in the workflow below.

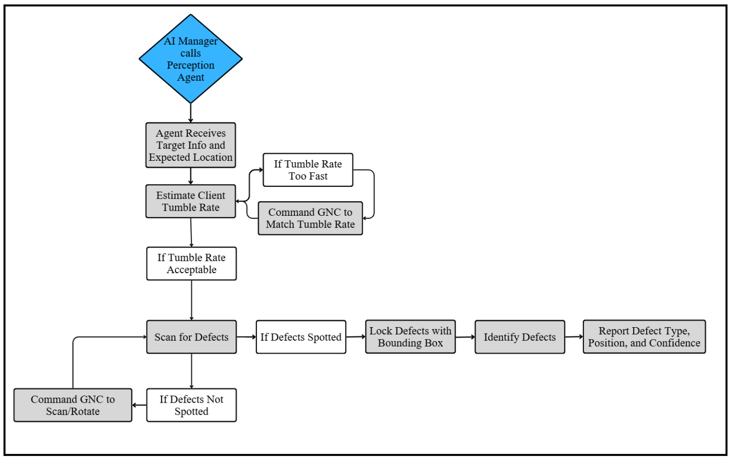


Figure 3: *AI Perception Agent Operation Example Flow Chart.*

4. System Architecture

4.1. System Breakdown

The greater system of this project is defined as the 'Spacecraft Management System', which consists of the launch vehicle, the spacecraft itself, and the ground team. The launch vehicle will be the SpaceX Starship, and the ground team will be based client to client, as well as some in-house operations. The spacecraft itself is the primary focus and can be further divided into 5 distinct subsystems: Servicing/Payloads, ADCS/GNC, Spacecraft Life Systems (Propulsion, Power, and Thermal), Structures, and Communications/CDH. Each subsystem will be further broken down in the following subsections.

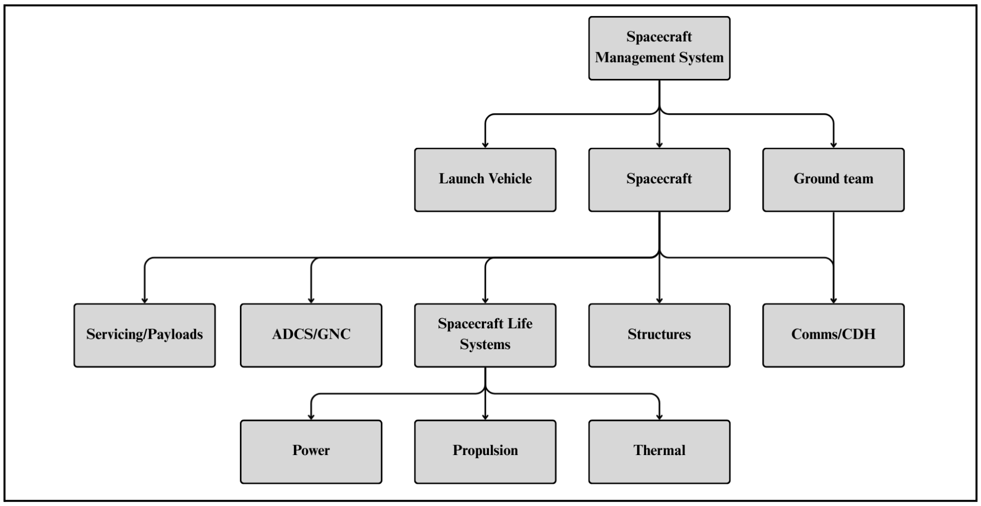


Figure 4: *System Architecture Breakdown*

4.2. Subsystem Breakdown

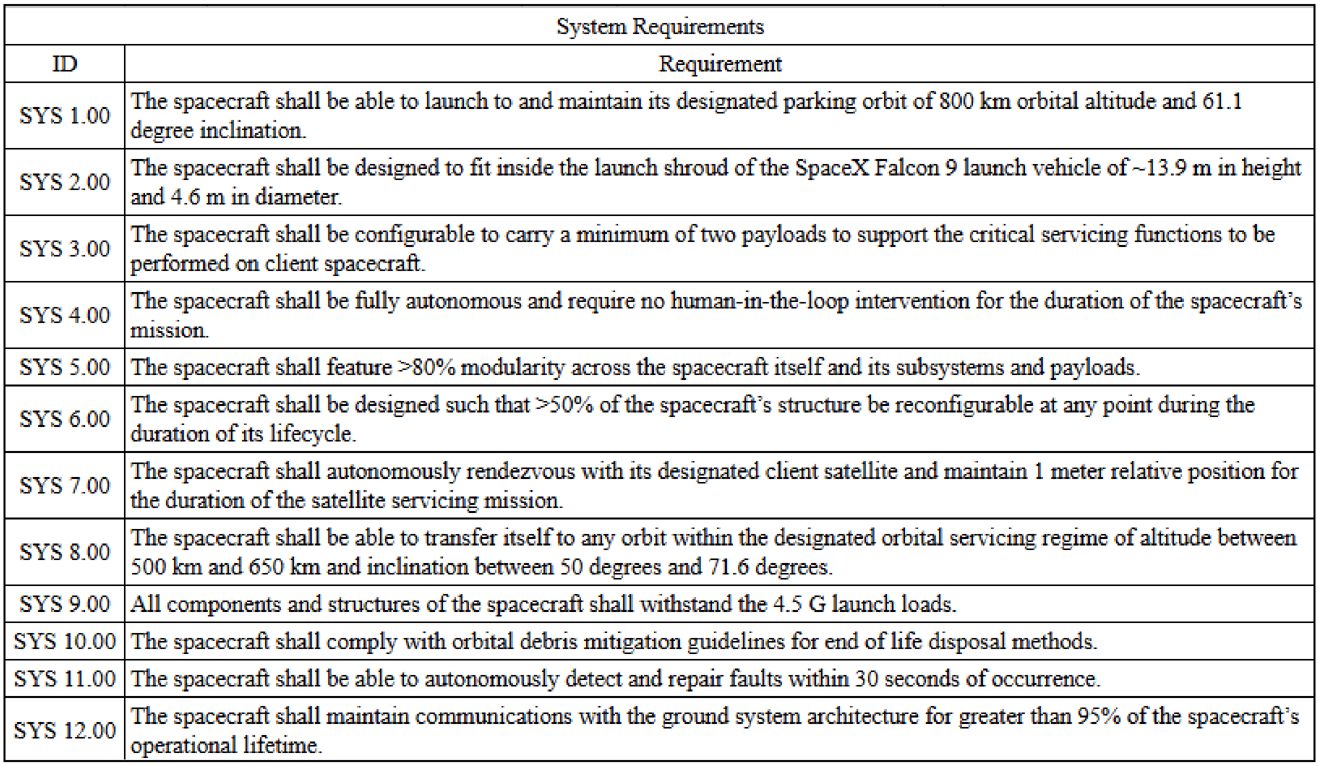
The spacecraft consists of multiple subsystems that work together to accomplish mission objectives. The servicing/payloads subsystem is responsible for client satellite servicing using modular payloads and specifically a robotic arm. The ADCS/GNC subsystem determines positioning and controls navigation by sending commands to the propulsion subsystem, which is used for maneuvering and docking. The power and thermal subsystems are crucial to the success of the overall system. The power subsystem stores and provides energy, which is distributed throughout SPARROW, and the thermal subsystem protects from extreme temperatures while maintaining proper operating temperatures. The structure's subsystem is responsible for integrating all components while also supporting modularity, durability, and manufacturability. The Comms/CDH subsystem distributes commands throughout the spacecraft, coordinates communication, and links all subsystems with the ground team. This allows the spacecraft to operate as one unified system.

