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INTELLIGENT
REPLANNING DRONE SWARM

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Pre-Study

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1.1	2025-12-04	Update according to feedback	Sections: 1, 2, 3, 4, 5, 6, 7

Contents

Glossary

ACO
Ant Colony Optimisation. 6

ad-hoc
Created or done for a specific purpose or situation without prior planning or structure. 5, 6

agent
A single UAV that is a member of a UAV swarm. 4, 8

CE
Chief Engineer. 11

CM
Configuration Manager. 12

CMP
Configuration Management Plan. 10

FANET
Flying Ad-hoc Network. 5, 6

FMU
Fault Management Unit. 4

IRDS
Intelligent Replanning Drone Swarm. 4, 5, 8

QCM
Quality & Configuration Manager. 11

QM
Quality Manager. 12

QMP
Quality Management Plan. 10

RM
Requirements Manager. 11

RMP
Requirements Management Plan. 10, 12

SAR
Search and Rescue. 4, 8

SM
Safety Manager. 11

SMP
Safety Management Plan. 10, 12

UAV
Unmanned Aerial Vehicle. 4–6, 8

V&V
Validation & Verification. 10

VVM
Validation & Verification Manager. 11

VVMP
Validation & Verification Management Plan. 10, 12

1 Introduction

- **Project title:** Intelligent Replanning Drone Swarm (IRDS).
  Orignal title: Intelligent Replanning Protocol for a Fail-Operational Drone Swarm.
- **Project owner:** Luiz Giacomossi

Search and Rescue (SAR) missions increasingly rely on autonomous multi-agent systems that can cover large areas quickly while maintaining an acceptable level of safety and reliability. Unmanned Aerial Vehicle (UAV) swarms offer clear advantages over single-UAV deployments in terms of robustness and scalability, but their effectiveness is still limited by the health of individual agents and by the difficulty of coordinating many autonomous units in uncertain environments.

The Intelligent Replanning Drone Swarm (IRDS) project addresses this challenge by investigating how a UAV swarm can remain fail-operational when one or more agents experience degraded health or fail entirely. Rather than allowing failed agents to silently drop out, the swarm should collectively detect degradations, redistribute tasks, and, where possible, assign secondary roles to compromised agents so that overall mission performance is preserved. Achieving this requires more than ad-hoc behaviours: it demands a structured protocol that combines distributed consensus, dynamic task allocation, and dependable communication.

This pre-study lays the analytical foundation for such a protocol. It frames the problem in the context of dependability engineering, reviews related work on UAV swarms, consensus mechanisms, and task allocation, outlines a baseline system architecture, and defines initial dependability objectives and constraints. The results of this pre-study guide later phases of the project, where the conceptual protocol will be specified, partly implemented and validated through fault-injection in a simulation environment.

1.1 Background

The Intelligent Replanning Drone Swarm (IRDS) project will address the challenge of maintaining mission continuity in Search and Rescue (SAR) operations when individual Unmanned Aerial Vehicles (UAVs) suffer degraded health or fail entirely. Previous work by [1] established a high-level blueprint for a safety-driven conceptual architecture for a fail-operational UAV swarm intended for SAR missions. The architecture contained a Fault Management Unit (FMU) to detect hardware component failures and broadcast a degraded health message across the swarm. The next step is to transform this information into a protocol for collective replanning.

In dynamic and uncertain environments, conventional single-UAV fault tolerance is insufficient. Instead, swarms must demonstrate fail-operational behaviour by continuing their mission despite the loss or degradation of one or more agents. This requires distributed consensus, adaptive task allocation, and resilient communication. The project shall build on current research on swarm resilience, distributed consensus, and communication architectures while focusing on dependable design and validation.

The IRDS project builds on this foundation by transforming that degraded health message into swarm-level replanning logic to enable the swarm to continue its SAR effectively even when one or more UAVs are degraded.

To achieve this, the following challenges must be addressed:

1) Distributed Consensus
2) Dynamic Task Allocation
3) Protocol Design
4) Validation

Distributed consensus is particularly challenging in the IRDS context because the swarm operates over wireless, potentially intermittent links, without a permanently available central controller or global clock. Agents may temporarily lose connectivity, rejoin the swarm, or report inconsistent health information, yet the swarm must still converge on a coherent view of mission state and required actions. Consensus algorithms therefore need to tolerate message delays, packet loss, and faulty or misleading health reports while remaining lightweight enough for resource-constrained UAV hardware.

