DESIGN OF A MULTI-VEHICLE MANAGEMENT SYSTEM (MVMS)

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ABSTRACT

This paper introduces the innovative prototype of a general-purpose Multi-Vehicle Management System (MVMS) that allows the operator to handle the whole process of UAVs fleet management: plan, supervise and control, by means of an intuitive XR immersive environment. The system has been designed around a modular and scalable backbone, being able to repliacte the most suitable architecture for the specific use case, from the simple centralized architecture to the more sophisticated cluster-of-clusters one and the 4G/5G web-based remote fleet control. The immersive VR environment allows the operator to handle the whole mission by interacting directly with the fleet and this represents a good step forward in operator's situational awareness. The system features also a simulation environment for test and training purposes and through which the prototype has been validated in its various features, such as mission planning, automatic geofence control, collision-risk prediction etc. The results show that this technological solution allows mission management with reduced workload in the most diverse use cases, from military, to civil applications, while ensuring at the same time alignment with future developments in UAV regulations, such as U-Space.

NOTATION

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Acronyms

AMC Acceptable Means of Compliance

API Application Programming Interface

AR Augmented Reality

ARC Air Risk Class

BVLOS Beyond Visual Line Of Sight

CAS Crew Alert System

ConOps Concept of Operations

EASA European Union Aviation Safety Agency

ETA Estimated Time of Arrival

GCS Ground Control Station

GPS Global Positioning System

GRC Ground Risk Class

HOTAS Hands-On Throttle-And-Stick

LUC Light UAS operator Certificate

MAVLink Micro Air Vehicle Link

MVMS Multi-Vehicle Management System

OSO Operational Safety Objectives

PDRA Pre-Defined Risk Assessment

PFD Primary Flight Display

RTH Return-to-Home

SAIL Specific Assurance and Integrity Level

SAR Search And Rescue

SORA Specific Operation Risk Assessment

STS STandard Scenario

TMPR Tactical Mitigation Performance Required

UAS Unmanned Aerial Systems

UAV Unmanned Aerial Vehicle

VLOS Visual Line Of Sight

VR Virtual Reality

XR EXtended Reality

INTRODUCTION

Technological progress has promoted the rapid and widespread deployment of drones for a wide variety of applications. The future foresees a massive use of UAVs, which will populate the skies alongside manned aircraft. Thus, the natural evolution lies in the simultaneous and coordinated use of multiple UAVs. Managing fleets of drones rather than individual ones presents several challenges, especially when operated in shared airspace. This paper presents a prototype developed by TXT e-Tech of an innovative fleet management system that aims to address these challenges.

STATE OF THE ART

A Multi-Vehicle Management System (MVMS) is a system composed of a Ground Station and a set of autonomous Unmanned Aerial Vehicles (UAV) that coordinate together to achieve a common goal.

Multi-drones typical use cases

The success of these systems is due to the following key aspects, which characterize the use of drones:

1) Drones are small, lightweight, easy to use and inexpensive.

Therefore, their use compared to, for example, a helicopter is preferred in countless use cases since the cost (including maintenance), simplicity, and therefore readiness for use are drastically reduced. Since they are cheap and simple, they can be used in large numbers and quickly, and this allows one to minimize the time to complete a mission, which is crucial, for example, in time-critical missions, such as locating a fugitive or a missing person for Search And Rescue (SAR) missions, in addition to the fact that it is possible to cover more easily areas that would otherwise be difficult to reach. Their simplicity and low cost make them particularly suitable for inspection and surveillance missions, for example of critical infrastructures, such as bridges, pipelines but also for large public events and these characteristics also make them suitable for all those missions that involve high-resolution aerial scanning or mapping of large territories. Finally, drones are making significant strides in the field of autonomous air transport (Ref. 1). Well-known companies have already experimented coordinated fleets to optimize the delivery of goods in both urban and rural areas.

2) Drones, by definition, do not require the presence of a human on board.

Therefore UAVs are ideal for all those scenarios that can be dangerous to humans lives, such as natural disasters like earthquakes, floods or fires where, depending on the equipment, drones can be used for rescue, research and, in some cases, even direct intervention. In these cases, drones can also help manned rescue vehicles find the optimal and safest route (Ref. 2). Finally, the absence of human personnel makes drones particularly suitable, for obvious reasons, also for military applications.

Typical technological solutions for MVMS

This section reviews the fundamental technological aspects that characterize these systems.

