PROJECT DELIVERABLE REPORT

Introducing advanced ICT
and Mass Evacuation Vessel design
to ship evacuation and rescue systems

D5.5 UAV Platform requirements and specifications v1

A holistic passenger ship evacuation and rescue ecosystem

MG-2-2-2018

Marine Accident Response

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1.0	2020/11/30	ADS	Final version & release

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Abbreviations

API	Application Programming Interface
EO	Electro-optical
FPS	Frames Per Second
GCS	Ground Control Station: The main control station of the UAS system.
GPS	Global Positioning System
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
IP	Internet Protocol: Addressing protocol used by machines to communicate on a IP network.
IR	Infrared
Mbps	Megabits Per Second
MEV	Mass Evacuation Vessel
RC	Radio Controller
Rx	Reception
Tx	Transmission
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UAVMS	Unmanned Aerial Vehicle Mission Software

1 Introduction

1.1 Goal of the document

This document describes requirements and specification of the Unmanned Aerial Vehicle (UAV) platform in the PALAEMON project. It goes through functional, non-functional requirements, constraints, risks and introduces the solution. It details the solution's functionalities and how it integrates with PALAEMON ecosystem

1.2 Summary

The PALAEMON project proposes the development and evaluation of a mass centralized evacuation system on large roll on-roll off and roll on-roll off-passenger-ship vessels. It is a smart ecosystem of critical components aiming to optimize decisions in emergency situations. It gathers information from onboard sensors all around the ship in order to detect and assess anomalies and suggest a mustering and evacuation plan.

The PALAEMON system covers the following phases, according to deliverable (D2.2 – Use Case Driven Requirements – Engineering and Architecture) :

- ***Normal operation***: The system monitors data to try to detect eventual incidents
- ***Incident***: Data is gathered in order to make a primary assessment of the incident and decide whether or not to fire the bridge alarm
- ***Bridge alarm***: The decision support system is turned on and the captain can decide to start the evacuation process
- ***Situation assessment***: Sensors gather exhaustive data in order to produce the best evacuation plan
- ***General alarm***: Passengers are alerted through every possible mean of the emergency situation and the plan to follow.
- ***Passenger mustering***: Passengers are guided in safe location before proceeding to exit the ship
- ***Boarding to Massive Evacuation Vessels (MEVs)***: Passengers embark into the evacuation vessels
- ***Launching***: MEVs are launched
- ***Clearing and rescue***: The MEVs clear from the ship and the crew proceeds to search and rescue last passengers.

Even though the ship is equipped with smart cameras, they are limited in range and coverage. Consequentially some areas cannot be observed (e.g., the hull, objects in the sea, etc.). This shortcoming can be fulfilled using a UAV equipped with a camera that will help looking at places unreachable otherwise.

1.3 Overall objectives

The UAV system acts as a support tool for the crew and fills different purposes. It mainly fulfills observation missions and reports information useful for situation awareness and decision making.

It is mainly targeting the following stages:

- Situation assessment: The UAS can be used to gather information on the current situation and allow its operators(s) to report eventual damages on the ship, men over board or other situations that would need further inquiries.
- Boarding to MEVs, Launching, Clearing and rescue: The UAV can be used to locate missing passengers and help MEV operators to proceed to rescue them.

Considering the urgency and stress of the situations in which the system is supposed to operate, the UAV shall be fast to deploy, easy to operate and tolerant to the ship's environment.

1.4 Structure

Next chapters of the document give a brief overview of available UAV technologies and enumerate the requirements (functional and non-functional), risks and constraints in the use of drones in the PALAEMON ecosystem.

It then introduces a solution based on previously defined requirements in the System Design section. After a breakdown presentation of the Unmanned Aerial System components, their usage is illustrated in a set of automated missions designed around assessment and individual rescue. These missions are divided in multiple sections based on the operational context and the state of emergency. The document also puts the emphasis on specific design details of the solution.

It pursues with a summary of the integration of the UAS in the PALAEMON ecosystem and explicates the exchanges of data between parties.

2 Overview of UAV ecosystem

There are many compelling humanitarian, safety, and economic reasons to use drones during and after ship evacuation:

- Drone technology can reduce evacuation worker, claims adjuster, and risk engineer exposure to unnecessary danger.
- Drones enhance the effectiveness of evacuation responders.
- Drones provide unique viewing angles not possible from manned aircraft.
- Drone technology is highly deployable.
- Drone technology is cost-efficient.

Below are some of the most common and/or most promising use cases for drones in evacuation procedure:

- Recon and Mapping
- Structural Assessment
- Temporary Infrastructure / Supply Delivery
- Search and Rescue Operations

2.1 Platforms, Payloads, Software

The variation in drone capability and design allows drone applications to be broad and flexible. It also enables drones to accomplish unique and specific missions as an emergency or disaster response and prevent or mitigate potential losses or casualties.

While platforms dictate the ability of the drone to access certain environments, its payload often determines the type of data it can collect. Remote sensors like Electro-Optical and InfraRed (EO/IR) cameras can help to establish situational awareness while communications relay payloads can be used to broadcast wireless frequencies with a better line of sight.

The data, its availability and processing hold major potential in the UAV usage, for example, when integrated into crowdsourced crisis maps and existing Geographic Information Systems (GIS).

Policies must be also implemented by lawmakers that ensure the safe integration of drones into the national airspace system while still being flexible enough to accommodate current and future drone deployment models.

The vast spectrum of capabilities provided by drones to intervene in uses cases like evacuation of a ship. Drones range in size from small aircraft that fit in the palm of one’s hand to platforms that rival manned aircraft in wingspan, weight, and power. Drones also vary significantly in their design, including rotary-wing flight systems like quad copters, fixed-wing aircraft, and lighter-than-air vessels like tethered blimps.

Each type of drone has unique capabilities in different operating environments. While small quad copters are better at penetrating dense areas, larger fixed-wing aircraft are better suited for surveying wide swaths of terrain for damage after a disaster.

Communications relay payloads allow drones to act as mobile communications stations, beaming Wi-Fi Internet, cellular service, radio, and other important signals to relief workers and disaster survivors alike. Specially designed capsules can safely remove people from dangerous areas and deliver necessary supplies.

Finally, drones need to be paired with sophisticated software to improve the data link between the drone and its operator as well as streamline sharing of drone-collected data with other stakeholders. Data from drones can integrate into cutting-edge disaster relief mapping software, such as crowd sourced crisis maps and GIS.

A list of the basic platform, payload, and software types is summarized below, followed by a series of representative examples.

2.2 Aerial Drone Types and Missions

This chapter illustrates multiple examples of UAVs for information purposes.

2.2.1 Drone types -examples

Drone type	Group 1 Vertical Take-Off and Landing (VTOL)	Group 2 Fixed wings	Group 3 Unmanned Aerial helicopters
Description	Vertical Take-Off and Landing (VTOL) small unmanned aerial system (UAS)	Fixed wings small, long-endurance, low-altitude unmanned aerial vehicle	Unmanned Aerial helicopters
Flight time	30 minutes	24+ hours	12 hours
Frame	Rotary wings	Fixed wings	Rotary wings
Altitude	Up to 150 meters	Up to 6000 km	Up to 5000 meters
Speed	50 km/h	148 km/h	180 km/h
Propulsion	Electric-motor, propeller	Heavy fuel	Turbo engine, combustion engine, propeller
Launch	Vertical take-off and landing	Catapult	Vertical take-off and landing
Max take-off weight	~10 kg	~22 kg	~1200 kg
Wing span	~20 cm	~3 m	~5 m
Payloads options	Dual sensor EO/IR/LI gimbal FLIR camera	Electro-optic imager: For high-resolution daytime imagery**;** Picture-in-picture daytime imagery from two imagers, allowing operators to focus on and maintain positive identity for objects of interest.; 170x continuous zoom from one high-resolution imager; Mid-wave infrared (MWIR) camera: Quality thermal imaging for	• Portable antennae for line-of-sight and satellite-based beyond line-of-sight data links. • Four-hook carousel to carry multiple loads in a single flight.

night-time and low-visibility operations.

Figure 1: VTOL UAV

Figure 2: Fixed wings UAV

Figure 3: Unmanned Aerial Helicopter

2.2.2 Applicable aerial drone types per mission

The evacuation as a disaster relief lifecycle can be split into four major stages: prevention, preparation, response, and recovery. Drones have applications in all four stages, though currently are used overwhelmingly in the response stage. During the response and recovery stage the most common missions are:

• Reconnaissance and Mapping • Structural Assessment • Temporary Infrastructure / Supply Delivery • Search and Rescue Operations.

Following we present a mapping between the use cases under consideration and the applicable drone types per mission.