Dynamic task allocation is likewise non-trivial. In SAR missions, tasks correspond to coverage of specific sectors, and reassigning them after failures must balance multiple objectives: Maintaining coverage of high-priority areas, respecting the limited energy and flight envelopes of individual UAVs, and avoiding unsafe overlaps or gaps. The allocation logic must react to health changes and failures in real time, without central optimisation, and must do so in a way that is consistent with swarm-level safety and reliability goals.

The contribution of the project team will be to create a decentralised replanning protocol that allows a degraded UAV to hand over its tasks, assume a secondary role, and allow the swarm to reach consensus on what to do – partly validated in simulation with fault injection.

1.2 Purpose

The purpose of this pre-study is to establish the foundations for a decentralised replanning protocol that ensures SAR missions can continue with maximum effectiveness despite UAV degradation. This includes:

- Review prior work on consensus, task allocation, and communication in UAV swarms.
- Define the conceptual system description and dependability objectives.
- Identify relevant standards and regulations to guide the project.
- Outline planned activities, roles, and deliverables for the project.

1.3 Scope

The scope of this project is limited to the design, simulation (using gym-pybullets-drone [2]), and validation and verification of the replanning protocol. The project will establish what the UAV swarm will do, not how to do it. Hardware implementation and certification are excluded. The replanning protocol will be validated using a modified version of the simulation software, using fault injection, to test the performance of the replanning protocol. The outcome will be a validated protocol design, documented processes, and assurance artefacts in accordance with the FLA402 course requirements and course guide [3].

2 Related Work

This project will build on three main strands of existing research:

- UAV swarms for search and rescue and related coverage missions.
- Distributed consensus and situation awareness in multi-agent systems.
- Dynamic task allocation and communication architectures for UAV networks.

The works reviewed in this section were selected because they either address SAR-oriented swarm behaviour, propose mechanisms for consensus or cooperative decision-making among UAVs, or survey task allocation and communication patterns relevant to resilient swarm coordination.

Together, these contributions provide the technical background for IRDS: They show how swarms can be organised, how information can be disseminated, and how tasks can be distributed. At the same time, they reveal important gaps with respect to health-aware, fail-operational replanning in SAR scenarios, where degraded agents must hand over responsibilities without compromising coverage or safety.

The most relevant characteristics of the reviewed works, including their mission focus, coordination strategy, and treatment of failures, are summarised in table 1. These works were chosen because they collectively cover cooperative SAR missions, dynamic task allocation in swarms, consensus formation in UAV networks, and communication architectures for flying ad-hoc networks, which are all directly related to the IRDS problem of dependable replanning.

Year	Title	Main Focus	Relevance to IRDS
2025	Design of a Fail-Operational Swarm of Drones for Search and Rescue Missions [1]	High-level blueprint for a conceptual architecture for a fail-operational UAV swarm.	Degraded health message.
2023	Cooperative Search and Rescue with Drone Swarm [4]	Distributed coordination and search resilience in UAV SAR missions.	Defines the application domain and justifies decentralised swarm cooperation for dependability.
2021	Autonomous and Collective Intelligence for UAV Swarm in Target Search Scenario [5]	Conceptual architecture for autonomous & collective intelligence in target search.	Serves as a theoretical base.
2025	Development of Adaptive Drone Swarm Networks [6]	Adaptive network layer (AeroSyn)	Suggests implementation model for health-state messaging
2025	Dynamic reconnaissance operations with UAV swarms: adapting to environmental changes [7]	Dynamic replanning under failure	Provides comparative benchmark and validation model
2025	Energy Efficient Scheduling for Position Reconfiguration of Swarm Drones [8]	Energy-efficient reconfiguration	Supports energy-aware task redistribution
2023	A Novel Distributed Situation Awareness Consensus Approach for UAV Swarm Systems [9]	Distributed consensus	Algorithmic basis for swarm agreement
2022	A Review of Consensus-based Multi-agent UAV Implementations [10]	Consensus-based UAV control	Practical implementation insights
2021	Review of Dynamic Task Allocation Methods for UAV Swarms Oriented to Ground Targets [11]	Dynamic task allocation	Framework for reallocation strategy
2019	UAV swarm communication and control architectures: a review [12]	Swarm communication architectures	Justifies decentralised, FANET-based design

Table 1: Previous work used as refenced in the project.