Types of architectures: The starting point is the definition of the fundamental architecture of the MVMS, i.e. the relationship between the Ground Control Stations (GCS) and the vehicles. The various typical alternatives are summarized below (Ref. 3):

- **Centralized architecture:**
  In the centralized architecture, a single central node (the Ground Station) is responsible for the overall coordination and control of the fleet. The advantage of this solution is simplicity hence effectiveness for small fleets, as it allows for optimized global decision-making. However, the centralization of functions in the GCS carries several limitations: the significant computational load involves high requirements in terms of computing power, especially when managing complex missions or large amounts of information. Another critical aspect concerns the stability and reliability, since this architecture exposes the system to a single point of failure: a malfunction or an attack on the central node can compromise the entire operation. Finally, scalability is limited, since as the number of UAVs increases, the central node can become a bottleneck (see Figure 1-a).

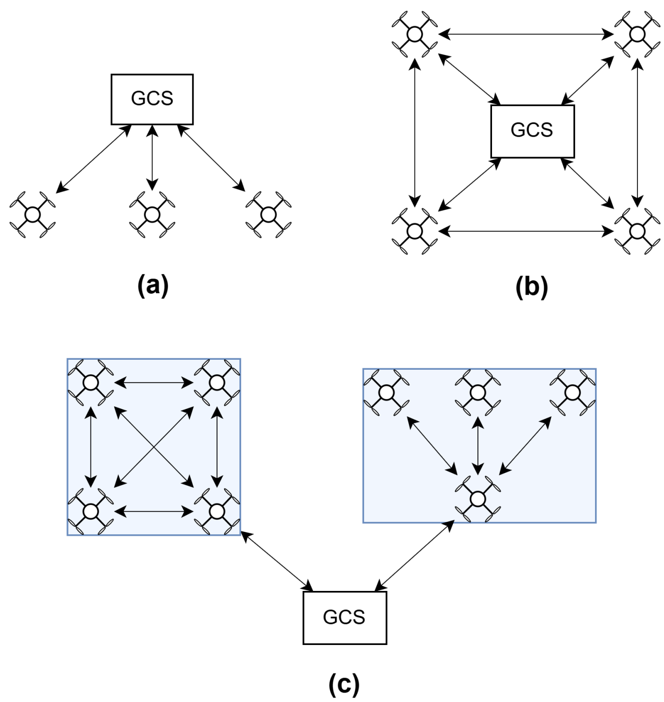

Figure 1. Representation of different MVMS architectures: (a) Centralized; (b) Distributed; (c) Hybrid.

- **Distributed architecture:**
  In the distributed architecture, each UAV acts au-

tonomously and is considered an equal entity within the system. Coordination between drones occurs through the exchange of mutual information, without depending on a central node. In contrast to the centralized architecture, this approach improves the flexibility, scalability and tolerance to failures of the system, making it more suitable for large-scale operations. However, it requires constant communication between drones and greater complexity in coordination mechanisms (see Figure 1-b).

- **Hybrid architecture:**
  A hybrid architecture combines elements of both centralized and distributed architectures, leveraging their respective advantages while mitigating their weaknesses. There are differnet ways to combine the two architectures like for example: a centralized architecture of clusters, that applies centralized control within individual clusters of UAVs, or a cluster of centralized architectures, that applies distributed methods for coordination between individual centralized sets of UAVs, or a combination of them. (see Figure 1-c).

MVMS Communications: Parallel to types of architectures, the communications between the various entities of the MVMS can be of various types (Ref. 4):

- **Vehicle-to-Ground (V2G):**
  Bidirectional communication between UAVs and the GCS, typical of centralized architecture. Allows for the continuous exchange of telemetry and flight instructions.
- **Vehicle-to-Vehicle (V2V):**
  Direct communication between drones, typical of distributed architecture. Useful for swarm operations, collision avoidance and extending the operational range beyond the direct range of the GCS.
- **Vehicle-to-Infrastructure (V2I) and Ground-to-Infrastructure (G2I):**
  Connects vehicles and GCS through external infrastructures like for example cellular networks (e.g. 4G/5G) (Ref. 5). This allows Beyond Visual Line Of Sight (BVLOS) operations, easier integration with air traffic management systems with services like weather, airspace traffic etc. Supports remote operations.

Depending on the use case, there can be also:

- **Sensor-to-Vehicle (S2V):**
  Allows drones to collect data from ground sensors, useful in contexts such as environmental monitoring, precision agriculture and also emergency management.