2.2.2.1 Reconnaissance and mapping

Group 2: Long endurance, high altitude reconnaissance and surveillance, wide-area imaging / mapping with heavy payloads •

Group 3: Long endurance, large payload drones, localized imaging / mapping with heavy payloads

Group 1: Long endurance reconnaissance and surveillance, wide-area imaging / mapping with light payload, Hand-launched, lightweight, low payload drones, Localized imaging / mapping with light payload

2.2.2.2 Structural integrity assessment

Group 3: Long endurance, large payload drones, Wide-area airborne surveillance/monitoring of damage

Group 2: Long endurance reconnaissance and surveillance, Wide-area airborne surveillance/monitoring of damage

Group 1: Hand-launched, lightweight, low payload drones, Local and interior airborne surveillance/monitoring of damage

2.2.2.3 Temporary infrastructure / Supply delivery

Group 3: Heavy lift, transport of reconstruction materials to worksite, Transport of Humanitarian Aid materials

Group 2: Long endurance, large payload drones, Airborne surveillance/monitoring of damage and imaging

Group 1: Hand-launched, lightweight, low payload drones, Airborne surveillance/monitoring of damage and imaging

2.2.2.4 Search and rescue operation

Group 2: Long endurance, high altitude reconnaissance and surveillance, EO/IR camera to locate survivors / detect hot spots / identify wreckage, Suited for wide-area searches (e.g. high seas).

3 Requirements

This section defines functional and non-functional requirements for the Unmanned Aerial System for PALAEMON as well as implied risks and constraints of such a system. These requirements constitute the basis for the solution proposed in this document. It is mostly a more specific breakdown of higher level requirements clarified in D2.6 (D2.6 PALAEMON Architecture V1).

3.1 Functional requirements

ID UAV-FR-01 Observation points	**Description** Operator can set custom observation points to be inspected by the UAV via Ground Control Station (GCS). The UAV can then perform an automatic flight to allow the operator to view the location
Rationale The UAV shall be used to observe areas unreachable by other optical devices.	

ID UAV-FR-02 Search and rescue	**Description** The GCS operator can trigger an automatic search pattern in specific areas to look for Man OverBoard (MOB). This sequence can be initiated from the ship as well as from the MEV.
Rationale During an emergency, individuals might fall in the water making them hard to locate, especially from a distance.	

ID UAV-FR-03 Hull inspection	**Description** The GCS operator shall have the tools to inspect areas of the hull that might have been damaged using the UAV. The operator can publish and transmit a report to the PALAEMON system from the GCS.
Rationale During the damage assessment phase of an emergency situation, ship's leaders might need to locate and assess structural damages in the ship	

ID UAV-FR-04	**Description** The GCS shows real-time UAV telemetry information including mission state, location, attitude, battery level / flight time left and

Flight monitoring	warnings. This information is visually accessible via the GCS graphical interface. This interface includes a 3D representation of the ship environment for faster understanding of the situation in a stressful context.
Rationale During a UAV flight, operators need to efficiently follow the mission execution in order to take the best decisions.	

ID <u>UAV-FR-05</u> Flight planning	**Description** The GCS allows the operator to plan UAV missions from basic orders (take-off, landing, return home) to complex PALAEMON related missions as described in this document. The flight planning tools are accessible via the graphical interface of the GCS.
Rationale The operator needs to be able to define automated missions via a dedicated interface.	

ID <u>UAV-FR-06</u> Video feedback	**Description** The UAV embeds a video camera (EO and/or IR). The GCS shows real-time video feedback from it.
Rationale An embedded video camera on the UAV is needed to create the image input information that helps situation assessment, searching for objects and decision making.	

ID <u>UAV-FR-07</u> Payload control	**Description** The UAV embeds a gimbal video camera. This gimbal, aside from automatic missions, can be manually controlled and oriented in order for the operator to observe specific areas during manual or automatic flights. The operator can also switch between camera modes (EO/IR) anytime when the option is available.
Rationale During automated or manual flights, the operator might need to adjust the UAV camera to observe areas that are currently out sight from the UAV.	

ID UAV-FR-08 Manual control	**Description** The UAV can be “manually controlled” (unlike automatic flights) via a remote controller using GPS positioning or ATTI (No-GPS modes. This allows the security operator to engage either safety measures or perform flights that are not allowed or implemented in automatic missions.
Rationale Due to unpredictable aspects of contingency situation aboard ships, not all mission scenarios can be automatically handled. In these situations, the operator might need to take manual control of the UAV either to avoid danger or perform specific actions.	

ID UAV-FR-09 Object location approximation	**Description** The operator can pinpoint at points of interest directly on the video feedback or the map. These point locations are visually represented in the 3D environment of the GCS.
Rationale During the damage assessment phase of an emergency situation, ship’s leaders might need to locate and assess damages in the ship	

3.2 Non-functional requirements

ID UAV-NFR-01 Recovery	**Description** The UAV is able to automatically recover from its flight when conditions are met. This implies coming back to the ship and land on a specific target that can be physically represented on the ship. The UAV system determines if this action is safe to perform and might demand a manual landing in abnormal cases.
Rationale The UAV shall be recovered after missions for further usage. This recovery is better automated to not create overhead for the operators in stressful contexts.	
Sub-requirements	

ID UAV-NFR-02	**Description** The UAV system monitors its health status in order to raise warnings as anomalies occur. These checks include flight’s

Self-monitoring	health, battery status, wind/weather conditions and radio link status.
Rationale Anomalies need to be detected by the operator and the system to take the best decisions and avoid danger considering the UAV usage.	
Sub-requirements	

ID UAV-NFR-03 Relative flight	**Description** The UAV system executes missions relatively from the ship's location. To this matter, it needs to adjust its flight path accordingly to the ship's location and dynamics.
Rationale Using a UAV without the ship location reference on a moving ship would cause the UAV to fly away or desync from the ship's location with time.	
Sub-requirements	

ID UAV-NFR-04 Scalability	**Description** Multiple occurrences of the system can be deployed on a single ship and operate simultaneously. They can be managed as independent systems.
Rationale UAVs can be installed on the ship as well as on the multiple MEVs that it might contain.	

ID UAV-NFR-05 PALAEMON integration	**Description** The UAV system is integrated with the PALAEMON system. The GCS receives ship telemetry (phases, location, and attitude) and weather information from it when needed it. The GCS can push events like objects locations and assessment reports to other parties
Rationale The UAV system needs information on the ship and local weather to operate properly. The system might need assessment and situation reports for decision making.	

ID UAV-NFR-06 3D environment	**Description** The GCS contains a 3D environment representation that summarizes the current situation (drone location, mission, ship…). It is meant to reduce operator's overhead in stressed and contingency contexts.
Rationale The system might be used in emergency situations that imply a reduction of the operator focusing capabilities. That means the system's usability and accessibility shall be enhanced to allow a quick and easy understanding of the situation.	

3.3 Constraints

ID UAV-CON-01 No fly-over	**Description** The UAV avoids paths that imply flying over passengers.
Rationale UAVs are inherently dangerous and are prone to fall, hit. This aspect shall be addressed to ensure safety of passengers.	

ID UAV-CON-02 Usable from MEVs and ship	**Description** The system can be used from the MEVs as well as from the ship. The GCS interface and available missions can vary depending on the launch point and availability of data from the PALAEMON system.
Rationale The system can be used from the ship (e.g. for assessment) and from the MEVs (e.g. search and rescue missions)	

ID UAV-CON-03 UAV-Ship compatibility	**Description** The landing pad should be positioned at the rear of the ship. The landing zone should be clear of all obstacles in a radius of 10 times the diameter of the UAV. The rear of the boat should be clear of

	obstacles above 0.5 passed the landing pad and the previously defined clear radius.
Rationale The UAV take-off and landing are critical phases of the flight plan, especially when automated. The environment surrounding the UAV during this phase should be compatible with usual possible behaviours of flying vehicles on take-off and landing.	

3.4 Risks

ID UAV-RI-01 Environmental risk	**Description** The inconsistent sea environment might make the system ineffective most of the time.
Probability Medium	
Mitigation /	

ID UAV-RI-02 Radio masking risk	**Description** The ship structure and shape might absorb radio waves causing disruptions in radio data links.
Probability Medium	
Mitigation - Provide flight patterns avoiding most of radio masking areas	

ID UAV-RI-03 Radio interference	**Description** The multiple radio sources from the ship system, environment or other UAVs can cause radio interference that make the system partially or totally unusable.

Probability
Medium
Mitigation - Radio frequency shifting on most UAS equipment

ID	**Description**
UAV-RI-04 Ship constraints	The ship might not match the minimal requirements for the Unmanned Aerial System (UAS) platform installation.
Probability Medium	
Mitigation - The system is designed to imply minimal adherence to the host ship.	

ID	**Description**
UAV-RI-05 Local regulations	The UAS might not match regulation in the local area making it illegal to use since no global regulation exists at the time on UAVs.
Probability Medium	
Mitigation - The system is designed to fit most common regulations in place in different countries.	

4 System design

The previously mentioned requirements are addressed through the following configuration. This chapter introduces the chosen solution from a system point of view, the different parts that composes it and how in integrates with other parts of the PALAEMON system.

4.1 Coordinates system

The UAV system uses the NED (North East Down) coordinates system, meaning that north is X, east is Y and Z is down, as shown in Figure 4.