The following subsections summarise the most relevant findings and limitations.

2.1 Cooperative Search and Rescue with Drone Swarm

This paper presents a cooperative search-and-rescue (SAR) strategy using UAV swarms. It explores collective intelligence, distributed coordination, and fault-tolerant cooperation among UAVs in dynamic SAR missions. The swarm shares situational data to maintain coverage and efficiency while adapting to UAV losses or degraded conditions.

2.2 Autonomous and Collective Intelligence for UAV Swarm in Target Search Scenario

This paper investigates collective intelligence architectures for UAV swarms performing target-search missions. It introduces autonomous decision layers combining individual UAV autonomy (sensing, navigation) with collective coordination for search coverage.

2.3 Development of Adaptive Drone Swarm Networks

This paper introduces AeroSyn, a hybrid network architecture that combines cellular and ad-hoc links. It enables UAVss to switch between connected and leader-follower communication modes to maintain stable swarm coordination.

2.4 Dynamic reconnaissance operations with UAV swarms: adapting to environmental changes

This paper develops a dynamic mission-replanning framework for UAV swarm reconnaissance using Ant Colony Optimisation (ACO). The model handles two events that force the system to adapt:

1) Swarm composition changes (e.g., UAV failures/additions).
2) Mission or environment changes (e.g., new area of responsibility).

2.5 Energy Efficient Scheduling for Position Reconfiguration of Swarm Drones

This study proposes an energy-balancing reconfiguration scheme for UAV swarms operating in urban wind fields. The model determines when and how UAVs should exchange positions to equalise energy use and extend swarm flight time.

2.6 A Novel Distributed Situation Awareness Consensus Approach for UAV Swarm Systems

This paper proposes a distributed situation awareness consensus framework that allows UAVs to share perception and align decision-making without a central controller. It introduces a dual-loop feedback mechanism to maintain robust cognitive agreement.

2.7 A Review of Consensus-based Multi-agent UAV Implementations

This review analyses consensus-based distributed control for UAV swarms. The review highlights practical issues in formation flight and target tracking, focusing on how communication delay and sensing accuracy affect practical use.

2.8 Review of Dynamic Task Allocation Methods for UAV Swarms Oriented to Ground Targets

This review surveys dynamic task allocation methods for UAV swarms facing changing ground-target situations. The review classifies dynamic task allocation models into global and local approaches and analyses algorithms including market-based, intelligent optimisation, and clustering strategies. Each method's advantages and practical performance trade-offs are discussed. The review identifies ongoing challenges such as communication limits and heterogeneous UAV swarms, and suggests future integration of AI and distributed optimisation for adaptive task allocation.

2.9 UAV swarm communication and control architectures: a review

This paper reviews UAV swarm communication and control architectures by comparing centralised (ground-based) and ad-hoc (FANET) models. The paper discusses autonomy levels, swarm coordination algorithms, and the potential of 5G networks to improve UAV-to-UAV communication. The paper highlights the need for hybrid architectures that combine distributed decision-making with reliable infrastructure support to overcome range, latency, and scalability issues.

2.10 Summary

In summary, existing research demonstrates that UAV swarms can coordinate search patterns, maintain basic connectivity in flying ad-hoc networks, and perform dynamic task allocation under various assumptions. However, most SAR-oriented swarm solutions either assume fully functional agents or handle failures by removing compromised units without explicitly restructuring the mission. Consensus-oriented works focus on agreement but do not couple consensus with health-aware task reallocation, while task-allocation studies often neglect detailed models of agent health and fault propagation. None of the reviewed works provides an integrated, fail-operational replanning protocol that combines distributed consensus on degraded health events, dynamic redistribution of search sectors, and assignment of secondary roles to compromised agents in a SAR context. Addressing this gap is the central focus of the IRDS project.

3 Baseline System Architecture & IRDS Concept

The baseline system consists of a UAV swarm executing a SAR mission, a human Search Manager, and supporting infrastructure such as the simulation environment and communication links. At this stage, the Swarm Coordination Module (SCM) is conceptual rather than fully specified, but it can already be decomposed into a set of logical sub-functions that reflect the core challenges identified in the background and related-work analysis.