Levels of autonomy: A central aspect that characterizes the different multi-drone management systems concerns the different levels of autonomy. These range from fully manual control (a human pilot directly in command of each aircraft) to fully autonomous control (drones operate, collaborate, and make decisions without human intervention). However, in most cases, intermediate hybrid solutions (Human-In-The-Loop) are more appropriate:

- **Autonomous pilot assistance:**
  The pilot controls the drone, but support functions such as obstacle avoidance, altitude/position maintenance, Follow-Me, or Return-to-Home modes are managed automatically.
- **Leader-follower:**
  The operator pilots a master drone, while the other aircraft follow it autonomously in formation. This allows a single pilot to indirectly control a swarm.
- **Supervised autonomy:**
  The most used for MVMS systems. Drones fly autonomously, but under the supervision of the operator, who can intervene manually if necessary. The drones manage navigation and tasks themselves as long as everything proceeds within normal parameters, but they request assistance from the pilot (or the pilot can take control) if they encounter unexpected difficulties. In this case, task-oriented control is often used, in which the operator limits himself to simply issuing high-level commands or assigning objectives (e.g., mapping an area).

REGULATION FRAMEWORK

As mentioned above, the development of multi-drone systems will revolutionize air operations. However, the use of these new systems must be placed within the existing regulatory framework with adequate risk management and coordination of shared airspace (Ref. 6).

Overview on EASA UAV regulation framework

The EASA regulation distinguishes drone operations into three categories, based on the increasing level of risk:

Open category: For low-risk operations, within 120 metres of height and in Visual Line Of Sight (VLOS), with subdivision into subcategories A1, A2 and A3, linked to the weight of the drone and proximity to people. There are specific pilot training requirements and limitations such as Remote ID or geo-fencing depending on the drone class.

Specific category: The Specific category covers all drone operations that do not fall under the Open category, as they involve higher risks or particular operating conditions. To operate in this category, the operator must submit a risk assessment through:

- STandard Scenario (STS): STS are operational scenarios predefined by EASA for activities with low residual risk, but which exceed the limits of the Open category. They allow operators to avoid a full risk assessment (check SORA below), provided that very specific conditions are met.

- Predefined Risk Assessment (PDRA): PDRAs are EASA-predefined risk assessments for recurring and medium-complexity operational scenarios, offering a simpler alternative to the full SORA process.
- SORA (Specific Operation Risk Assessment): SORA is a 10-step structured and modular method used to assess in detail the operational risk of a drone mission. It is mandatory for all operations that are not covered by an STS or PDRA, including swarm or multiple drone missions. These 10 steps include: the detailed definition of the mission (ConOps), the risk assessment for people and things on the ground (Ground Risk Class - GRC), with methods for its mitigation, the risk assessment in the air, meaning collisions with air traffic present (Air Risk Class - ARC) with the respective planning strategies for its mitigation, an analysis of the risks in case of the drone exiting the operating volume and an analysis of the tactical capabilities of the aircraft to prevent collisions in flight (Tactical Mitigation Performance Required - TMPR). These are collected and combined to define the overall SAIL risk level (Specific Assurance and Integrity Level) from I to VI. Based on SAIL, the levels of robustness required to meet the Operational Safety Objectives (OSO) are determined. All this is finally collected in the documentation to be presented to the authority.
- LUC (Light UAS Operator Certificate): is the level of maximum operational autonomy in the Specific category. It is a certification issued by the national aeronautical authority that recognizes an organization's ability to authorize its missions without having to interface with the authority each time.

Certified category: Concerns high-risk missions, such as for example transporting passengers or cargo in densely populated areas. It requires certifications similar to traditional aviation, both for the drone and the operator.

U-Space: U-space is a set of digital services designed to ensure safe and coordinated access to airspace for drones. It was born as a response to the need to integrate UAS (Unmanned Aerial Systems) in complex environments shared with traditional manned air traffic (Ref. 7). This airspace is characterized by fundamental services like:

- Network Identification Service: identifies operators and tracks the position and trajectory of drones in real time.
- Geo-Awareness Service: provides information on operating conditions, space restrictions and time limits.
- Flight Clearance Service and Traffic Information Service: ensures that authorized flights are free of conflicts with each other and warns operators of air traffic in proximity.
- Weather Information Service: provides updated meteorological data.
- Compliance Monitoring Service: notifies the operator of any violations of operational constraints or deviations from the authorized flight plan.

Gap analysis between EASA regulation and multi-drone use cases

In the EASA regulation, multi-drone operations and swarms are mostly concerns suggestions on specific training modules for pilots, but without defining detailed operational restrictions, like the ones that can be found, for example, in the Open Category. In that sense, the Specific Operation Risk Assessment (SORA) method remains the main regulatory tool for risk assessment and approval of multi-drone missions.