4.3. Interfaces

The Comms/CDH subsystem serves as the central interface between all subsystems, linking the spacecraft to the ground team and coordinating data exchange internally and for clients. It handles commands between all subsystems and collects system data, which allows for closed-loop control and overall system integration. The ADCS/GNC subsystem interfaces with both the Comms/CDH for command input and state feedback, and the propulsion subsystem to execute docking maneuvers and trajectory/attitude adjustments. The propulsion subsystem interfaces with the ADCS/GNC subsystem as just stated, and the Comms/CDH subsystem to provide a physical interface for orbital maneuvering and rendezvous operations. The servicing/payload subsystem interfaces with the Comms/CDH subsystem for the execution of CSFs, and relies on the structure's subsystem to provide modularity and storage. The power, thermal, and structures subsystems all interface with each other as well as all other subsystems. The power subsystem stores and provides the energy needed for every other subsystem. The thermal subsystem interfaces with all other subsystems by providing thermal protection from the freezing vacuum of space and by radiating heat out of the spacecraft when necessary. The structures subsystem provides the housing for all other subsystems and is responsible for ensuring modularity and the integration of all subsystem components into the spacecraft. All together, these subsystems make up the overall unified spacecraft system where Comms/CDH handles coordination, ADCS/GNC and propulsion handle control and actuation, servicing/payloads execute CSFs, life systems (power & thermal) support operations, and structures physically integrate the entire system

5. Requirements

Table 1: *Requirements Table*



System Requirements	
ID	Requirement
SYS 1.00	The spacecraft shall be able to launch to and maintain its designated parking orbit of 800 km orbital altitude and 61.1 degree inclination.
SYS 2.00	The spacecraft shall be designed to fit inside the launch shroud of the SpaceX Falcon 9 launch vehicle of ~13.9 m in height and 4.6 m in diameter.
SYS 3.00	The spacecraft shall be configurable to carry a minimum of two payloads to support the critical servicing functions to be performed on client spacecraft.
SYS 4.00	The spacecraft shall be fully autonomous and require no human-in-the-loop intervention for the duration of the spacecraft's mission.
SYS 5.00	The spacecraft shall feature >80% modularity across the spacecraft itself and its subsystems and payloads.
SYS 6.00	The spacecraft shall be designed such that >50% of the spacecraft's structure be reconfigurable at any point during the duration of its lifecycle.
SYS 7.00	The spacecraft shall autonomously rendezvous with its designated client satellite and maintain 1 meter relative position for the duration of the satellite servicing mission.
SYS 8.00	The spacecraft shall be able to transfer itself to any orbit within the designated orbital servicing regime of altitude between 500 km and 650 km and inclination between 50 degrees and 71.6 degrees.
SYS 9.00	All components and structures of the spacecraft shall withstand the 4.5 G launch loads.
SYS 10.00	The spacecraft shall comply with orbital debris mitigation guidelines for end of life disposal methods.
SYS 11.00	The spacecraft shall be able to autonomously detect and repair faults within 30 seconds of occurrence.
SYS 12.00	The spacecraft shall maintain communications with the ground system architecture for greater than 95% of the spacecraft's operational lifetime.

Table 1 outlines the system requirements that were used to design SPARROW. From these system requirements, subsystem requirements were derived, which allowed each subteam to design its systems and structures. Subsystem requirements were created for Structures, Power, Propulsion, and Thermal (PPT), Guidance, Navigation and Control (GNC), and Command and Data Handling and Communications (CDHC). These subsystem requirements can be found in the Appendix.

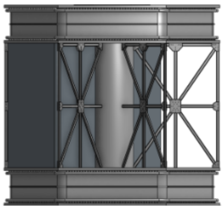
6. System Design

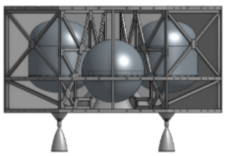
6.1. Structures

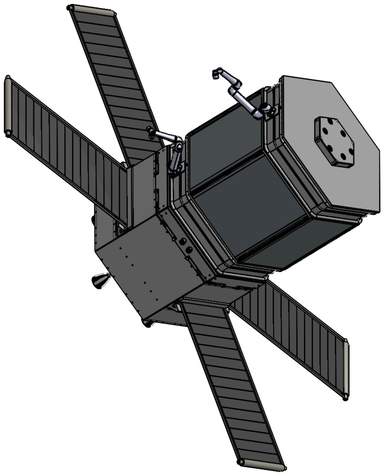
The structure subsystem defines the physical architecture of the SPARROW spacecraft and provides the mechanical backbone by which the spacecraft's subsystems are successfully integrated. As such, the structure must satisfy launch constraints, structural integrity requirements, and the system's core design philosophy centered on modularity.

SPARROW is built around a modular hexagonal chassis, which allows for clear segmentation of major subsystems, including propulsion and power, avionics and electronics, and servicing payloads. This geometry was selected to maximize the volumetric efficiency of the spacecraft within the specified launch fairing while providing several flat surfaces for mounting and integration. The hexagonal layout further emphasizes reconfigurability, enabling rapid replacements, upgrades, and the ability to service a variety of mission objectives. The primary structural materials used are aluminum alloys and steel, selected for their balance of strength, manufacturability, and mass efficiency. Separating each segment of SPARROW are dual-sided CNC-machined base plates, which provide rigid interfaces and precise alignment between all modules and segments. The internal truss structures reinforce the chassis, distributing loads experienced during launch conditions, up to 4.5 g, and further ensuring that natural frequency requirements are met to avoid failure and coupling. The propulsion segment of the system is structurally supported by a vast truss network that firmly secures four propellant tanks mounted near the base of the spacecraft. This configuration ensures optimal load paths and efficient load transfer throughout the structure during high thrust conditions (launch). It is in this segment that the solar arrays are also mounted at the mid-plane, distributing loads symmetrically and minimizing the bending moments. The central segment houses the avionics and computing hardware within a modular enclosure. Each face of this segment is designed to be removable, allowing for easy access, maintenance, replacement, and upgrades. This design directly supports the system-level requirement of greater than 50% structural reconfigurability over the spacecraft lifecycle.

The servicing segment contains the modular payload bays as well as two separate robotic arm track systems. These tracks enable the robotic arms to traverse the entirety of the spacecraft's external perimeter, providing full access to client satellites during servicing operations. One of the two arms is tasked with stabilizing and capturing client satellites, while the other performs the necessary repairs, refueling, or manipulation. The structural design of the robotic arm tracks ensures a smooth motion while maintaining stiffness and alignment. Additionally, the top face of this segment houses all optical systems in a similar reconfigurable segment, such as the central segment. Overall, SPARROW’s structural system enables a highly modular, serviceable, and robust spacecraft architecture that is capable of withstanding launch conditions and further supporting complex in-orbit operations.







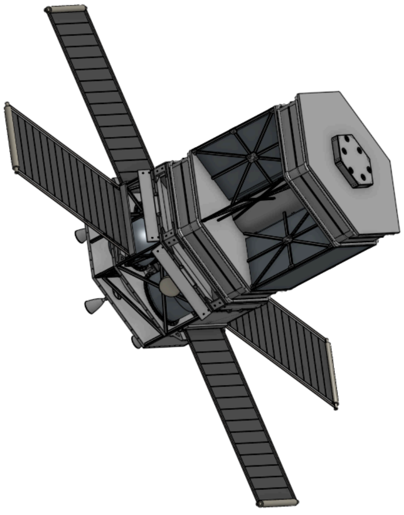


Figure 5: *SPARROW Structure Overview*

6.2. Propulsion, Power, Thermal

6.2.1. Propulsion

The propulsion subsystem is responsible for all major burns during the mission, including raising and lowering orbital altitude, phase changes, and plane changes. The success criteria, system-level requirements, and subsystem requirements directly drive it. The propulsion system is designed to provide 4000 m/s of delta-V, allowing for the spacecraft to reach multiple clients in one sortie. The system features four chemical, bipropellant thrusters with modular fuel tank architecture arranged symmetrically at the base of the spacecraft. The system is capable of multiple restarts and provides significant thrust for the spacecraft's requirements. Overall, the propulsion system provides a balance of weight, efficiency, and thrust to facilitate the autonomous serving missions.

6.2.2. Power

The power subsystem is responsible for generating and distributing the power needed to maintain SPARROW at nominal operations. This includes utilizing a solar array architecture to extend and retract solar arrays, solar panels to generate power, and a modular electrical power system (EPS) that stores and distributes the power to all components. The chosen solar array architecture, which is the roll-out-solar-array (iROSA), was chosen for its long-mission reliability, flight heritage, low stowed power density, voltage range, specific power, and high modularity. The power system is able to generate the required power, 1.1kW, with the XTJ Prime solar panels that are integrated into the iROSA. The End of Life (EOL) area needed to generate the required power with these solar panels is 28.7 m^2 and allows us to place 4 rectangular solar arrays on SPARROW. We can operate at nominal conditions for beginning-of-life (BOL) and end-of-life (EOL) between 0 and ~84 degrees from the sun. In addition, for sun angles <81 degrees, we can gain 120% of the power needed.