In the baseline architecture (fig. 1), each UAV is equipped with a Fault Management Unit (FMU) that monitors onboard hardware and reports a health status. These health reports, together with task and sector information, are processed by the SCM, which spans the swarm and is realised cooperatively by all agents rather than as a single central component. Conceptually, the SCM is expected to include at least the following subcomponents:

- State & Health Monitor – collects health information from FMUs and mission state data (sector ownership, role assignments, etc.) and exposes an abstract, swarm-level view of agent status.
- Consensus Module – implements a distributed mechanism for reaching agreement on critical events (e.g. agent degraded, task handed over) under intermittent connectivity and possible faulty reports.
- Task & Sector Allocation Module – manages the assignment of search sectors and other tasks to agents, including reallocation when health changes, with the goal of preserving coverage and workload balance.
- Role Allocation / Behaviour Module – determines which high-level role each agent should perform (e.g. search, relay, return-to-base, standby) based on its health, assigned sectors, and mission phase.
- Communication & Networking Interface – abstracts the underlying flying ad-hoc network, providing message dissemination and routing services required by the consensus and allocation logic.

The current baseline diagram will be refined in later phases, but already at the pre-study stage it is important to recognise that the IRDS ”box” inside the SCM is not a monolithic entity. Instead, it is expected to be realised as a cooperation of these subcomponents, each addressing a specific technical challenge. The subsequent System Design Description will formalise these modules, define their interfaces, and allocate requirements to them.

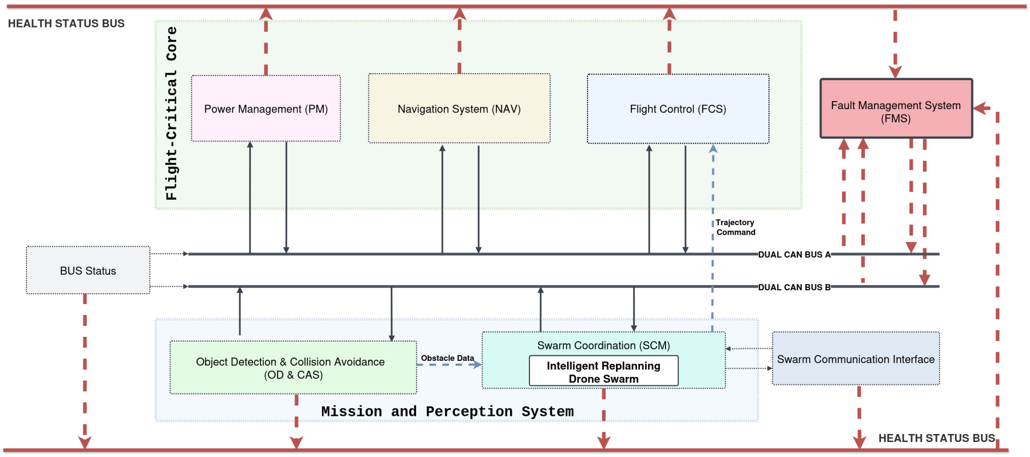

Figure 1: Baseline system architecture.

A larger version of figure 1 can be found in the Appendix (figure 3).

4 Dependability Perspective

For the IRDS project, dependability is not achieved by management plans alone; it must be built into the technical design of the replanning protocol and the swarm architecture. In particular, the system must tolerate individual UAV failures, detect and contain faults, and maintain coordinated behaviour even under degraded conditions. Management plans (requirements, safety, V&V, quality, configuration) support these goals by structuring the process, but the underlying capability comes from architectural choices such as redundancy, robust consensus mechanisms, and fault-aware task allocation.

This section outlines how reliability, availability, and safety are interpreted for IRDS and specifies initial quantitative targets that will later be refined and validated in simulation.

4.1 Reliability

In the IRDS context, reliability refers to the probability that the swarm completes its SAR mission objectives despite individual agent degradations or failures. Technically, this will be pursued by:

- Designing the protocol so that critical mission information is replicated across agents, avoiding single points of failure.
- Using a distributed consensus mechanism that tolerates communication loss and faulty health reports within defined bounds.
- Ensuring that task and sector ownership can be reassigned when an agent fails, without leaving sectors permanently unsearched.