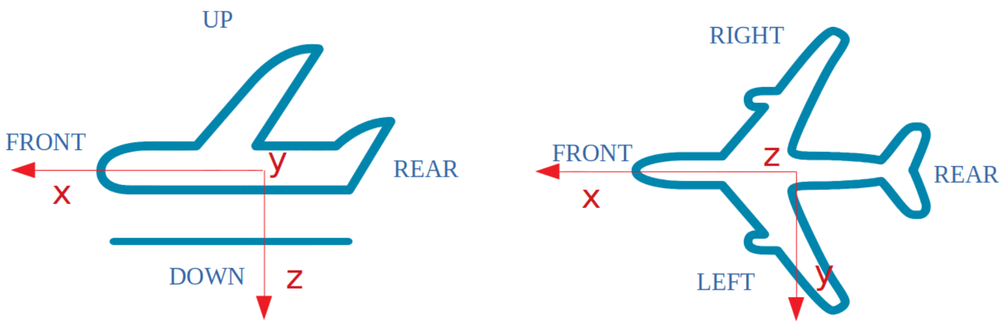

Figure 4 : UAV coordinate system

On the other hand, the ship coordinate representation system is illustrated in Figure 5.

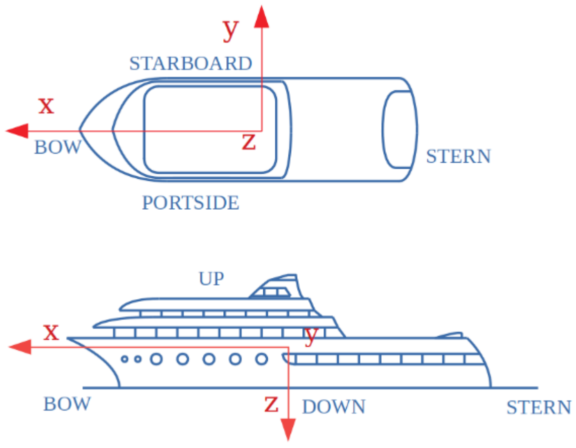

Figure 5: Ship coordinate representation in UAV system

When sharing information with the other parts of the PALAEMON system, this information has to be taken in account during the integration phase, so location information can be translated correctly between both systems.

4.2 Components

The UAV system is composed of three major components, whose connection with the PALAEMON platform is shown in Figure 6:

- **Air segment**: Part of the system that is flying, mainly the UAV.

- **Ground segment**: Part of the system that stays on ground, fixed or mobile. It includes the radio controller for manual control override, the ground control station and related logistic infrastructure.
- **Data link**: The data link ensures the transport of the communication data between the ground segment and the air segment. It is most often based on radio technology (e.g.: Wi-Fi module, Bluetooth or other point-to-point radio device)

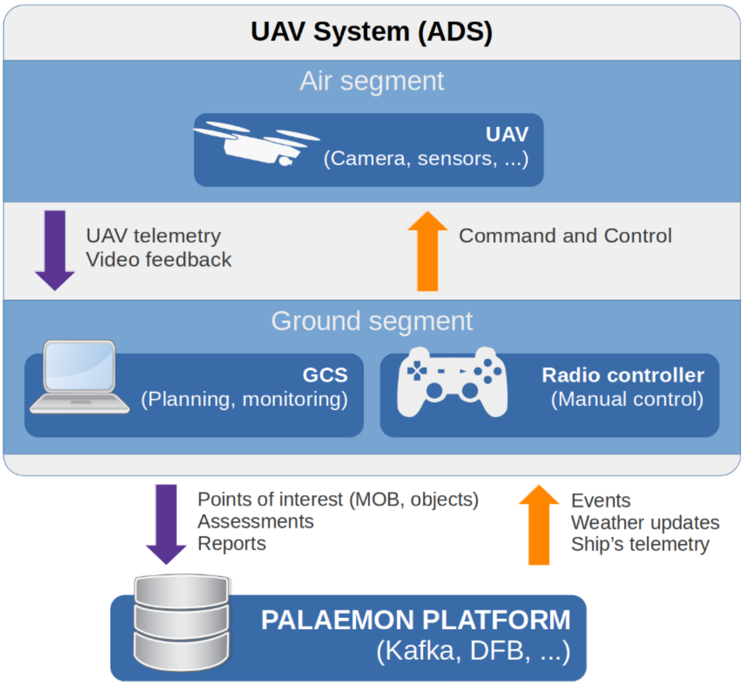

Figure 6: Basic UAV system representation

4.2.1 Ground segment

The ground segment is mainly responsible for controlling and monitoring the flight. It shall be used from one to two UAV operators/pilots:

- In automated missions via GCS mode, one flight operator plans and monitors the flight using the GCS. One safety operator uses the radio controller to ensure the safety of the flight and can take control of the flight at any time.
- In manual mode: One operator has the control of the UAV using the radio controller and fulfills the mission. An additional optional operator can however monitor the flight and push information to the PALAEMON system.

The GCS is responsible for producing data to be pushed to the PALAEMON system, as well as receiving information, alerts and notifications from the PALAEMON system. These data can be generated in GCS mode and manual mode.

4.2.1.1 Radio controller

The radio controller has absolute control over the UAV at any time and shall be turned on for the UAV to fly. It is used by a trained and qualified UAV operator considering difficulties that can be encountered in these operating environments.

The radio controller provides the following features, gathered in Table 1:

Table 1: Radio controller feature table

Feature ID	Feature	Related requirements	Related chapters
FT-RC-01	Manual control of the flight in GPS mode with the following minimum command set: up, down, front, back, left, right, take off, landing.	UAV-FR-08	4.4.4
FT-RC-02	Show the video feedback of the UAV embedded camera.	UAV-FR-06	4.4.1
FT-RC-03	Control over the UAV embedded camera orientation in the capability range of the UAV device.	UAV-FR-07	4.4.1 4.4.4
FT-RC-04	Show basic status of the UAV depending on available information: e.g. GPS global position, height from take-off point.	UAV-NFR-02	4.4.4

4.2.1.2 Ground Control Station

The ground control station (GCS) is conceived to plan and monitor flights. It is the way to create automated missions for its linked UAV. It contains the 3D environment of the ship showing the UAV location, points of interests, mission plan(s) and the camera footprint. It also handles communication with the PALAEMON system.

The GCS provide the features compiled in Table 2:

Table 2: Ground control station feature table

Feature ID	Feature	Related requirements	Related chapters
FT-GCS-01	Monitor the flight – Show the operator UAV position, attitude, battery level and flight time left	UAV-FR-04	4.3
FT-GCS-02	Show the 3D environment of the situation – Allows the operator to understand the situation faster	UAV-FR-04 UAV-NFR-06	4.3
FT-GCS-03	Mission planning tools – Provide tools for the operators to plan missions defined for PALAEMON	UAV-FR-01 UAV-FR-02 UAV-FR-	4.3.1 4.3.2

		05 UAV-NFR-01 UAV-NFR-03	
FT-GCS-04	Loading missions to the UAV – Missions are loaded into the UAVMS software of the air segment using the GCS	UAV-FR-01 UAV-FR-02	4.3.1 4.3.2
FT-GCS-05	Pin objects and create points of interest – The operator can pinpoint that enhance situation awareness and be used to report elements to the PALAEMON platform.	UAV-FR-01 UAV-FR-09	4.3
FT-GCS-06	Retrieving weather data and ship telemetry from the PALAEMON system – Gathers necessary information from the PALAEMON system for the UAS to operate.	UAV-NFR-02 UAV-NFR-05	0
FT-GCS-07	Display UAV video stream feedback – Show the video acquired from the UAV's camera on the GCS.	UAV-FR-04 UAV-FR-06 UAV-FR-09	4.4.1
FT-GCS-08	Video camera gimbal control – The operator can move the gimbal and look at areas of interest during the UAV flight	UAV-FR-07	4.4.1 4.2.1.2
FT-GCS-09	Shares information and events to the PALAEMON system – The operator can choose to create and send reports that can be sent to the PALAEMON system data bus.	UAV-NFR-05	5

4.2.2 Air segment

The first part of the air segment is the UAV. It embeds its own autopilot (hardware and software responsible for flight stability and commands execution) which receives orders from the radio controller and the UAV Mission Software (UAVMS). The autopilot uses GPS-based navigation, whose coordinates are acquired/approximated using its sensors (GPS, IMU …). The UAV also embeds a camera whose properties will be defined later in this document. This camera can be mounted on a gimbal to offer more degrees of freedom than the UAV's attitude.

The second part of the air segment to be introduced is the UAV Mission Software (UAVMS). It handles the mission execution phases that are out of the scope of the autopilot capabilities. Most autopilots, if not all, do not have the requirements to execute PALAEMON-specific missions. For this matter, UAVMS acts as a man-in-the-middle between the GCS and the UAV's autopilot. It follows the mission execution and translates the GCS missions' orders to commands understandable by the autopilot. It also provides the UAV with more advance flight capabilities and safety handling options.