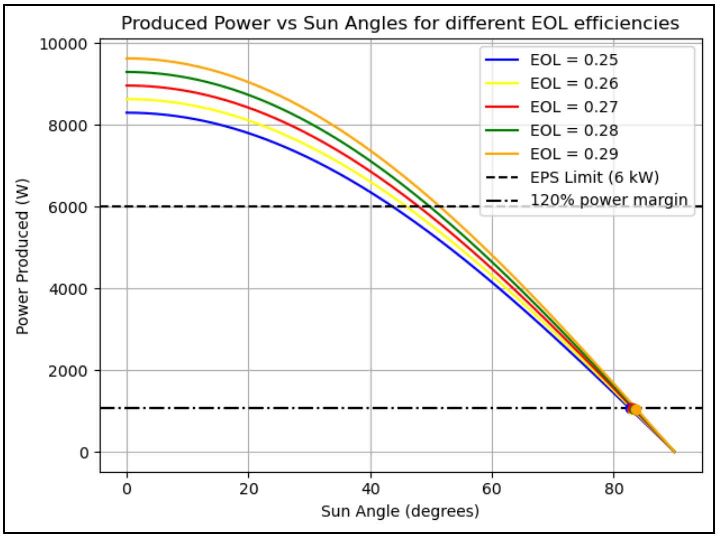


Figure 6: *Produced Power at different sun angles with varying EOL efficiencies*

To store this power and survive eclipses, 3 highly modular EnduroSat EPS modules are used. Two advanced EnduroSat EPS modules (2 battery packs) and one regular EnduroSat EPS module (1 battery pack) are used to provide a maximum power output of 6kW. With the chosen EPS, our state-of-charge (SoC) for both BOL and EOL can survive a 40 min eclipse and provide ~4000 Wh for a 3-hour outage.

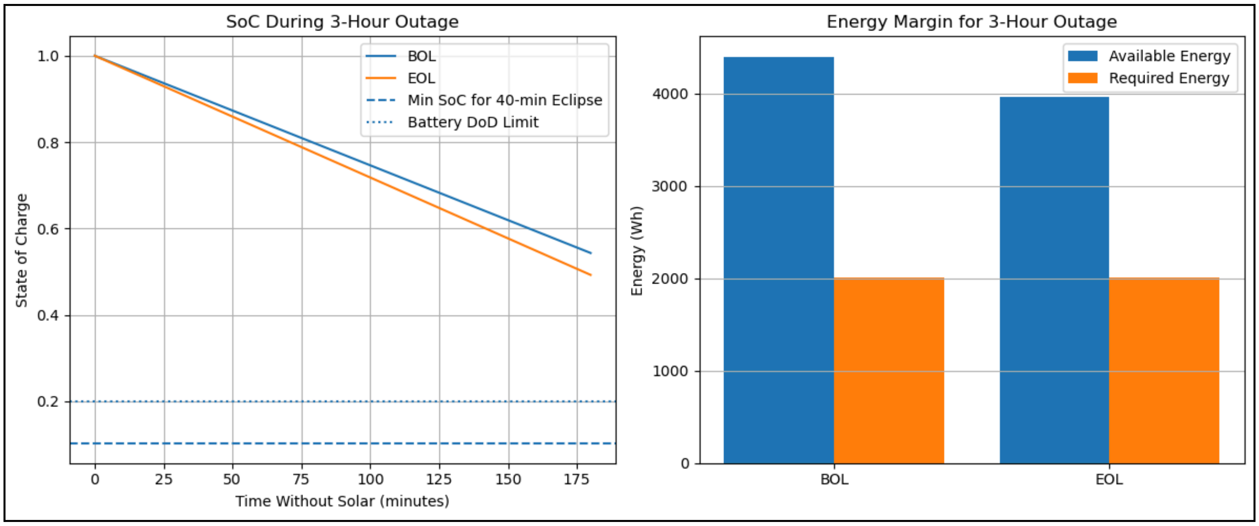


Figure 7: *State of Charge degradation and Energy Margin for BOL & EOL over a 3-hour outage.*

The EnduroSat EPS has a built-in battery management system (BMS), which will be in charge of distributing and regulating the power throughout the bus. A safe mode is implemented for worst-case scenarios. The power required to run the bus for key operations is 670V, and the power required for the bus to survive is 450V. The safe mode will be activated by our AI computer when it detects SPARROW's power to be <450V and begins to turn off non-essential components. SPARROW can survive roughly 300 minutes (5 hours) through worst-case scenarios when our safe mode is activated. During safe mode, the AI computer will self-diagnose and begin repairing itself until power is restored for key operations, safe mode will be deactivated, and all components will be turned on.

6.2.3. Thermal

The Thermal subsystem is in charge of maintaining internal temperature and keeping components in a safe thermal range. The goal is to keep the temperature between 0-20 degrees Celsius as this is comfortably in the operational temperature range of the majority of our systems. The one exception to this is the hydrazine tanks, which have a higher operational temperature and have their own dedicated heating. The thermal control consists of a combination of passive and active thermal control systems. It uses 20 layer MLI, a 6 m^2 radiator, Kapton Polyimide heaters, and heat pipes for thermal control. The internal thermals are managed using a proportional controller to manage the heater output with the goal of keeping the temperature close to 10℃.

The following graphs show the thermal conditions during a sample servicing mission. During the 150-minute mission, SPARROW reaches an average internal temperature of just over 15℃, which is well within the viable temperature range of SPARROW.

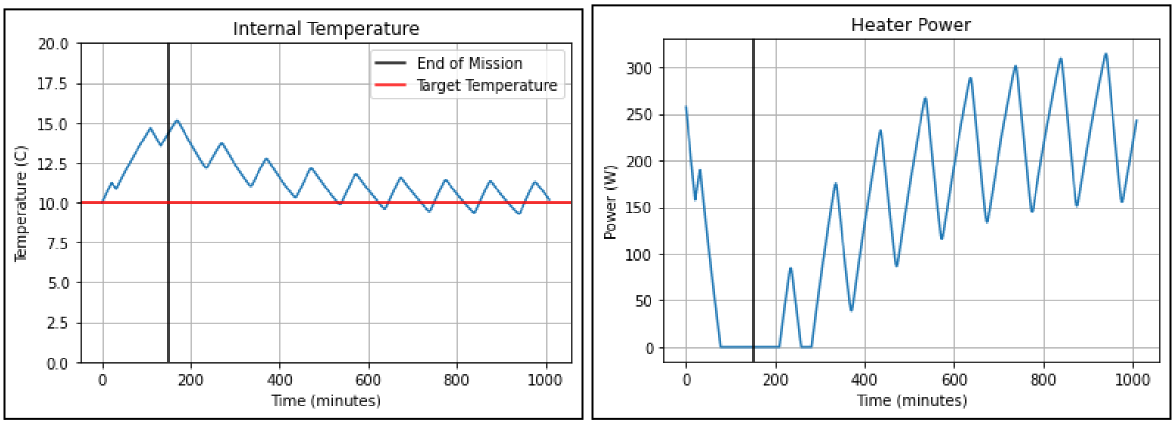


***Figure 8:** Temperature and Heater Power during and Following Servicing Mission*

The ANSYS simulation uses a simplified SPARROW model using an internal hotbox representing the total thermal output of the components and heaters. It also models the MLI, heat pipes, and Radiator.