4.2 Availability

Availability captures the ability of the swarm to remain operational over time, even when individual agents must be removed, return to base, or switch to secondary roles. The IRDS protocol contributes to availability by:

- Allowing agents to continue participating in the swarm in reduced-capability roles (e.g. communication relay) rather than dropping out entirely.
- Supporting on-line task redistribution so that coverage is maintained when agents become unavailable.
- Minimising the time between fault detection and completion of task handover.

To make availability measurable, the following could be defined: Targets such as a maximum allowable downtime per drone (time between a failure or degradation event and the swarm regaining a complete and consistent task allocation) and a limit on the fraction of mission time during which required coverage is not maintained due to reconfiguration.

4.3 Safety

Safety is concerned with preventing the replanning protocol from introducing hazardous behaviours, such as collisions, loss of separation, or uncontrolled flight due to inconsistent commands. From a technical point of view, this means that:

- Fault detection and consensus must be designed so that no single faulty agent can drive the swarm into an unsafe state within the assumed fault model.
- Task reallocation must respect spatial and temporal safety constraints, such as minimum separation distances and maximum allowed overlap in sectors.
- The protocol should provide guaranteed safe task reassignment, meaning that agents only act on commands that have passed defined consistency and plausibility checks.

These safety aims will be supported and refined through the Safety Management Plan and preliminary safety analyses, but their realisation ultimately depends on protocol properties that can be analysed and tested using model-based verification and fault-injection simulation.

5 Standards & Regulations

The selection of standards (table 2) for the project ensures that the project is consistent with recognised international standards and guidelines.

ID	Title	Relevance
IEEE Std 1012™-2024	IEEE Standard for System, Software, and Hardware Verification and Validation [13]	Supports verification and validation activities across all project phases, ensuring that both system and software meet their specified requirements and intended use.
ISO/IEC/IEEE Std 29119-1:™-2022	Software and systems engineering - Software testing - Part 1: General Concepts [14]	Provides the foundational concepts and high-level framework for software testing, helping the project understand what aspects of the system must be tested.
ISO/IEC/IEEE Std 29119-4:™-2021	Software and systems engineering - Software testing - Part 4: Test techniques [15]	Provides test design techniques to ensure systematic and effective test coverage of the system.
ISO/IEC/IEEE Std 15288:™-2023	Systems and software engineering - System life cycle processes [16]	Defines processes for the full system lifecycle, including development, verification, and validation.
ISO/IEC/IEEE 29148:2018	Systems and software engineering - Life cycle processes - Requirements engineering [17]	Supports the project's requirements engineering activities by providing guidance for creating clear, consistent, and verifiable system and software requirements.
ISO 10007:2017	Quality management - Guidelines for configuration management [18]	Useful for ensuring proper configuration management throughout the project lifecycle, supporting traceability, version control, and change management.
ISO 9001:2015	Quality management systems — Requirements [19]	Manages overall project quality by establishing requirements for a quality management system to ensure consistent, reliable processes and deliverables.
ISO/IEC 25002:2024	Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — Quality model overview and usage [20]	Supports the project's software architecture work by providing guidance on evaluating software product quality, helping ensure the system meets defined quality characteristics.
IEEE 730-2014	IEEE Standard for Software Quality Assurance Processes [21]	Defines the requirements for a Software Quality Assurance Plan (SQAP), supporting structured and traceable software development processes.
JAR-DEL-SRM-SORA-MB-2.5	Specific Operations Risk Assessment (SORA) [22]	This methodology ensures that the system complies with the legal and safety requirements for conducting risk-based assessments of unmanned aircraft operations within Europe.
ARP4761™A	Guidelines for Conducting the Safety Assessment Process on Civil Aircraft, Systems, and Equipment [23]	Provides guidance on performing safety assessments to identify hazards and define corresponding safety requirements for aerial vehicles.

Table 2: Selected standards and guidelines.