From single drones to multi-drones gap filler proposal

Given the considerations made above, general high-level guidelines can be proposed to assist the operator in conducting the SORA risk assessment for multi-drones scenarios:

- **Drones number:**
  Can be defined based on the operating environment and aircraft characteristics (size, range). An excessive number could increase the risk of collisions (ARC) and overload the operator thus reducing his capability to manage the operation.
- **Minimum distance between drones:**
  A minimum drone-drone safety distance could be defined proportionate to the inertia, maneuverability, and performance of the drones (acceleration, speed, braking capacity) to limit the risk of collisions.
- **Maximum distance between drones:**
  This is especially important for distributed architectures, where drones communicate with each others on different levels of hierarchies. In that case, maintaining a maximum distance could avoid communication loss between drones. It might also be useful to set up backup links with the ground station.

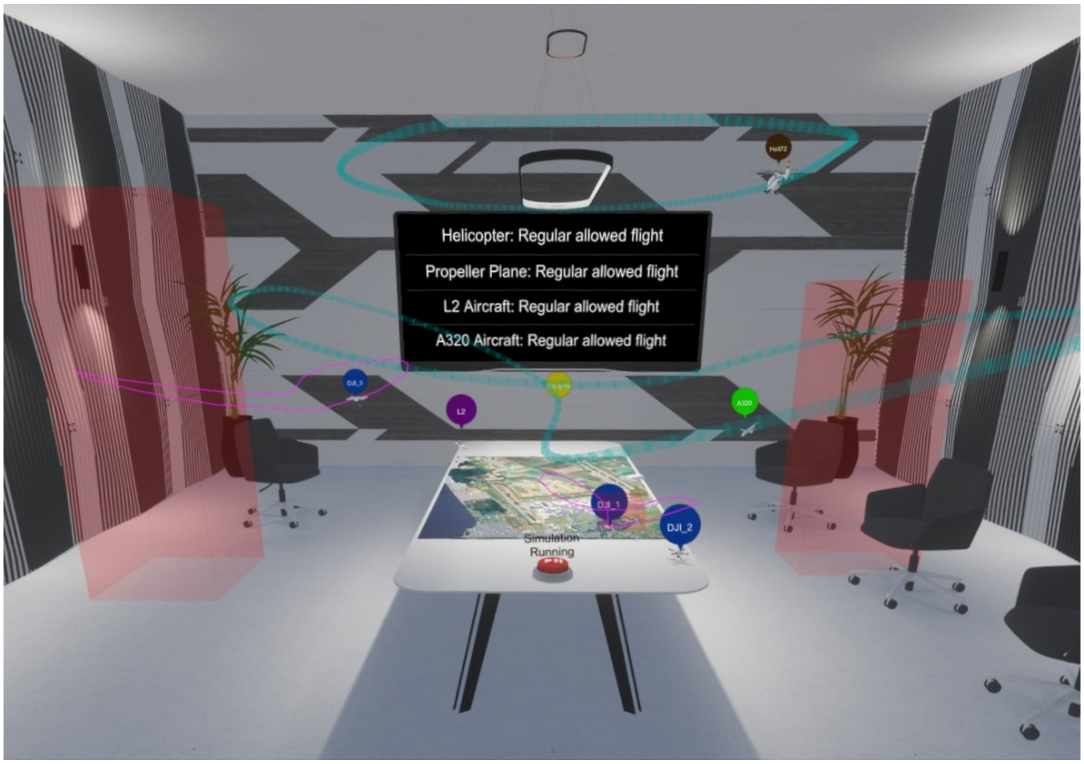

Figure 2. XR immersive environment

PROTOTYPE HIGH-LEVEL DESCRIPTION

The main features and innovations of the MVMS prototype developed by TXT E-Tech are summarized below:

General purpose - modular architecture:

This prototype is designed as a modular and scalable system that can potentially adapt to any available technological solution. The idea is to create a backbone to which the various modules can be attached, allowing to replicate the technological alternative best suited to the specific use case with every architectural solution, from the simple centralized one to the more sophisticated hybrid cluster-of-clusters.

Cloud-based architecture:

This is also facilitated by the prototype's cloud-based nature, meaning that the frontend communicates with backend via web. This kind of solution allows both communications with dedicated hardware for drone transmission, or directly to the drones via 4G/5G networks, or alternatively, with a simulation environment that allows for testing of systems and training of operators.

Simulation environment:

As mentioned, the designed MVMS comes also with a sophisticated simulation environment that allows for the testing, validation, and experimentation of new systems, algorithms, and technological solutions, and the training of personnel for specific missions of any nature.