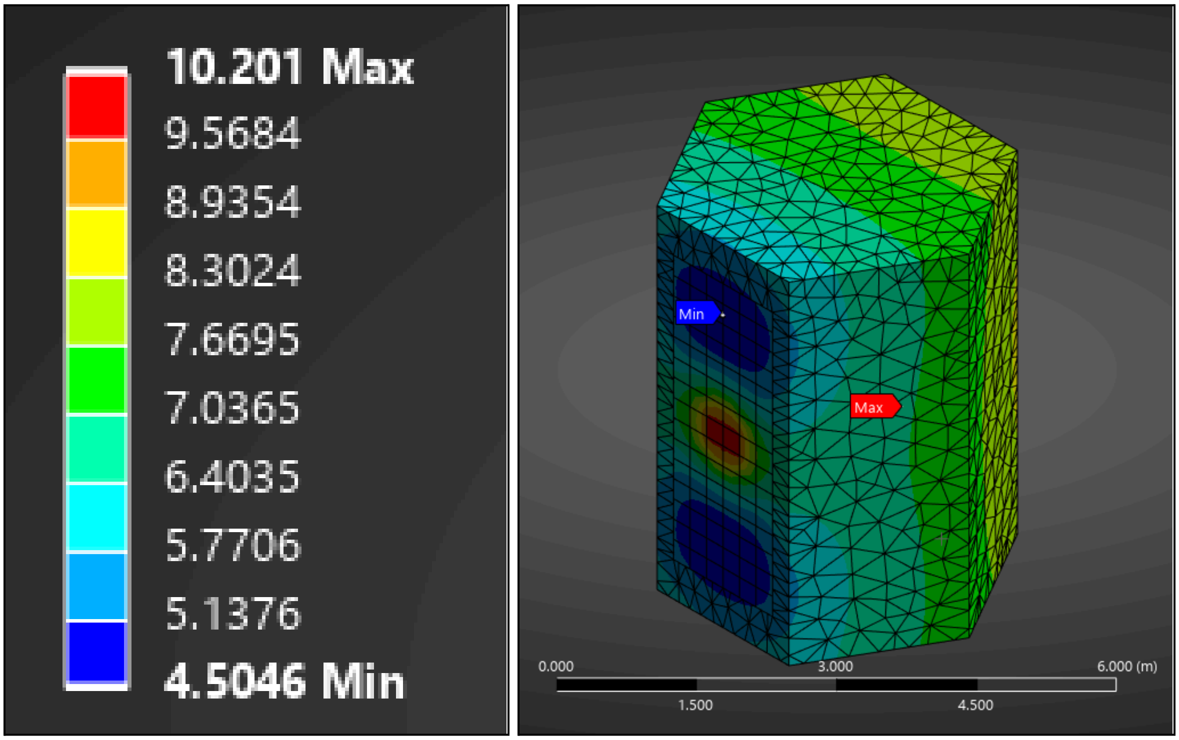


***Figure 9:** Internal Temperature During Eclipse*

The above picture showcases the thermal load after a 180 minute eclipse on the simplified model of SPARROW. As can be seen the spacecraft stays well within the target thermal conditions. The biggest thermal variance happens on the radiator with the heatpipe connection being much hotter than the other parts of the radiator. However the overall variance is low showing a good distribution of thermal energy.

6.3. Guidance, Navigation, & Control

6.3.1. ADCS Architecture

Figure 10 shows the ADCS functional block diagram. This architecture is shared across all mission phases, with only the guidance reference changing between modes.

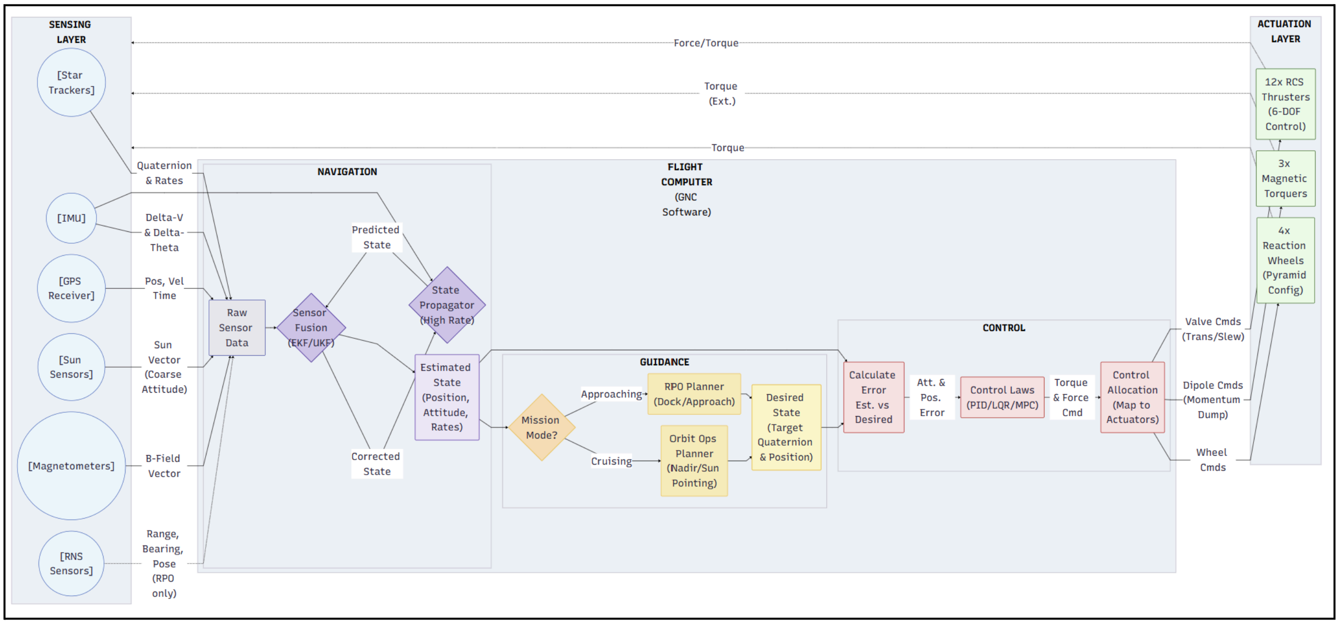


Figure 10: *ADCS Functional Block Diagram*

6.3.2 Control Law

A single MRP proportional-derivative controller is used in all phases of the mission:

$$L_{cmd} = -K\boldsymbol{\sigma}_{B/R} - P(\boldsymbol{\omega}_{B/N} - [B^{N}]\boldsymbol{\omega}_{R/N})$$

Commanded torque is mapped to the four wheels via a reaction wheel pyramid configuration. When reaction wheels become saturated, the magnetic torquers will help desaturate the wheels.

6.3.3 Guidance Modes

Five guidance modes are sequenced by the flight software event system (***Table 2***).

Table 2: *Guidance Modes*

Mode	**Reference**
Sunpointing	Body +Z □ Sun
Ground Pointing	Body +Z □ Specified Ground Location
Velocity pointing	Body axis □ V-bar

Hill pointing	Body □ LVLH frame
Target pointing	Body +x □ Target satellite

6.3.4 Navigation

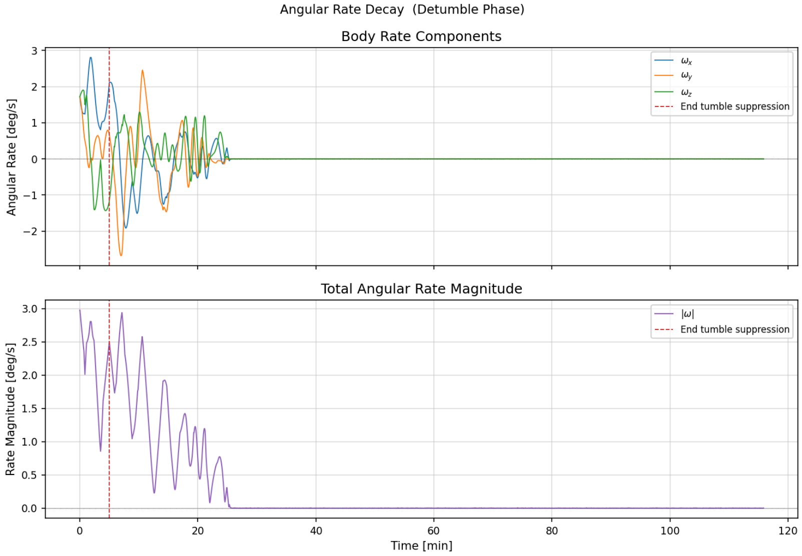
The navigation system uses a hybrid estimation strategy. An inertial Unscented Kalman Filter fuses star tracker and gyro measurements to produce accurate attitude estimates. A custom HybridNav module pairs the UKF's attitude output with the IMU's direct angular-rate measurement, giving the controller both high-accuracy pointing knowledge and high-rate feedback. A secondary sunline square-root UKF estimates the sun direction from eight coarse sun sensors for eclipse detection.

To determine the optimal transfer maneuvers, the analysis propagates each spacecraft's state using the universal-variable form of Kepler's equation, which employs Stumpff functions to compute the future positions and velocities for any conic orbit. For each candidate departure time and flight time, Lambert's problem is solved to obtain the transfer-orbit velocity vectors that connect the propagated position of the chaser to the future position of the target. The required impulse magnitudes follow from the difference between these Lambert velocities and the spacecraft velocities at the burn times, and the burn directions are given directly by those vector differences. Scanning across the time grid identifies the combination that minimizes total delta V and defines the timing, direction, and magnitude of the necessary maneuvers.