6 Planning of Activities

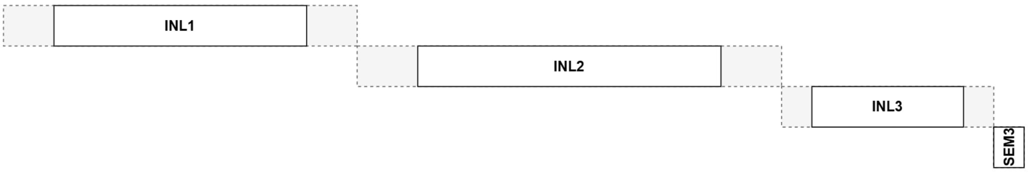

Figure 2: Timeline of milestones.

6.1 Pre-study & Planning Phase (INL1)

- Date: 2025-09-01 - 2025-10-05
- Literature review of related work
- Baseline system description
- Define the perspective of dependability
- Define relevant standards and guidelines
- Create Project Plan
- Create Management Plans
  - Configuration Management Plan (CMP)
  - Quality Management Plan (QMP)
  - Requirements Management Plan (RMP)
  - Safety Management Plan (SMP)
  - Validation & Verification Management Plan (VVMP)

6.2 SEM1

- Date: 2025-10-09
- Oral examination of the Pre-study & Planning Phase

6.3 Execution & Validation Phase (INL2)

- Date: 2025-10-06 - 2025-11-16
- Requirements elicitation
- Safety requirements elicitation
- Validation & Verification
- Configuration Management
- Quality Management
- Design replanning protocol by developing distributed consensus and task allocation logic
- Modify simulation software (gym-pybullet-drone [2]) for fault injection and protocol tests.

6.4 SEM2

- Date: 2025-11-20
- Oral examination of Execution & Validation Phase

6.5 Reporting Phase (INL3)

- Date: 2025-11-17 - 2025-12-07
- Final report

6.6 SEM3

- Date: 2025-12-11
- Presentation of the project

7 Roles & Responsibilities

The IRDS project is organised according to a role-based structure. Each role has clearly defined responsibilities and authority to avoid overlaps and ambiguity.

- Chief Engineer (CE)
  - Provides overall technical leadership and ensures that all work aligns with the system concept, dependability objectives, and project scope.
  - Has final approval authority on system-level design choices, architectural decisions, and trade-offs between competing dependability attributes.
  - Integrates results from all other roles.
- Requirements Manager (RM)
  - Elicits, documents, and maintains requirements, with a focus on clarity, feasibility, and verifiability.
  - Ensures traceability between stakeholder needs, system functions, and dependability objectives.
  - Has authority over the requirements baseline: May approve or reject changes to requirements and request clarifications from other roles.
  - Collaborates with the SM and VVM, but final decisions on requirements content rest with the RM, subject to CE arbitration in case of conflict.
- Safety Manager (SM)
  - Identifies hazards and defines safety goals and safety requirements.
  - Ensures that safety considerations are incorporated into the design of the replanning protocol and the system architecture.
  - Has authority over safety-related decisions (e.g. acceptance of safety mitigations, safety goals), subject to alignment with project scope and design as agreed with the CE.
- Validation & Verification Manager (VVM)
  - Defines the V&V strategy, including test cases, fault-injection scenarios, and acceptance criteria.
  - Ensures that all requirements are verifiable and that V&V results are traceable to requirements and design artefacts.
  - Has authority to accept or reject deliverables based on verification and validation results and to request corrective actions.
  - Validates that the implemented protocol meets stakeholder needs from a V&V perspective, while recognising that final design authority remains with the CE.
- Quality & Configuration Manager (QCM)
  - Maintains consistency and traceability across all project artefacts through configuration management.
  - Manages version control, document reviews, and configuration baselines.
  - Has authority to approve changes to controlled documents and baselines and to reject outputs that do not meet agreed quality criteria.

To avoid ambiguity, conflicts between roles are resolved as follows:

- The CE is the final decision-maker for system-level design and technical trade-offs.
- The RM has authority over the content and structure of requirements, while the VVM has authority over whether those requirements are adequately verified and validated.
- The SM has authority over safety goals and safety requirements; If a safety concern conflicts with other project objectives, it is escalated to the CE for resolution.
- The QCM may block the release of artefacts that do not meet quality or configuration-control criteria, but cannot override technical design decisions; Such disagreements are also escalated to the CE.

This division of responsibilities is intended to ensure clear ownership of decisions while preserving efficient coordination and avoiding overlaps that could slow down the project.