Depending on the actual UAV used, the UAVMS host device can vary. It needs to communicate with the UAV autopilot Application Program Interface (API) to work, meaning the UAVMS is not necessarily embedded onboard the UAV, despite belonging to the air segment and being assimilated to the UAV component

The environment and use cases of the UAV in the context bring a consequent number of constraints on the UAV selection, especially on safety, agility of the vehicle.

The particularities of the scenarios that will be addressed in this project say that the most suitable selection would be to choose **rotary wings micro UAVs** (weight less than 2 kg) for the following reasons:

- overall manoeuvrability
- greater tolerance to impacts and less damaging power
- easier integration on different ships because of less constraints
- can launch from anywhere
- regulations more compliant over the world
- fast deployable, needs less logistics
- can be embedded inside MEVs
- easier to control using the RC
- lower costs than heavier UAVs.
- more units can be carried on the ship

On the other hand, this solution usually has the following drawbacks:

- overall less wind resistance
- lesser range of possibilities of embedded payloads
- less customization capabilities

The air segment provides features that are summarized in Table 3:

Table 3: Unmanned aerial vehicle feature table

Feature ID	Feature	Related functions	Related chapters
FT-UAV-01	Take-off and landing on and from the ship using a designated landing pad	UAV-FR-01 UAV-FR-05 UAV-NFR-01 UAV-NFR-03	4.3.1 4.4.3
FT-UAV-02	Replaceable, expendable air segment – the air segment can be replaced in the UAS if lost	UAV-NFR-04	0
FT-UAV-03	Mission execution – UAS missions specifically designed for the PALAEMON project.	UAV-FR-01 UAV-FR-05 UAV-NFR-01 UAV-NFR-03	4.3
FT-UAV-04	Flight safety measures – Safety measures that are defined in order to avoid the system to hurt individuals or damage the ship.	UAV-NFR-01 UAV-NFR-02 UAV-NFR-03	4.4.2
FT-UAV-05	Flight health monitoring – Use of available telemetry data to detect flight anomalies during flights.	UAV-NFR-02	0
FT-UAV-06	Relative flight to the ship – Flying around the ship and planning missions using the ship as the main reference.	UAV-FR-01 UAV-FR-03 UAV-NFR-03	4.3.1 4.4.2 4.4.3
FT-UAV-07	Launch from the MEVs – take-off from the MEV	UAV-NFR-04	4.3.2
FT-UAV-08	Can perform search and rescue flight patterns – Implementation of specific patterns used in search and rescue operations	UAV-FR-02	4.3.2.1
FT-UAV-09	Gather information from camera and embedded sensors – The UAV navigation is based on its embedded sensors (GPS, IMU, video, …)	UAV-FR-04 UAV-NFR-02	**¡Error! No se encuentra el origen de la referencia.** 4.3
FT-UAV-10	Sustain winds up to 5 meters per second – The UAV can fly in windy conditions up to its resistance limit.	UAV-NFR-07	0 4.4.2

4.2.3 Data link

Radio access technologies ensure the reliable transport of information between the air and the ground segments. It should be able to cover the flight range required for PALAEMON's missions execution. The data link range fixes the maximum distance at which the UAS can operate.

This distance, to be permissive enough for the PALAEMON project, should take in account multiple ranges:

- **Ship length**: Longest ships are around 500 meters.
- **Safe flight distance**: 300 meters is enough to cover most of safe distances.
- **Safe navigation path size**: Considering the vehicle, positioning accuracy, wind and ship movements 100 meters of segregated area is enough to keep the UAV in its operation path.

Once added, these values result in a minimum data link range of 900 meters. Ranges above this value can be used to extend the operation range of the UAS. For example, such a distance is achievable using 2mW 2.4GHz radio links.

4.3 Missions

The UAV system for PALAEMON includes specific missions for PALAEMON purposes. They are split into two phases:

- **From ship missions**: This category contains missions that are executed from the ship. They require the ship's PALAEMON system to be online and accessible as they need to access specific data like the ship's telemetry to run. In these missions, the UAV uses the ship as a reference and execute its flight relatively to it.
- **From MEV missions**: Contains missions in which the UAV is operated from the MEV. They are limited in generally more limited in functionalities due to the absence of communication with the PALAEMON system. Automated missions are GPS based only and UAV recovery possibilities are limited.

Both phases allow the operator to pinpoint areas of interest by using the camera feedback displayed on the GCS. The GCS approximates these points' locations to GPS and/or XYZ coordinates using the UAV and camera telemetry. The type of coordinates produced depends on the available telemetry and can be reported to the PALAEMON system.

The GCS adapts to each phase to provide a visual feedback of the current situation including the current mission status, the UAV location and camera footprint.

The operator is allowed to switch between missions from the same execution mode. The UAV then finds paths to transition safely between missions.

4.3.1 From ship mission mode

In this execution mode, missions and orders are executed relatively from the position of the ship. Missions use predefined flight path to navigate around the ship in order to guarantee maximum safety for passengers. Automatic take-off and landing on the ship's landing pad are enabled when the environment allows it.

Points of interest that are created in this execution mode use relative location coordinates from the ship.

Communication with the PALAEMON system must be established and ship's telemetry available to run missions in this mode. Before the UAV launches, an UAV system status event is sent to the PALAEMON system announcing the UAV is about to take off and that the system therefore needs ship's telemetry to be sent. Analogically, another event is sent as the UAV terminates its mission.

4.3.1.1 Hull and close water observation

This mission involves inspecting elements that are visible in a close area around the ship. The UAV navigates around the ship using predefined safe paths and send video feedback of areas of interest.

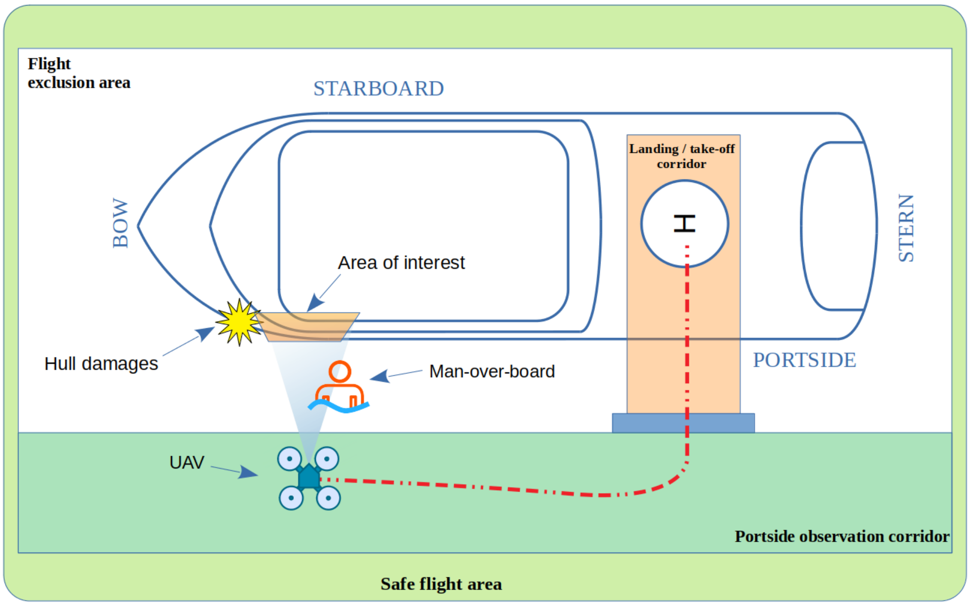

Figure 7: Near hull area inspection

The GCS operator selects an area of the hull to be observed and start the mission. As we observe in Figure 7, the UAV takes off and makes its way to its closest observation spots by following flight paths. The UAV adjusts its gimbal camera to point at the area so the video feedback of the requested location can be observed by the operator. The GCS operator can switch inspection area on-the-fly during the mission, the UAV then adjusts its position to match operator's new orders.

4.3.1.2 Relative observation point

This mission type allows the operator to position the UAV at a relative position to the ship. Positions implying flying over the ship are not allowed for safety reasons. Once the UAV is positioned, the operator can then use the UAV as an observation point by piloting the UAV's gimbal camera from the GCS. This observation mode is not limited to ship's areas allows to fly further from the ship while staying stationary in the ship's reference, as illustrated in Figure 8.