Extended Reality Mission Control:

In order to maximize the situational awareness, the developed MVMS provides the operator with an immersive Extended Reality system that allows to control and interact directly with the mission by displaying the entire UAV fleet on a tactical table with a representation of the surrounding environment in which they are flying. The operator is also provided with an intuitive, customizable widget-based interface that gathers all necessary information needed to monitor the fleet's status, including 2D and 3D maps with aircraft trajectories, dashboards showing the status of each aircraft, CAS systems, and even PFD displays that enable the operator to manually pilot the aircraft (Figures 2 and 3).

Compliance with future UAV regulation:

The system was also designed to be aligned with current developments in UAV regulations, with particular reference to modern airspace concepts such as U-Space. The system's features, such as visualization of the entire airspace using Extended Reality, or the web-based architecture through which is possible to easily share all the information within the entire airspace, contribute to make the prototype aligned with future developments in shared airspace between manned and unmanned aircraft.

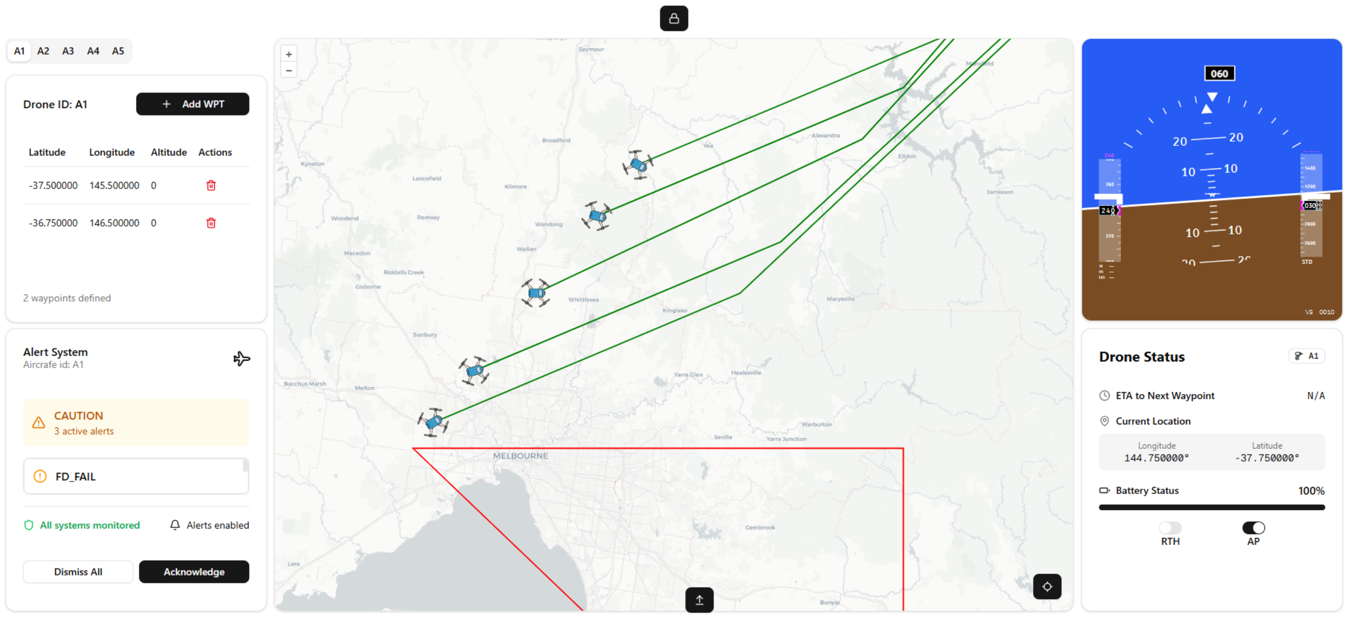

Figure 3. Widget interface

SYSTEM ARCHITECTURE

The following section provides an overview of the developed architecture.

The prototype consists of a Ground Station capable of managing a fleet of UAVs through a web-based application, providing a real-time XR and widget-based interface for mission planning, execution, monitoring, and control. As mentioned, the system comes also with a simulation environment through which the prototype has been tested and validated.

The role of the GCS can be summarized in the following tasks:

- **Flight Plan Management:**
  Create, edit, and execute flight plans for individual or coordinated multi-aircraft operations.
- **XR Real-Time Monitoring and Control:**
  Track live telemetry, receive alerts, and issue commands during mission execution through a Extended Reality and a widget-based interface, supporting dynamic decision-making and enhanced situational awareness.
- **Mission Simulation:**
  Execute realistic mission scenarios in a simulated environment, for real-existing systems testing, pre-flight mission validation and operator training.