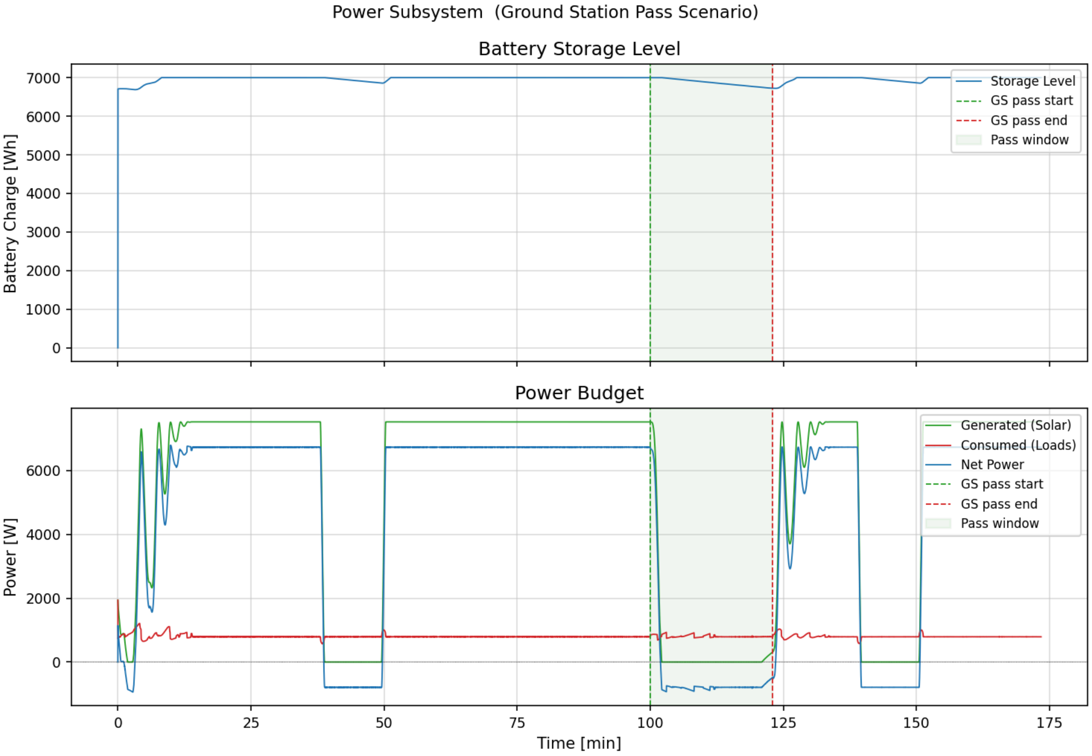
6.3.5 Simulation Validation

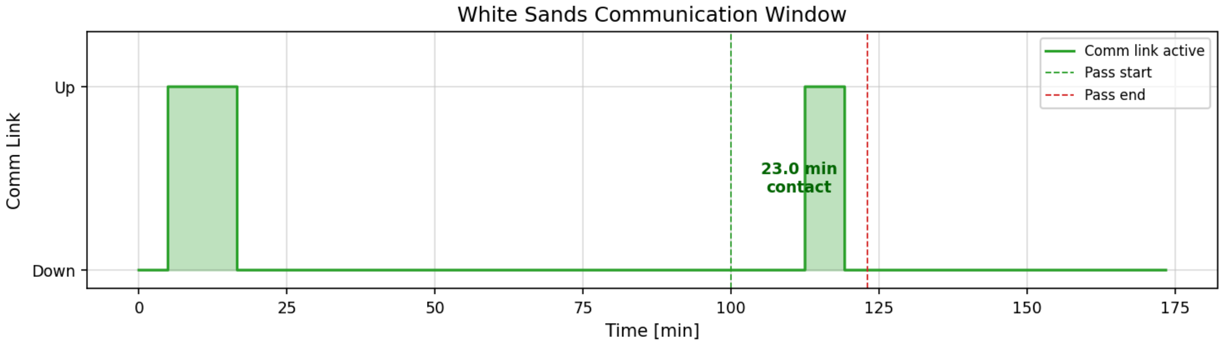
The ADCS is validated using the Basilisk astrodynamics framework with SPICE ephemerides, WMM 2020 magnetics, and Earth shadow geometry. To validate the ADCS, we create a "Day in the Life" simulation for SPARROW. This sim consists of 4 phases:

Phase 1– Detumble. Starting from 5 deg/s per axis tumble, SPARROW must stabilize the angular rates and converge to a sun-pointing orientation.

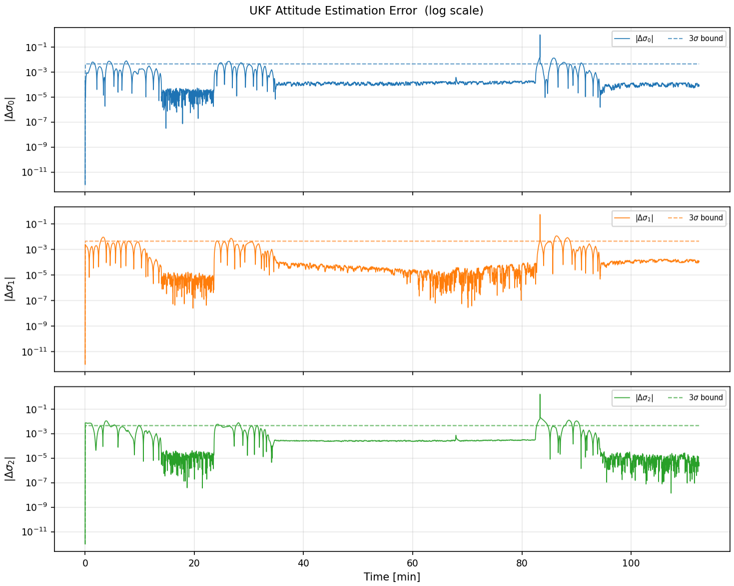


Phase 2–Ground Station Pass. The spacecraft tracks White Sands for over 10 min of contact while battery state of charge remains positive throughout the sun□ground□sun transition.

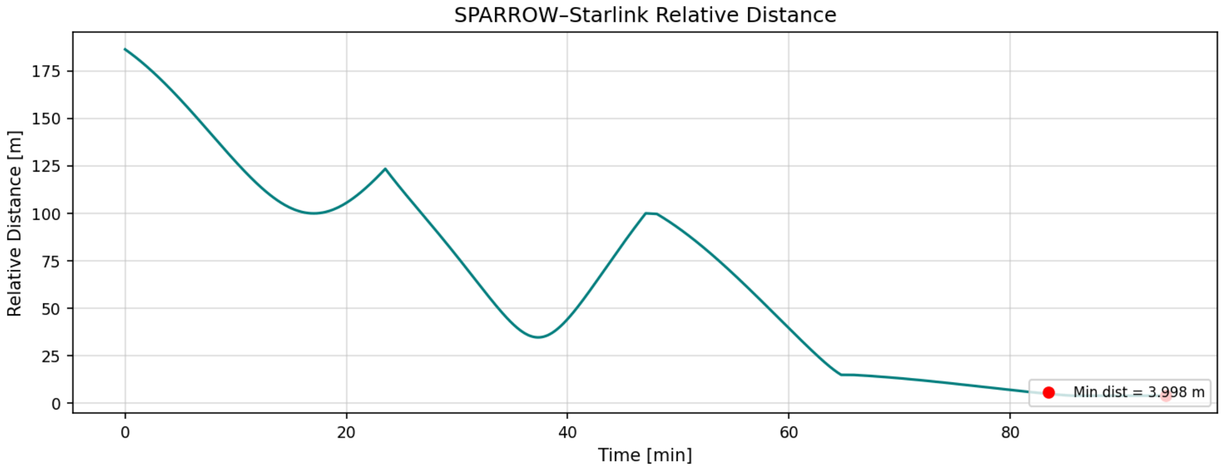




Phase 3–Hohmann Transfer. A two-burn transfer lowers SPARROW from 800 km to 550 km. Navigation errors remain within 3σ UKF covariance bounds.



Phase 4– Proximity Operations. Clohessy-Wiltshire glidescope hops (100 m□, 15 m□, 4 m□contact) drive relative separation to near zero.



6.4. Command & Data Handling and Communications

6.4.1. Communications

The SPARROW communication system utilizes Ku and K bands to ensure compatibility with client satellites and availability of commercial-off-the-shelf hardware. The architecture emphasizes modularity and redundancy, particularly for the critical telemetry system. A dedicated relay system allows SPARROW to augment client communications and is swappable based on mission requirements.

Telemetry communications operate on 14 GHz (Rx) and 12 GHz (Tx) using passive antennas with large radiation patterns, reducing pointing demands and power consumption. The relay communications will employ a Software Defined Radio (SDR) receiving at 18-20 GHz to ensure Starlink and Kuiper downlink compatibility. An SDR relay antenna will perform pointing procedures without requiring mechanical motion that could inhibit client servicing procedures. Interference is mitigated by the SPARROW chassis, which physically shields the original client signal during relay operations.