8 Expected Outcomes

The deliverables expected from each phase are:

8.1 Pre-study & Planning Phase

- Baseline system description
- Project Plan
- Requirements Management Plan
- Safety Management Plan
- Validation & Verification Management Plan
- Configuration Manager
- Quality Manager
- Review protocols

8.2 Execution & Validation Phase

- System Architecture
- Design Specification
- Configuration Logs
- Review Protocols
- Requirements Specification
- Safety Goals & Requirements
- Preliminary Safety Assurance Case
- Risk Analysis
- Validation Protocols
- Verification Protocols
- Test Specification

8.3 Reporting Phase

- Final Report

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Appendix

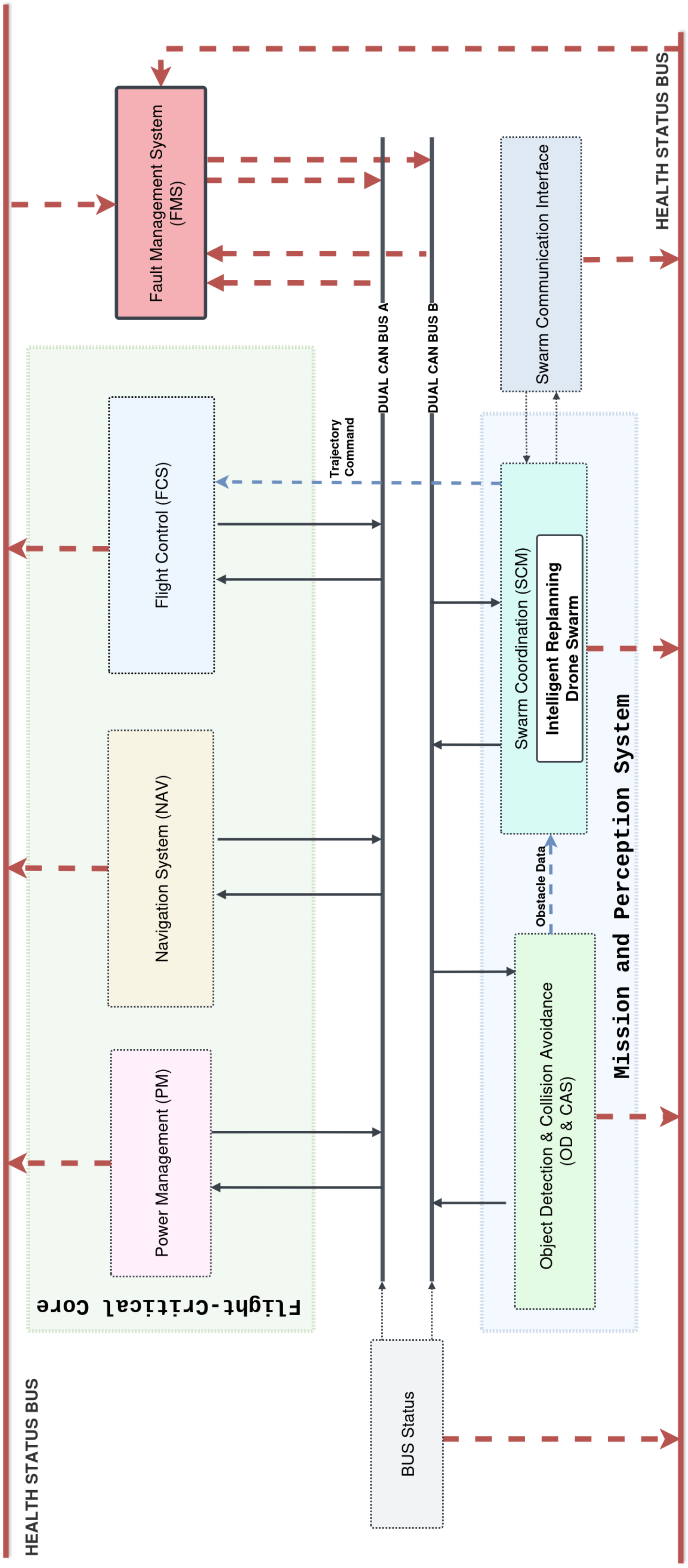

Figure 3: Baseline system architecture.