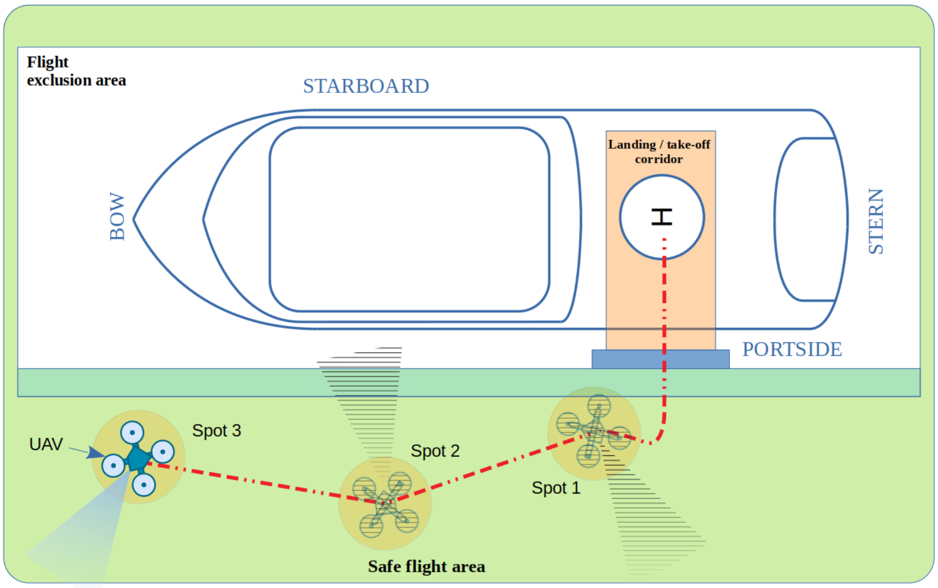

Figure 8: Relative observation point

The UAV can be re-positioned by selecting a new observation point while the mission is active.

4.3.2 From MEV mission mode

This execution mode is designed to be executed from the MEV. It uses GPS-based navigation and commands. It can run disconnected from the PALAEMON system, without ship's telemetry and weather information. It does not include automated landing phases.

Points of interests created in this execution mode are located using their GPS coordinates.

4.3.2.1 Search and rescue

This mission helps the operator creating search patterns in a selected area. The operator defines a scan area in which he/she desires the UAV to perform the search. The GCS then creates a flight plan, so the embedded camera efficiently covers the integrity of the designated area (Figure 9). The take-off phase can be executed either automatically or manually by an operator depending on the environment.

The search area is defined by a GPS coordinate point, a width, a depth and an orientation.

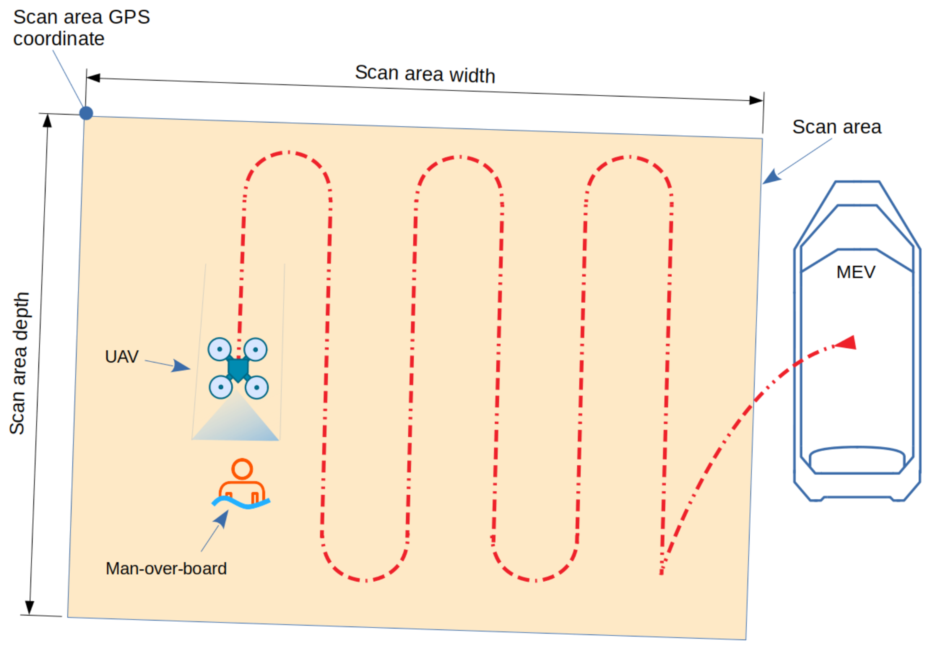

Figure 9: Search and rescue mission

4.3.2.2 Absolute point observation

This mission works the same way than the "Relative observation point" mission, except it is detached from the ship's reference coordinates. The GCS operator designates a GPS spot on the map for the UAV to reach, as displayed in Figure 10. Take-off phase can automatic or manual. The operator is granted full gimbal camera control during the flight.

The operator can modify the spot location on the same mission.

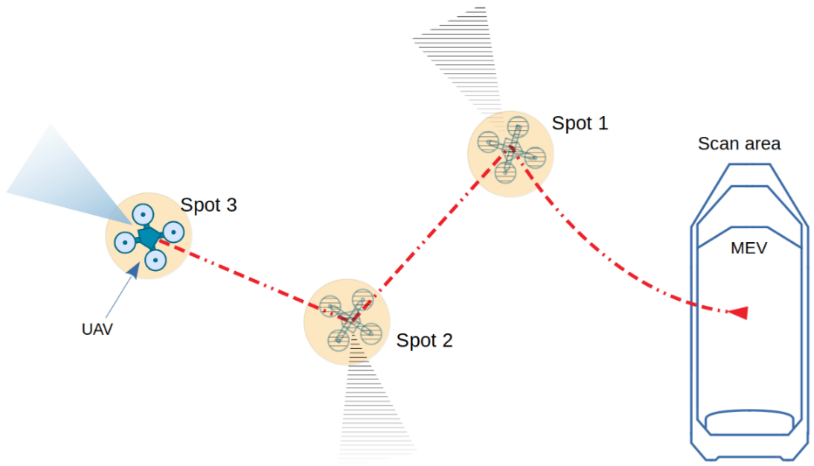

Figure 10: Absolute observation spot mission

4.4 Design details

In order to meet the requirements defined in Section **¡Error! No se encuentra el origen de l a referencia.**, the UAV system implements a set a behaviors that are active depending on the current execution mode as well as component performances.

4.4.1 Camera device

The UAV is equipped with a camera device able to cover the 3D space below the UAV with two degrees of freedom (horizontal and vertical axis) in order to be able to execute PALAEMON missions.

To guarantee this level of visibility coverage, the camera may need to be mounted on a gimbal device or similar that provides one or multiple degrees of freedom. Since horizontal axis rotations of the camera can be achieved by manipulating the rotary wings UAV's yaw during the flight, the gimbal needs to provide at least the vertical axis also Y axis from at least 0 to 180 degrees (i.e., ahead to below the UAV).

Used with a rotary-wings UAV, the fixed camera (aligned with the vehicle heading or not) view can be oriented by manipulating the vehicle yaw.

One of the camera's main purposes is to locate individuals overboard for rescue missions. This requirement is used to define minimum necessary performances specifications for the camera.

Trigonometry can be used to approximate the coverage distance size on one dimension of the camera this way:

$$coverage = tan\left(\frac{fov}{2}\right) \times distance \times 2$$

Where:

- *fov* is the camera field of view angle
- *distance* is distance between the camera and target

from there, the distance covered per pixel is

$surface_{pixel} = \frac{coverage}{pixel_{count}}$ with $pixel_{count}$ the number of pixels in this dimension

Then the total number of pixels in a dimension that feature the object or individual is

$pixels_{object} = \frac{object_{\text{size}}}{surface_{pixel}}$ with $object_{size}$ the size in meters of the object or individual to observe.

These calculations are accurate for the centre-line of the camera; however results can slightly vary for other points closer the edge of the image.

Using (Sampling Theorem (Nyquist/Shannon)), an object should match the size of at least 2 pixels to be visible every time for single-pixel detection; but for convenient detection, a minimum of a 5-pixel representation for EO is preferred. Also, IR/thermal cameras enhance individual detection capabilities of operators in MOB scenarios, allowing individuals to be visible on 2 pixels, as individuals generally have different body temperature than the water. (at least for a short period of time).

Table 4 contains information data for different observation distance on an object by the UAV in one of the worst case scenarios. The table is given for $pixel_{count}$ = 720, fov = 60°, $object_{size}$ = 0.4m and variable camera distance from the object.

Table 4: Pixels per object depending on the camera distance

Camera distance (meters)	Total distance coverage of the camera (meters)	Distance covered by a single pixel (meters)	Pixels per object	Percentage of the image representing the object (%)
1	1.15	0.0016	249.4	34.64
3	3.46	0.0048	83.1	11.55
5	5.77	0.0080	49.9	6.93
10	11.5	0.016	24.9	3.46
15	17.3	0.024	16.6	2.31
20	23.0	0.032	12.5	1.73
30	34.6	0.048	8.3	1.15
50	57.8	0.11	3.6	0.49
70	115.5	0.16	2.5	0.35
100	159.1	0.12	3.2	0.25

4.4.2 Flight path constraints

The usage of predefined flight paths (see Figure 11) is preferred for safety reasons: it drastically reduces the risks for collision avoidance between the UAV and the ship or passengers. It aims to define a segregated flight path for the UAV at a safe distance from the ship to avoid fall damages in case of a UAV failure.