Link budget analysis confirms that the EbN0 for all links exceeds the 12 dB threshold, with data rates safely below the Shannon limits. During proximity operations, client satellites will be commanded to low-power modes to prevent receiver saturation.

6.4.2. Command & Data Handling

The C&DH system is driven by the high computational demands of autonomous AI operations, specifically for computer vision, navigation, and robotic arm manipulation. The flight computer is selected for low power draw and native integration with NASA's cFS framework. 200 TOPS is required of the AI computer to ensure simultaneous AI model execution. The chosen AI computer will need to meet and preferably exceed this minimum TOPS to allow adequate computing power for operations. Further, the unit will need to be radiation-hardened for space operation while also allowing adequate cooling.

7. Trade Studies

The design of SPARROW was guided by a series of trade studies that were used to make key design decisions for the system and its subsystems. The trade study methodology the team used was a standardized weighted Pugh matrix approach. This methodology weighed design choices or components based on their characteristics, such as mass, power consumption, TRL, or performance. To decide a winner, the design choices or components were scored 1-5 for the given characteristics, and then averaged. The 'winner' was chosen based on which had the highest average. For example, chemical propulsion was chosen as the winner since it had the highest average score compared to electric, nuclear, or solar sail. The detailed trade study tables, including scoring criteria and final selections, are provided in the Appendix.

8. Risk Assessment

This section presents the project's risk analysis, including initial risk identification, mitigation strategies, and post mitigation assessment. Given the complexity of the spacecraft and the number of integrated subsystems, it is not feasible to anticipate every possible failure mode. However, by focusing on the core devices and functions essential to mission success, we have defined the following set of primary risks.

A. **Thruster reaches qualification life:** Extended mission duration or repeated maneuvering may cause the thrusters to approach or exceed their qualified operational lifespan, potentially limiting the spacecraft's navigation abilities.
B. **Solar Panel mechanism failure:** In case ROSA fails to deploy or retract properly, this mechanism might compromise the spacecraft's power generation and thermal balance needs.

C. **RCS Failure during proximity operations:** A malfunction of the RCS during close-range maneuvers could result in loss of fine attitude control, increasing the risk of collision or failed docking procedures.
D. **Structure failure under launch loads:** Unexpected mechanical stress during launch could exceed structural tolerances, leading to deformation or failure of critical components before orbital operations begin.
E. **Micrometeorites Impact:** Micrometeorites may puncture exposed surfaces such as solar panels or thermal blankets, degrading system performance or causing localized damage to sensitive subsystems.
F. **Prolonged loss of ground station communication:** Extended communication outages could prevent command uplink or telemetry downlink, which could delay mission operations or lead to mission failure.
G. **AI decision-making anomaly:** Autonomous algorithms may produce unexpected or incorrect decisions during critical phases, which could lead to catastrophic failures.
H. **Sensor degradation:** Over time, thermal, optical, or inertial sensors may degrade due to radiation exposure or thermal cycling, reducing the accuracy of navigation and state estimation.

Each risk is evaluated based on its likelihood of occurrence and the severity of its consequences. The figure below demonstrates our preliminary risk analysis. The risks classified as red in the matrix are considered unacceptable risks that directly threaten mission success. The yellow in the matrix represents moderate risks that are not immediately mission-threatening but still require monitoring and, where feasible, mitigation measures. The green in the matrix indicates low risks, which are acceptable within the mission profile and generally do not require active mitigation beyond standard operational procedures.

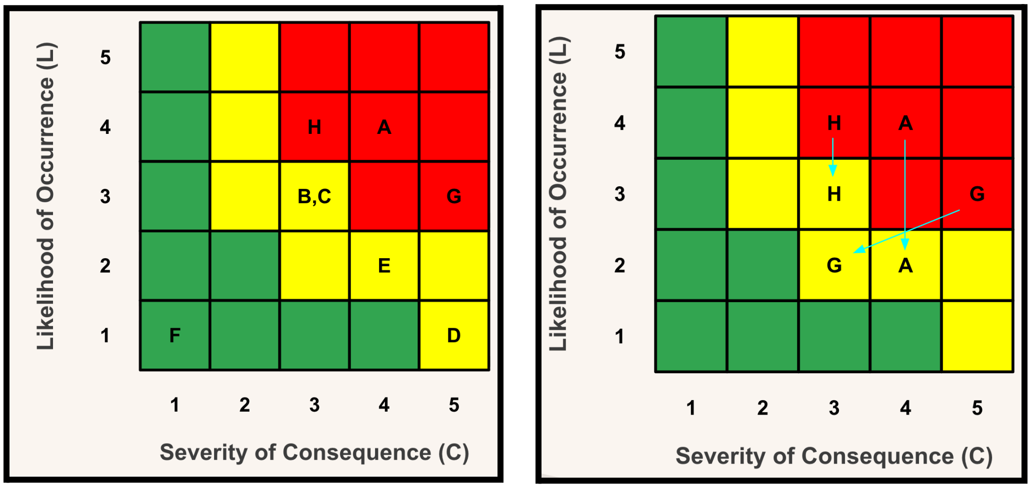


Figure 11: *Risk Analysis Matrices*

Seen in the images above are the pre- and post-mitigation risk analyses. The mitigation strategy for risks **A, H,** and **G**, which fall within the mission-threatening risks are as follows:

A.) Risk mitigation for thrusters reaching qualification life:

- Employ four thrusters to distribute the burn time across multiple engines, reducing individual firing duration while maintaining the same delta V and propellant efficiency.
- Optimize delta V expenditures during orbital maneuvers to minimize fuel consumption and extend operational life.

G.) Risk mitigation for AI decision-making anomalies:

- Train AI models using hard-coded fault simulations to improve resilience against anomalous inputs or unexpected conditions.
- Implement fallback AI modes and maintain a redundant onboard computer to ensure continuity of autonomous operations in case of primary system failure.

H.) Risk mitigation for sensor degradation:

- Incorporate sensor redundancy to prevent single-point failures from compromising navigation or state estimation.
- Design modular interfaces that allow easy swapping of components during the mission, enabling rapid replacement or reconfiguration in case of degradation.

9. Program Plan

9.1. Manufacturing Feasibility

The SPARROW spacecraft is designed to use as many commercial-off-the-shelf (COTS) components as possible, with a strong emphasis on manufacturing feasibility. This approach aims to minimize manufacturing time, reduce costs, and lower operational risks by leveraging components with high TRL and proven flight heritage.

The main subsystems that leverage the emphasis on COTS components are GNC/ADCS, Comms, and CDH. These subsystems all focus on computing hardware, sensors, actuators, etc., so selecting commercially available products significantly increases the ease of manufacturing. Other components that can leverage the COTS emphasis are the thermal components, thrusters and fuel tanks, batteries, and solar panels. This allows for quick development and integration between systems.

Custom manufacturing is then limited mainly to the structural components, as well as interfaces between subsystems. Per the requirements of the system, the spacecraft must be tailored to fit within the launch vehicle's fairing, abiding by all of its constraints, which falls within the custom manufacturing threshold. Additionally, structural members are custom-made and fitted to the spacecraft's needs for modularity. However, despite the custom parts of the spacecraft, the design keeps manufacturing ease in mind through simplified geometry and modular interfaces.

Overall, the emphasis on COTS components, while maintaining customizability with its structure, ensures that SPARROW is both feasible and manufacturable within a realistic timeline.

9.2. Timeline & Path to PDR

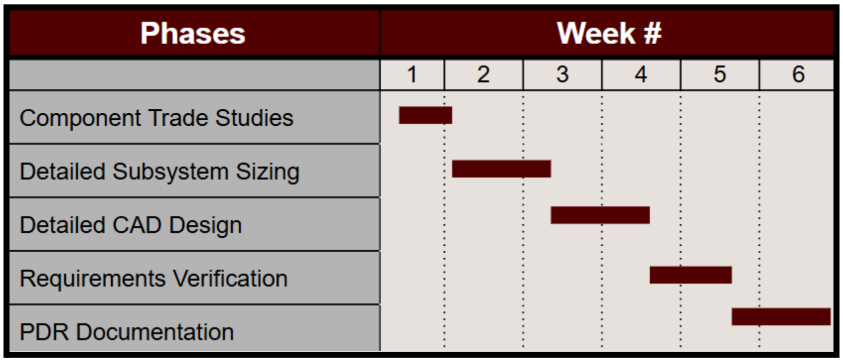


***Figure 12**: Timeline to PDR*

The figure above shows the project’s timeline to Preliminary Design Review, or PDR. The timeline is expected to take 6 weeks and is broken down into 5 phases. The first phase involves conducting trade studies on specific components such as sensors or cameras. The second phase is a detailed subsystem sizing study. During this phase, the team can confirm subsystems meet their preliminary sizing goals or whether they need to be adjusted/modified. Thirdly, the detailed CAD design phase is where the design will go from its current state to a mostly developed model. The second-to-last phase, requirements verification, is where the team will ensure the design meets all requirements before beginning phase 5, which is all PDR documentation.