The prototype is composed of a diverse set of components that interact together. From an architectural perspective, they can be divided into:

- **Frontend:** The user-facing web application, responsible for presenting data and enabling user interaction.
- **Backend:** A collection of services and modules that manage data processing, storage, authentication, and communication with the frontend and with drones.

System Frontend

The system's frontend is composed of two main parts, each with a different role:

- the XR interface for direct real-time fleet visualization and interaction to increase overall situational awareness of the operator (Figure 2).
- the widget-based interface for fleet management, providing the operator with necessary tools for status monitoring and intervention (Figure 3).

The choice of Virtual Reality (VR) as a solution to increase situational awareness in aircraft fleet management is due to the fact that it is a technology that allows the user to interact directly with the environment, thus providing information to the operator in a more natural way, thus reducing the pilot's processing workload.

The immersive VR environment was developed on UNIGINE, a game engine used to create realistic 3D simulations and interactive environments, widely used in industries such as aerospace, automotive, and architecture. It can handle large datasets, double-precision coordinates, and offers realistic physics and lighting, making it well-suited for the project's purpose.

Instead, the widget-based interface is developed with React, a widely adopted JavaScript library known for its efficiency and component-based architecture and Next.js framework, a good combination that ensures scalability and a responsive user experience. Indeed, as mentioned before, all the main components of the MVMS architecture are designed with modularity and re-usability in mind, facilitating integration with future extensions and also other systems.

This also motivates the choice of a widget-based interface, which allows the operator to choose the best configuration of the various windows based on the specific needs. The widgets (e.g. map, CAS, PFD, etc.) can be selected, moved, and resized as desired, to give complete flexibility to the operator. When managing a fleet or operating in a potential U-Space airspace, being able to view all information easily and simultaneously is essential.

System Backend

The system's backend is structured as follows: the two user interfaces (widgets and XR) communicate with the drones and the simulation through a Communication Module, as does all the dedicated drone piloting hardware (HOTAS). The widget interface is web-based and therefore exchanges information directly with the Communication Module, while the XR user interface, with its display and controls, communicates with a dedicated backend that manages the XR system's internal logic and which in turn interfaces with the Communication Module. Then, the latter communicates with the physical drones and the Simulation Framework, sending commands and receiving telemetry data from them. Specifically, communication with the physical drones occurs via MAVLink (Micro Air Vehicle Link), a widely used communication protocol between Ground Stations and small unmanned vehicles. Finally, the system sends mission data to the Database for data logging purposes. The architecture is reported in the following diagram (Figure 4):

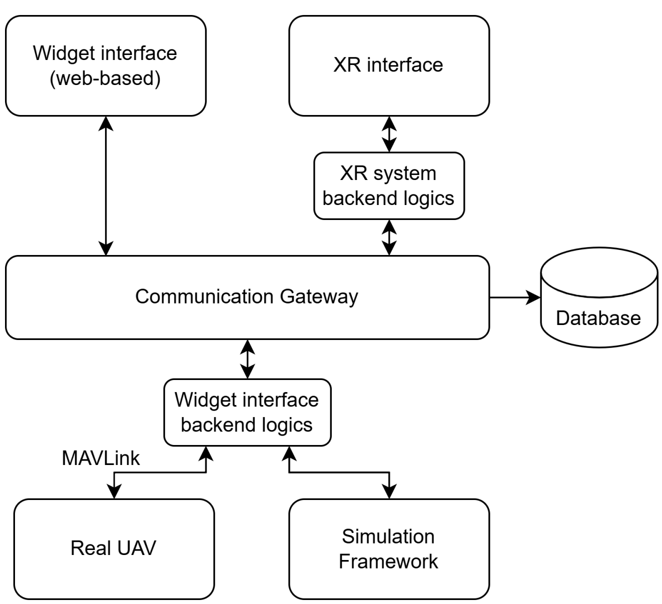

Figure 4. System architecture

System functionalities

The core modules of the system, namely, the various functionalities available for the user, are reviewed below:

- **VR Immersive Environment**
  The immersive VR environment recreates an elegant 3D control room, at the center of which is a tactical table. Above the latter, the portion of airspace of interest is represented, along with the aircraft flying within it in real time. The immersive environment also features various visual interfaces and buttons through which the user can interact with the mission, both with real and simulated aircraft. For example a wall-mounted display shows important messages and alerts concerning the status of the aircraft and a toggleable interface attached to left-hand controller displays specific UAV status (Figure 2).