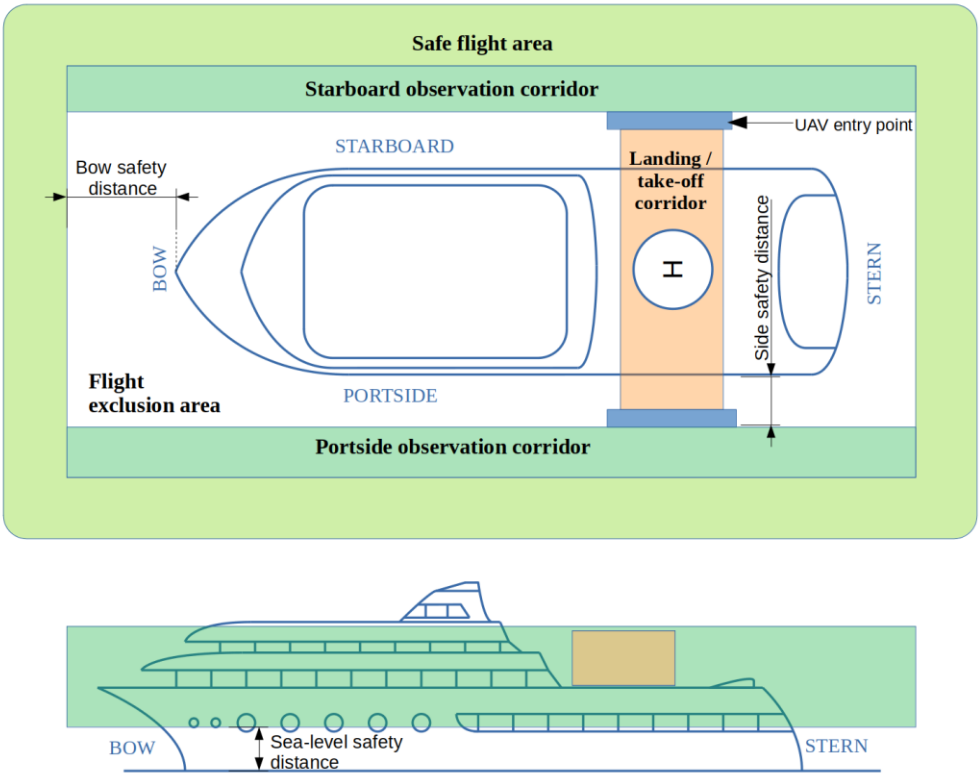

Figure 11: Safety paths representation example

To implement these paths properly, safety distance needs to be determined in order to guarantee the safety of the passengers during UAV flights. Although there is no adopted international regulation or rule on this kind of measures, French regulation provides mathematic formulas that can be used to estimate safety distances and have an idea of the measures to take.

The safety distance (sample illustration in Figure 12) is defined by the combination of travelled distance during operator's reaction time and the distance obtained from the ballistic trajectory calculation as defined by french regulation on UAVs in "Paragraph 3.7.5 of the December 17, 2015 Order on the design of civilian aircraft operating without a person on board, the conditions of their employment and the required capabilities of the persons who use them)". (cf. (Paragraphe 3.7.5 de l'Arrêté du 17 décembre 2015 relatif à la conception des aéronefs civils qui circulent sans personne à bord, aux conditions de leur emploi et aux capacités requises des personnes qui les utilisent))

The safety distance between UAV and passengers is described as such:$D_{safety} = D_{reaction} + D_{ballistic}$

$D_{reaction} = speed_{UAV} \times T_{reaction}$ where reaction time $T_{reaction} = 3seconds$

$$D_{ballistic} = speed \times \sqrt{\frac{2 \times height_{UAV}}{g}}$$

with gravity constant
$g = 9.81m \cdot s^{-1}$

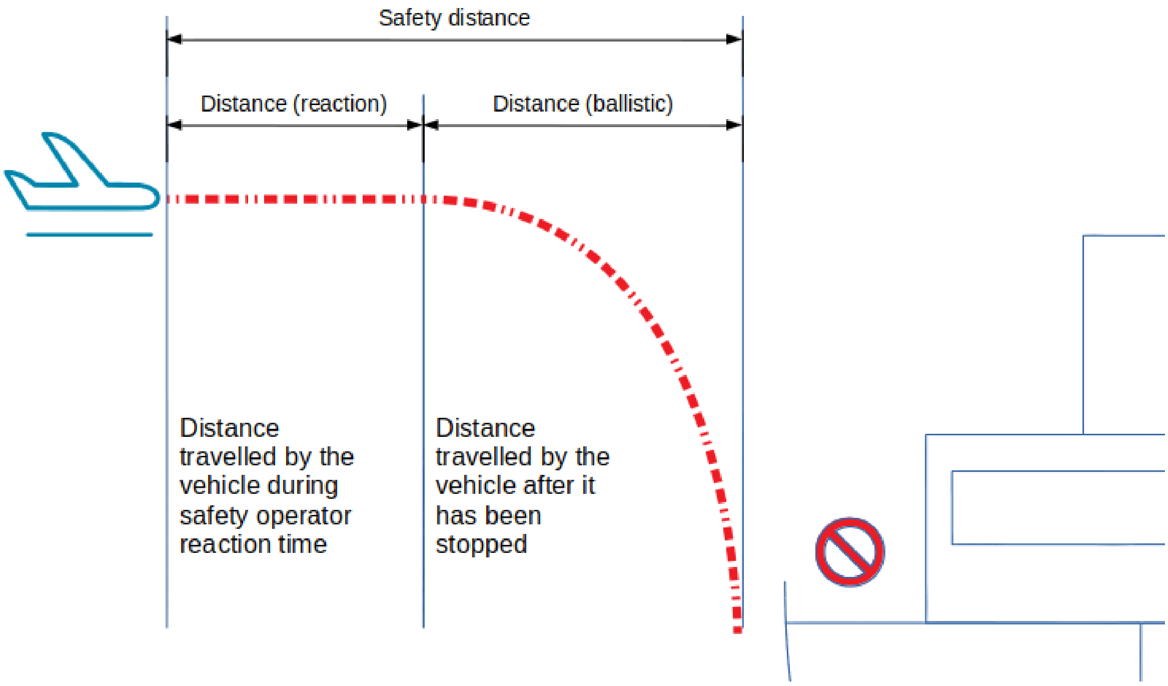

Figure 12: Visualization of safety distances

The speed variable in the previous formulas is described as the addition of UAV ground speed and maximum wind speed. However, since the UAV is navigating around a ship with the passengers on it, we consider the ship's lower floor as the ground, meaning the speed variable is defined by the speed difference between the UAV and the ship, plus the potential wind speed.

This gives the following formula for UAV speed calculation for the worst-case scenario:

$$speed_{UAV} = maxspeed_{UAV} + maxspeed_{ship} + maxspeed_{wind}$$

Maximum wind speed is defined by the maximum wind speed supported by the rotary-wings UAV (usually between 10 and 15 m/s).

In order to improve video observation capabilities, flight paths should be as close as possible to the ship. Considering the previous formulae, it is clear that the maximum ship's speed has a greater impact on the overall safe navigation distance. Since this ship speed is mostly effective as the ship goes forward or backward, it is acceptable to consider ship speed null when the UAV is flying on the left or right side of the ship.

The UAV maximum speed depends on the UAV device (usually between 15 to 25 m/s).

Height is defined as height above the ship's floor; this can vary depending on ships, UAVs and missions.

On top of the previous safety distance calculations, standard GPS technologies inaccuracy (usually around 10 meters) can be taken in consideration and added to the final result.

Table 5 shows D_{safety} and $D_{ballistic}$ values for different values of height and UAV speed profiles using parameters $maxspeed_{wind} = 15$

Table 5: Examples of safety distance depending on UAV speed and flight height

Height (meters) ↓	Safety distance D_{safety} (meters)				Ballistic distance $D_{ballistic}$ (meters)			
Maxspeed$_{UAV}$ *(m.s*$^{-1}$*)* →	1	5	10	20	1	5	10	20
10	71	89	49	155	23	29	16	50
20	80	100	55	176	32	40	22	71
30	88	109	60	192	40	43	27	87
50	99	124	68	217	51	64	35	112
70	108	136	75	237	60	76	42	132
100	120	150	83	263	72	90	50	158

Since there are no strictly determined rules about safety in this kind of environment and especially specific PALAEMON scenarios, these formulas and values are shown for informational purposes. Safety measures need to be adjusted for each new integration.

Since the system is designed to be as generic as possible to be adapted and installed on various ship constructs, every custom parameter, as ship shape, UAV device and missions should be taken into consideration to ensure optimal safety and efficiency of the system.

4.4.3 Automatic landing and take-off

Automatic missions contain the full flight including take-off and landing phases. These are critical phases for the UAV for multiple reasons:

- The UAV is in physical contact with this ship
- Collisions risks are higher as the UAV flies close to the ships

These phases need high-precision manoeuvres to succeed and the system could refuse to perform one or the other in unfriendly environments, forcing the operator to land or take off manually using the RC.

To ensure flight control precision, the system requires fixed reference(s) “objects”, whose positions are known and can be detected and precisely located relatively to the UAV. These landmarks can be implemented in many ways from physical objects or marker recognition, to position triangulation radio signals.