10. Lessons Learned

10.1. Innovative Concepts

Throughout the entire design process, several innovative concepts and engineering solutions were discussed, and although not all were implemented, they played a crucial role in the final system architecture. The first of the innovative concepts was placing two robotic arms on tracks that encircle the outer shell of SPARROW. The tracks allow both arms to have full, 360° authority, and can articulate themselves to access multiple locations to perform tasks. This concept was pursued and would be refined further as the project advances through its lifecycle.

The next innovative concept, which was ultimately not pursued, was an orbital docking station that SPARROW can use. The docking station would act like a garage, or gas station, where companies can launch parts to the station for SPARROW to utilize in client sorties. SPARROW could return to this docking station for refueling between missions, and switch out modular payloads for future missions

The third and final concept involves fully modular payload compartments. These compartments allow for quick swapping of tools, replacement parts, end effectors, etc. This idea was pursued and ultimately had a heavy influence on the design of SPARROW.

10.2. Technology Gap Assessment

In order to make SPARROW possible, there are a few key technological advancements that are critical for the system. The first of which is the AI that controls all aspects of the mission from decision-making to orbital transfer calculations, to diagnostics, and so on. Current AI models are limited in their ability to take full authority over a system, thus making this a primary area for advancement.

The second major technological gap is the use of a fully autonomous robotic arm. Although there are excellent robotic arms currently available, SPARROW requires one that can perform complex tasks, using precise end effectors with pressure-sensing capabilities. The robotic arm(s) will need elite dexterity, sensing, and control, which will need considerable research and development.

The third major technology gap is a high-performance onboard computer (OBC). Similar to the robotic arm, OBCs exist currently and perform very well for their applications; however, improving on data processing, autonomous capabilities, and environmental protection is essential to a spacecraft like this.

10.3. Biggest Challenges

During the development and design process of the spacecraft, the team had a few design challenges that were the biggest hurdles to overcome. One of the challenges was meeting a strict size constraint, including sizing components and subsystems around this constraint. Another challenge was figuring out how to achieve the high modularity of the spacecraft. Many concepts for modularity were explored throughout the process, and as previously mentioned, the team came up with a design that drove the entire system design. Finally, another challenge that the team faced was overall system-level integration across all subsystems. This includes working around the placement of sensors, solar panels, cameras, etc. This challenge emphasizes the importance of systems-level engineering and iterative design.

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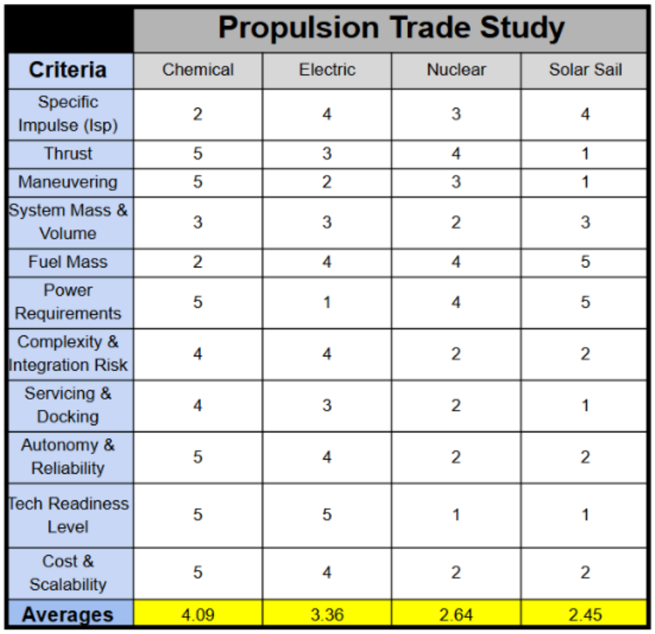
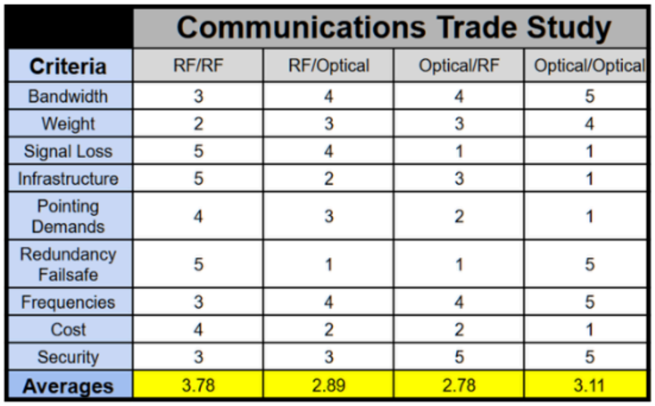
Appendix

Subsystem Requirements	
ID	Requirement
STRC 1.00	The structure shall withstand a first mode > 150 Hz in the longitudinal axes as well as 50 Hz in the lateral axes.
STRC 2.00	The structure shall comply with the size constraints of the Starship launch shroud which has a volume of 150 m^3.
STRC 3.00	The structure shall have mass < the maximum allowable payload mass of the Starship which is 17.4 metric tons.
PROP 1.00	The propulsion system shall carry 4000 m/s of deltaV required to maneuver to any satellite within the designated orbital servicing regime.
PROP 2.00	The propulsion subsystem shall feature a propulsion system capable of refiring the thrusters >10 times per mission to successfully transfer itself to a client and return to the spacecraft's parking orbit.
POW 1.00	The power system shall be capable of providing a constant power output of >7 kW for full operation of the spacecraft for the duration of the life cycle.
POW 2.00	The power system shall provide sufficient power to the essential functions of the spacecraft during eclipses and other power outages for > 3 hours.
POW 3.00	The power system shall be capable of managing and allocating the power draw to the spacecraft subsystems with automated priority sensing to sustain 120% of the power needed.
THM 1.00	The thermal systems shall be capable of keeping all components within their operational temperature range with a <5 K design margin at all times.
THM 2.00	Thermal subsystems shall reject all excess heat from the spacecraft.
ADCS 1.00	The ADCS shall determine the spacecraft's navigation state with an accuracy of ≤ 0.05 meters for position ≤ 0.01 meters/second for velocity and ≤ 0.5 degrees for attitude.
ADCS 2.00	The ADCS shall determine the attitude rates of the spacecraft with an accuracy of ≤ 0.01 degrees/second
ADCS 3.00	The ADCS shall control the spacecraft with an error less than ≤ 0.1 degrees for attitude ≤ 0.1 meters for position and ≤ 0.01 meters/second for velocity
RNS 1.00	The RNS shall determine the client satellite's relative position with an accuracy ≤ 0.05 m within 10 m and ≤ 1 m when within 1 km
RNS 1.10	The RNS shall determine the client satellite's relative attitude with an accuracy ≤ 0.5° when within 10 m and ≤ 2° when within 1 km
RNS 1.20	The RNS shall determine the client satellite's relative velocity with an accuracy ≤ 0.01 m/s when within 10 m and ≤ 0.05 m/s when within 1 km

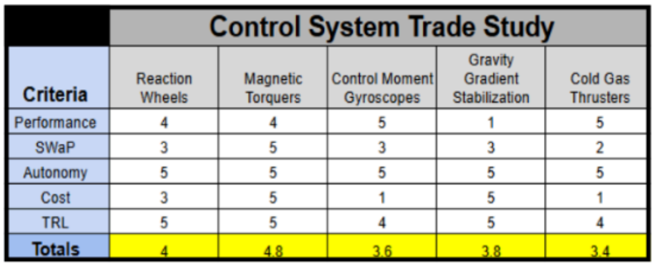
RNS 1.30	The RNS shall determine the client satellite’s relative angular velocity with an accuracy ≤ 0.01°/s when within 10 m and ≤ 0.05°/s when within 1 km
RNS 2.00	The RNS shall maintain valid relative state estimation over ranges from 5 km initial acquisition down to 0.1 m contact and docking
COMM 1.00	The communications system shall be able to establish two-way communication in ≤ 5 seconds of entering the ground station visibility cone.
COMM 2.00	The communications system shall be capable of receiving information on client satellites and their repair needs at least daily.
COMM 3.00	The communications system shall be available for commanding and monitoring for ≥ 95% of ground station passes.
C&DH 1.00	The C&DH system shall be capable of ≥ 200 TOPS for artificial intelligence computations.
C&DH 2.00	The C&DH system shall be capable of interfacing with the command and data handling systems of at least half of the client satellites using compatible communications protocols.