- **VR Real-time display of aircraft position**
  Aircraft are depicted in the immersive environment as they fly, displaying their position and attitude in real time. They come with a label displaying the aircraft ID. The aircraft's planned trajectory is also graphically represented with a line or tube with different colours (depending on the type of aircraft).

- **Geofencing and No-Fly-Zones Management**
  The system is also capable of managing restricted areas such as Geofences or No-Fly Zones. When setting up the flight plan, placing waypoints within them is indeed prohibited. Moreover, if an aircraft crosses a restricted area during the mission, the aircraft's label will turn red to immediately draw the operator's attention, and an alert message will appear on the appropriate screens in the VR environment. Restricted areas are also identified in the widget-based interface maps.

- **Collision Risk Management**
  The system also includes collision risk management. The system identifies whether two trajectories approach each other beyond a given threshold at the same time, hence identifying a high-risk collision event. Even in the VR environment, when two aircraft approach each other below a certain threshold, red spherical areas appear surrounding the two aircraft.

- **Post-mission Data Logging**
  The system includes a module responsible to record key simulation data for all aircraft and drones. It captures and stores in database time-stamped position data throughout the simulation, for post-analysis, debugging, and performance review or archival purposes.

- **Flight Plan Management:**
  This component allows operators to create, update, and delete waypoints for each drone of the fleet. A dedicated widget of the widget-based interface helps operator with this task. It also supports import of external mission plans.

- **Crew Alert System (CAS):**
  The system features a Crew Alert System (CAS) that provides interfaces (including a dedicated widget) for promptly notifying users of anomalies, critical events or potential issues occurring during real-time monitoring of the mission (Figure 5).

- **Map Interface:**
  To enhance user's situational awareness an integrated map widget, from widget-based interface, that displays real-time positional data (and telemetry) for all active drones, whether operating in simulation or in the real world. Features include zoom, centering on selected drones, and following specific aircraft.

- **Aircraft Status And Control Panel:**
  This component provides real-time monitoring of critical drone parameters, including battery level, GPS coordinates, aircraft type, Estimated Time of Arrival (ETA) and so on. It offers quick insights into the operational status of each drone. These information are shown both in the VR environment and in the widget-based interface (Figure 6).

- **Fleet real-time control:**
  In addition to status monitoring, the widget includes essential control functionalities, such as toggling the autopilot mode and activating the Return-to-Home (RTH) procedure (Figure 7) or resuming the mission planned track. RTH can be activated by the user, either from the widget-based interface or from VR or can be automatic due to low battery.

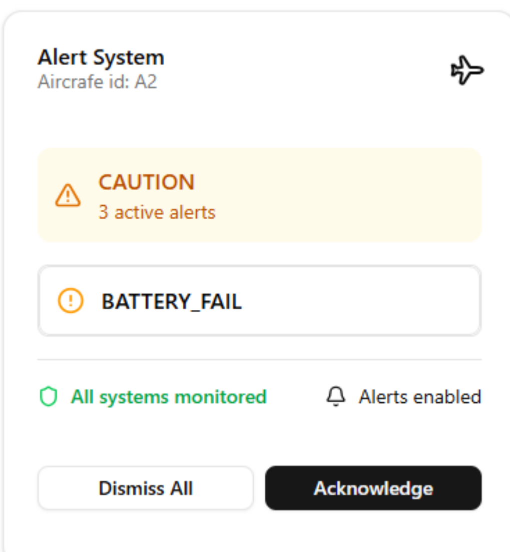

Figure 5. CAS widget

- **Primary Flight Display (PFD):**
  The widget-based interface includes also a Primary Flight Display (PFD), that replicates the typical essential flight instruments needed for piloting of the aircraft. The PFD is updated in real time using telemetry data from the selected drone. This component is particularly useful for manually-piloted missions.

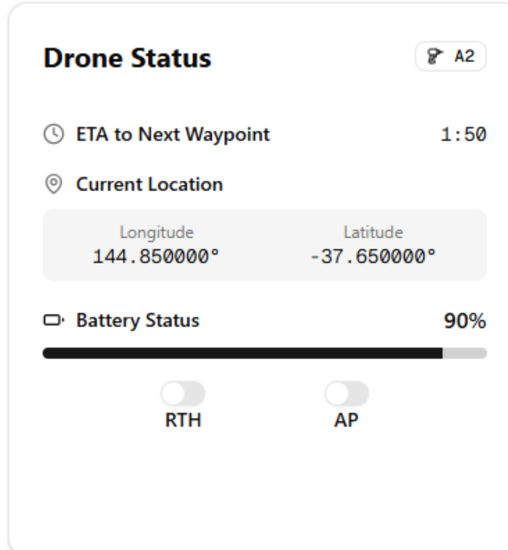

Figure 6. UAV Status widget

SYSTEM TEST AND VALIDATION

The following section illustrates the steps undertaken during the system testing and validation process, aimed at validate the backend components and interfaces, both widgets and the immersive VR environment, with the various input commands. As mentioned, the various tests were performed using the system's integrated simulation environment.