To this end, the UAV system for PALAEMON project uses ArUco markers (AruCo Markers)

As stated by the official ArUco documentation (cf. (AruCo Markers)),

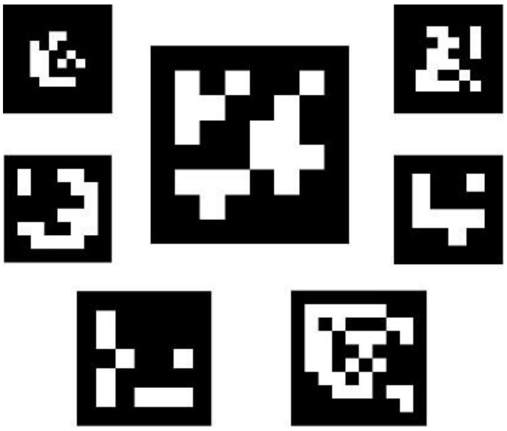

Figure 13: ArUco marker samples

Deploying this kind of marker on the landing pad as localization solution provides the following advantages:

- Only requires a camera to be recognized (i.e., PALAEMON UAVs are prepared for that).
- Compared to radio-based solutions, there is no need to embed a specific device on the UAV, which is impossible on some UAVs (e.g., small-sized UAVs, integration capabilities limitations ...).
- Knowing the marker size, both relative position and relative attitude to the camera can be calculated.
- Adaptable, easily deployable on any ship, movable (comes as the landing pad).
- Scalable: multiple markers can be placed for different purposes or multiple UAVs on the same ship.
- Contains large patterns easily recognizable compared to other marker solutions

On the other hand, this solution brings some constraints as well:

- Should be illuminated at night, or in poor visibility situations.
- Should be visible from high ground, implying the size of the marker needs to be consequent enough to be recognized by the algorithm.

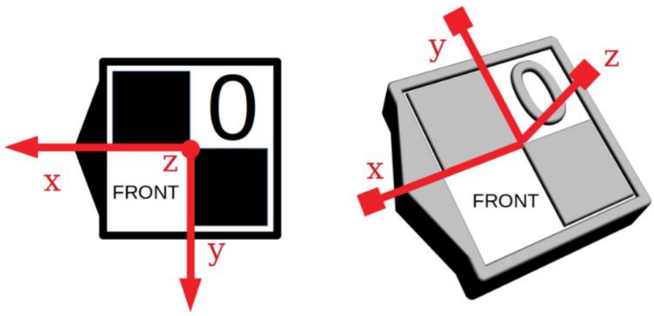

Figure 14: ArUco marker coordinate system representation for the document

(Note that XYZ axis match official ArUco documentation)

OpenCV library provides multiple dictionaries of ArUco markers to be used. The UAV system uses dictionary 0 / DICT_4x4_50 (4 x 4 bits, 50 elements).

Within the 50 existing markers in the library the twenty firsts are reserved for the PALAEMON project generic specification, whereas the last 30 are open for custom implementations. Among the PALAEMON specific, only a few markers implementations are mandatory, others are optional. Optional markers exist so the system can be adapted to ships of different size and generally aim to provide basic guidance for the UAV. For the sake of illustration,

Table 6 presents some ArUco markers that will be used in the scope of the project.

Table 6: ArUco markers signification for UAV system in PALAEMON project

Marker ID	Description	Mandatory status
0	Indicates the landing pad position. The centre of the marker is the centre of the landing pad. This marker should be exploitable by the UAV from at least two to seven meters away from it.	Mandatory
1	Indicates the presence of the landing pad near this marker. This marker is usually larger than the landing pad marker and indicates to the UAV that it should lower above this marker its height until it sees the landing pad marker. This marker is usually visible from a higher ground than the landing pad marker. The landing pad marker can be printed inside this marker.	Optional
2	Usually placed on the starboard side of the ship, this marker indicates that the landing pad is located to its left. It is recommended that UAV aligns with the marker’s vertical centre-line before moving towards left.	Optional
3	Usually placed on the port side of the ship, this marker indicates that the landing pad is located to its right. It is recommended that UAV aligns with the marker’s vertical centre-line before moving towards right.	Optional
4	Indicates to the UAV that the landing pad is more to the rear of the ship. It is recommended that UAV aligns with the marker’s horizontal centre-line before moving towards ship’s rear.	Optional
5	Indicates to the UAV that the landing pad is more to the front of the ship. It is recommended that UAV aligns with the marker’s horizontal center-line before moving towards ship’s front.	Optional
6	When seen by the UAV, forces the system to cancel the landing.	Optional
7-19	<Reserved>	

To complement the previous table, Figure 15 presents an example of multiple ArUco markers positioned on a ship to help the UAV to locating itself around (relatively to) the vessel.

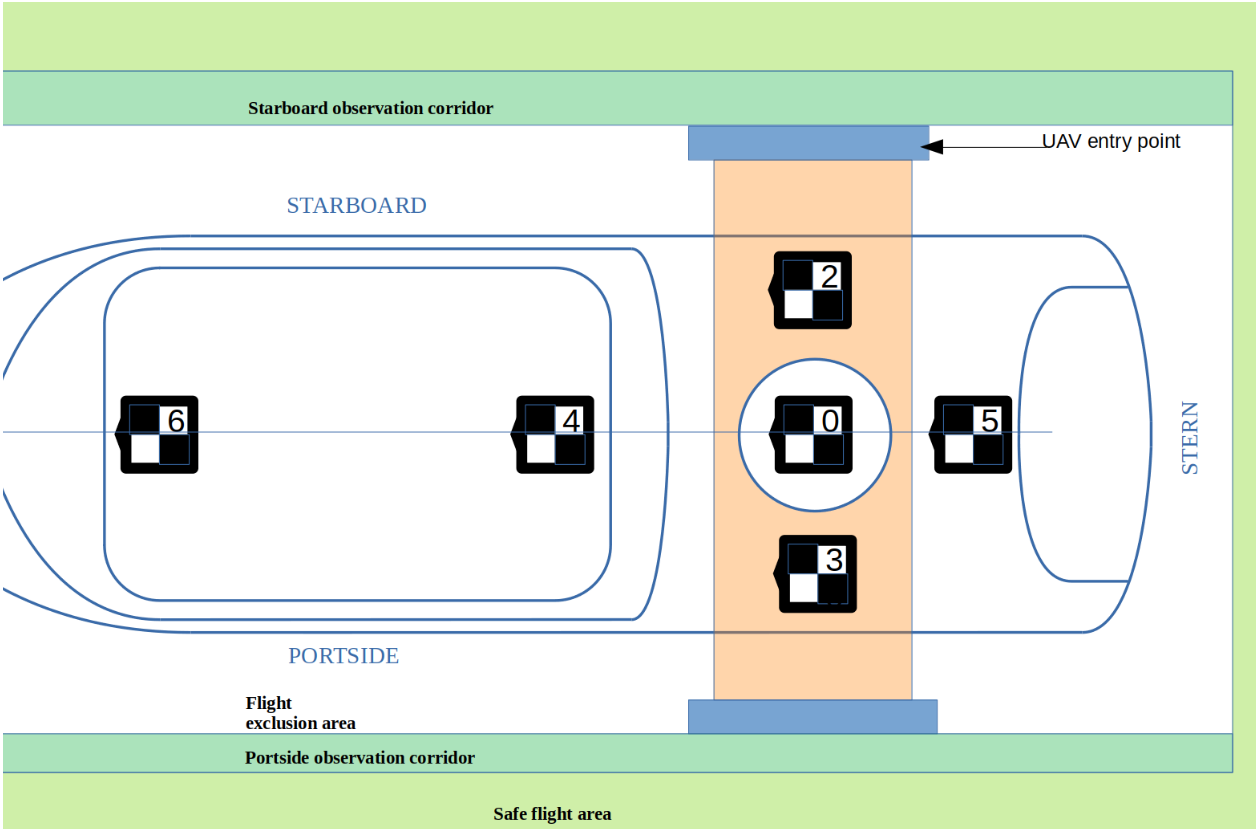

Figure 15: Example of ArUco markers placement on a ship

Most of the time, guiding the UAV to the approximate location of the landing pad should be necessary to initiate the landing phase.

Landing phase steps:

1. The UAV is flying and located outside the ship perimeter. The return to ship order is triggered on mission termination or GCS operator's command.
2. The UAV navigates around the ship to join one entry points.
3. The UAV adjusts its altitude/height to match the configured height for entering the ship perimeter.
4. The UAV slows down and joins the landing pad approximate position using relative GPS guidance or marker indications.
5. The UAV lowers its height until it locates the landing pad marker on camera. During this step, not detecting the marker soon enough would abort the landing and demand that the operator executes a manual landing.
6. The UAV uses the landing pad marker to adjust its position while landing, aiming for the marker's centre.

Take-off phase steps are mostly landing phase steps reversed.