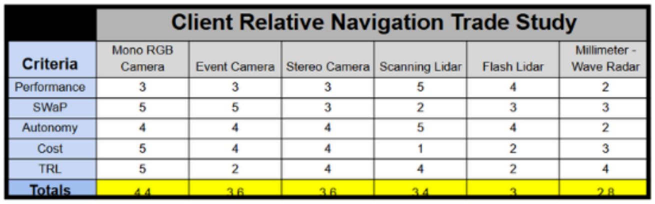
Criteria	Chemical	Electric	Nuclear	Solar Sail
Propulsion Trade Study				
Specific Impulse (Isp)	2	4	3	4
Thrust	5	3	4	1
Maneuvering	5	2	3	1
System Mass & Volume	3	3	2	3
Fuel Mass	2	4	4	5
Power Requirements	5	1	4	5
Complexity & Integration Risk	4	4	2	2
Servicing & Docking	4	3	2	1
Autonomy & Reliability	5	4	2	2
Tech Readiness Level	5	5	1	1
Cost & Scalability	5	4	2	2
Averages	4.09	3.36	2.64	2.45



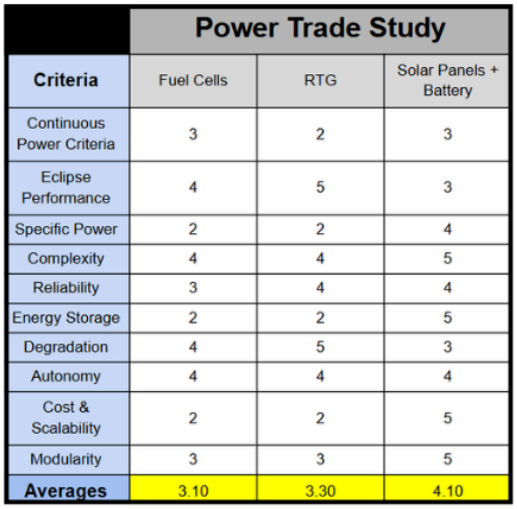
Criteria	RF/RF	RF/Optical	Optical/RF	Optical/Optical
Communications Trade Study				
Bandwidth	3	4	4	5
Weight	2	3	3	4
Signal Loss	5	4	1	1
Infrastructure	5	2	3	1
Pointing Demands	4	3	2	1
Redundancy Failsafe	5	1	1	5
Frequencies	3	4	4	5
Cost	4	2	2	1
Security	3	3	5	5
Averages	3.78	2.89	2.78	3.11



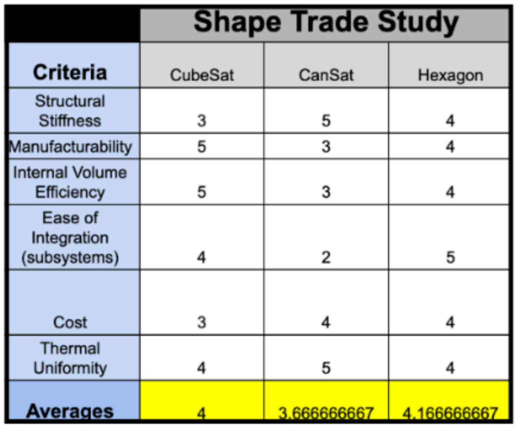
Criteria	Reaction Wheels	Magnetic Torquers	Control Moment Gyroscopes	Gravity Gradient Stabilization	Cold Gas Thrusters
Control System Trade Study					
Performance	4	4	5	1	5
SWaP	3	5	3	3	2
Autonomy	5	5	5	5	5
Cost	3	5	1	5	1
TRL	5	5	4	5	4
Totals	4	4.8	3.6	3.8	3.4



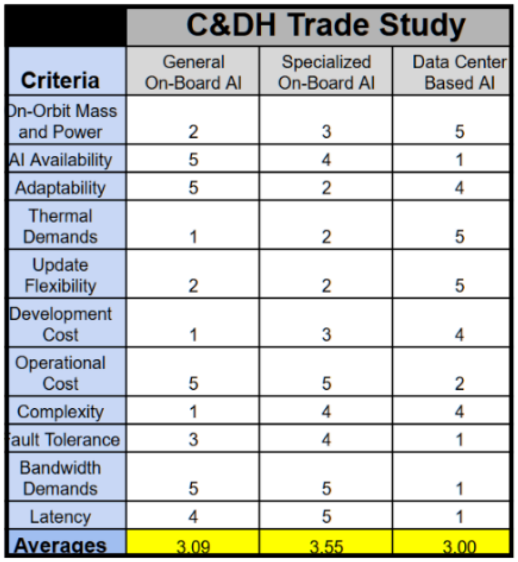
Criteria	Mono RGB Camera	Event Camera	Stereo Camera	Scanning Lidar	Flash Lidar	Millimeter - Wave Radar
Client Relative Navigation Trade Study						
Performance	3	3	3	5	4	2
SWaP	5	5	3	2	3	3
Autonomy	4	4	4	5	4	2
Cost	5	4	4	1	2	3
TRL	5	2	4	4	2	4
Totals	4.4	3.6	3.6	3.4	3	2.8



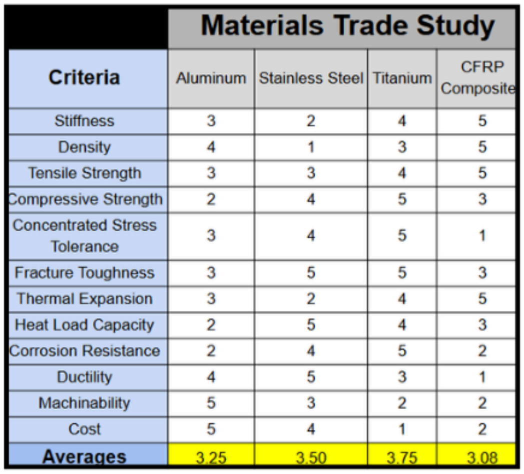
Criteria	Fuel Cells	RTG	Solar Panels + Battery
Power Trade Study			
Continuous Power Criteria	3	2	3
Eclipse Performance	4	5	3
Specific Power	2	2	4
Complexity	4	4	5
Reliability	3	4	4
Energy Storage	2	2	5
Degradation	4	5	3
Autonomy	4	4	4
Cost & Scalability	2	2	5
Modularity	3	3	5
Averages	3.10	3.30	4.10



Criteria	CubeSat	CanSat	Hexagon
Shape Trade Study			
Structural Stiffness	3	5	4
Manufacturability	5	3	4
Internal Volume Efficiency	5	3	4
Ease of Integration (subsystems)	4	2	5
Cost	3	4	4
Thermal Uniformity	4	5	4
Averages	4	3.666666667	4.166666667



Criteria	General On-Board AI	Specialized On-Board AI	Data Center Based AI
C&DH Trade Study			
n-Orbit Mass and Power	2	3	5
AI Availability	5	4	1
Adaptability	5	2	4
Thermal Demands	1	2	5
Update Flexibility	2	2	5
Development Cost	1	3	4
Operational Cost	5	5	2
Complexity	1	4	4
ault Tolerance	3	4	1
Bandwidth Demands	5	5	1
Latency	4	5	1
Averages	3.09	3.55	3.00



	Materials Trade Study			
Criteria	Aluminum	Stainless Steel	Titanium	CFRP Composite
Stiffness	3	2	4	5
Density	4	1	3	5
Tensile Strength	3	3	4	5
Compressive Strength	2	4	5	3
Concentrated Stress Tolerance	3	4	5	1
Fracture Toughness	3	5	5	3
Thermal Expansion	3	2	4	5
Heat Load Capacity	2	5	4	3
Corrosion Resistance	2	4	5	2
Ductility	4	5	3	1
Machinability	5	3	2	2
Cost	5	4	1	2
Averages	3.25	3.50	3.75	3.08