4.4.4 Radio controller operation

The UAV can be manually piloted using the radio controller. Multiple flight modes are be available depending on the UAV device. However, the device must provide a minimal set of functions:

- The RC operator should be able to perform UAV take-offs and landing using only the controller.
- GPS flight mode: The UAV mainly uses GPS to maintain its position horizontally and vertically. This allows the UAV to stay stationary in the world coordinates system, however it might drift from the ship's position as the ship moves. Operator's throttle, pitch and roll commands control the UAV GPS position.
- The RC operator should be able to modify the UAV's yaw in-flight.
- The RC operator should have control over the camera's gimbal position.

During the RC operator overrides automatic collision avoidance features and ensures the safety of the flight.

5 System

5.1 Integration

5.1.1 Connectivity

All parts of the system should be able to communicate to each other to guarantee the correct operation during the missions.

As shown in Figure 16, in the UAV system, the GCS is the bridge to the PALAEMON core (as a matter of fact, the main elements/communication interfaces that will interplay with the UAV system will be based on Apache Kafka and Data Fusion Bus)1. The GCS uses IPv4 links to communicate with both the UAVMS and PALAEMON system, however these should be placed on different networks in order for them work separately, or said otherwise, the GCS and UAVMS have their own independent network (i.e., security issues).

The UAV and the RC are connected via proprietary radio links.

1 Should the reader wants a deeper information about these elements, we recommend taking a look at PALAEMON's deliverable D2.6 "PALAEMON Architecture v1" (D2.6 PALAEMON Architecture V1)

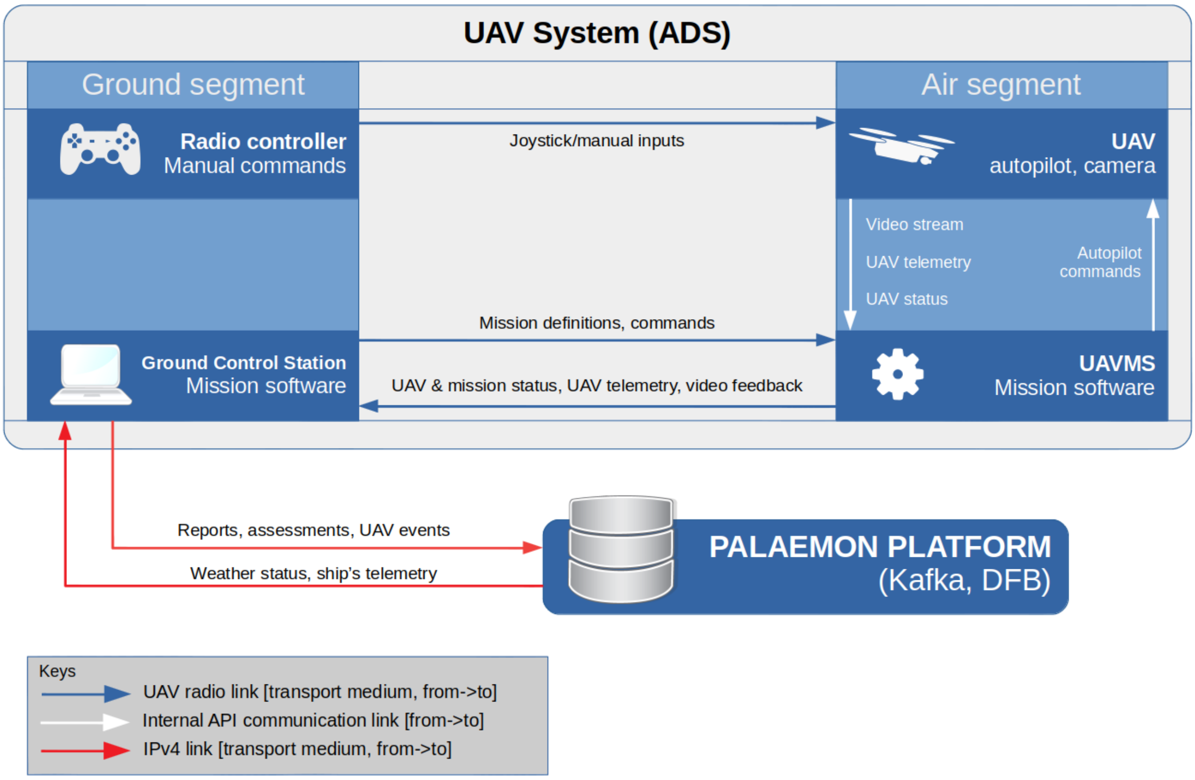

Figure 16: UAS-PALAEMON Platform interaction

5.1.2 Data exchanges

The data exchanges content between the GCS and the PALAEMON system are detailed in the following subsections. Some of this information and data providers might still need to be defined.

5.1.2.1 Events

Events are used to synchronize components of the PALAEMON system and limit data exchanges between parties when they are not needed to save resources. They are fired spontaneously and are not bound to frequencies.

Table 7: Event messages

Name	Description	Unit
UAV system status	Tells the current status of the UAV system, in particular when the system starts and stops flying. Sent by the GCS	Enumeration

5.1.2.2 Weather information

Table 8: Weather information data

Name	Description	Unit	Frequency

Wind speed	The current wind speed around the ship. It allows the UAV system to determine if environmental conditions to fly are met. Read from the PALAEMON system.	m/s	0.2 Hz When the UAV system is in use.

5.1.2.3 Ship's telemetry

Table 9: Ship telemetry data

Name	Description	Unit	Frequency
Ship's longitude	Current GPS coordinate of the ship	Radians	2 Hz When the UAV system is in use.
Ship's latitude	Current GPS coordinate of the ship	Radians	
Ship's altitude	Current GPS coordinate of the ship	Meters	
Ship's pitch	Current attitude of the ship	Radians	
Ship's roll	Current attitude of the ship	Radians	
Ship's yaw	Current attitude of the ship	Radians	

5.1.2.4 Object reports

Based on observations made with the UAV, the GCS can report information on objects and assessment made by the operator to the PALAEMON GCS.

Table 10: Object reporting data

Name	Description	Unit
Classification	The type of object to be reported (e.g. MOB, hull damage, Dangerous object)	Enumeration
X	Position from the centre of the ship at the moment of observation.	Meters
Y	Position from the centre of the ship at the moment of observation.	Meters
Z	Position from the centre of the ship at the moment of observation.	Meters
Latitude	GPS coordination of the object at the moment of observation.	Radians
Longitude	GPS coordination of the object at the moment of observation.	Radians
Altitude	GPS coordination of the object at the moment of observation.	Meters

Critical status	Depending on the nature of event, defines the critical aspect of the object. (e.g. critical level of a hull damage : Low, medium, high)	Enumeration
Description	Optional text for complementary information on the object to be reported.	Text

6 Conclusions

The elaboration of an unmanned aerial system answering requirements for PALAEMON use cases is achievable with compromises. In order to guarantee the safety of the crew, specific choices of components have to be made that may lower the capabilities of the system.

The possibilities are also limited by the current state of UAV technology. Battery capacity and weight, reliability of positioning system are limiting factors in most UAV operations, and even more in this kind of environment as high availability of the system is primordial since time of emergency in unpredictable.

However, automation and autonomy of drone systems is a major development point that can make UAVs fitting these use cases better. It eases operators work in stressful situations, and can highly compensate other drawbacks by enhancing safety, reliability of execution and provide missions sets; given the host infrastructure answers constraints and requirements.

7 References

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Annex I

Requirement association matrix

This table links requirements to features defined in the solution elicitation.

Table 11: Requirement association matrix

Requirements	Associated features
UAV-FR-01	FT-GCS-03 FT-GCS-04 FT-GCS-05 FT-UAV-01 FT-UAV-03 FT-UAV-06
UAV-FR-02	FT-GCS-03 FT-GCS-04 FT-UAV-08
UAV-FR-03	FT-UAV-06
UAV-FR-04	FT-GCS-01 FT-GCS-02 FT-GCS-07 FT-UAV-09
UAV-FR-05	FT-GCS-03 FT-UAV-01 FT-UAV-03
UAV-FR-06	FT-RC-02 FT-GCS-07
UAV-FR-07	FT-RC-03 FT-GCS-08
UAV-FR-08	FT-RC-01
UAV-FR-09	FT-GCS-05 FT-GCS-07
UAV-NFR-01	FT-GCS-03 FT-UAV-01 FT-UAV-03 FT-UAV-04
UAV-NFR-02	FT-RC-04 FT-GCS-06 FT-UAV-04 FT-UAV-05 FT-UAV-09
UAV-NFR-03	FT-GCS-03 FT-UAV-03 FT-UAV-04 FT-UAV-06
UAV-NFR-04	FT-UAV-02 FT-UAV-07
UAV-NFR-05	FT-GCS-06 FT-GCS-09
UAV-NFR-06	FT-GCS-02
UAV-NFR-07	FT-UAV-10

Constraints and risks references

Table 12: Constraints and risks references

Constraint / Risk	Reference
UAV-CON-01	4.3.1 4.4.2 4.4.3
UAV-CON-02	4.3.2 0
UAV-RI-01	/
UAV-RI-02	4.3
UAV-RI-03	/
UAV-RI-04	4.4.2 4.4.3
UAV-RI-05	0 4.4.2