Hardware specifications

The hardware setup used includes:

- VR Headset: Meta® Quest® (OpenVR compatible) for XR interface
- PC used to run UNIGINE VR simulation with the following specifications: Processor: AMD® Ryzen® 7 7770 8 core; RAM: 32 GB; Graphics: NVIDIA® GeForce® RTX® 4080.
- PC used for drones simulation, for visualization of client web interface and for HOTAS commands input. Its specifications are: Processor: 12th Gen Intel® Core® i7-1255U 1.70 GHz; RAM: 16 GB; Graphics: Intel® Iris® Xe® Graphics

Missions specifications and results

Several missions were conducted to test and validate the system in all its components.

The most comprehensive one was a mission that simulated shared airspace between several aircraft, both manned and unmanned. In this mission, total of six aircraft were used, including:

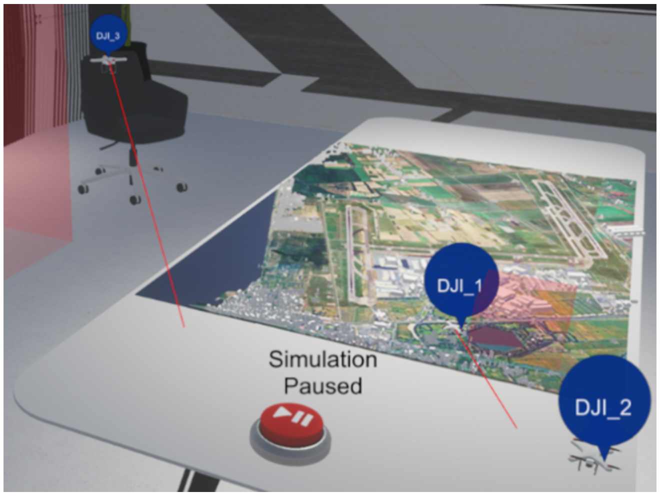

Figure 7. Drones in RTH mode. The RTH path is highlighted in red as well as the square-shaped geofence.

- Three quadcopter drones.
- A widebody fixed-wing airliner (similar to the Airbus A320), called "A320".
- A fixed-wing transport aircraft (similar to the Cessna Citation), called "L2".
- A medium-size helicopter.

The environment chosen for the mission is the Fiumicino Airport area (Rome). This environment is displayed above the tactical table in scale with 3D details, based on real elevation and building data. The mission involves pre-programmed paths for the various aircraft during the planning phase, which, in the case of UAVs, are then changed in real time, thanks to the various maneuvers. These paths are designed to ensure that at least one UAV and one fixed-wing aircraft enter a geofence and that the trajectories of two of the UAVs come close together. Moreover, the transit of the two UAVs at that point of proximity occurs at two close instants of time so that the collision risk management algorithm is triggered. In the mission, three geofences were manually set and rectangular in shape. They are 2D geofences, hence prohibiting overflight at any altitude above the defined area. In this mission, various maneuvers, controls, and interfaces were tested. Among these, the mission includes the trigger for the Return-To-Home maneuver, the real-time modification of a waypoint, and the battery discharge of one of the three drones to reach a sufficiently low level to trigger a notification on the CAS. The XR environment controls are also tested, including movement in the immersive space, the trigger for stopping and resuming the simulation, and the various joystick controls. The consistency between the information displayed by the widget-based web interface and the information reported in the XR immersive environment is also tested. A second group of missions tests the piloting of the single drones using HOTAS and PFD. These missions test also the enabling and disabling of the Autopilot command from the widget interface.

First, the correct management of flight plans was verified. The creation, modification, and deletion of waypoints for multiple drones was then tested simultaneously. During the simulation, the drones demonstrated that they correctly followed the imposed trajectories. The automatic detection of geofencing violations and the Return-to-Home (RTH) command were then tested together. After the RTH input command the following waypoint has been replaced with the home position (Figure 7) and during the maneuver the drone 1 crossed a geofence. The VR interface correctly highlighted the passage (Figure 8).

In parallel, it was confirmed that the ETA (Estimated Time of Arrival) calculations were consistent with the planned trajectories and that all information was correctly saved in the backup database.

The CAS system was tested for the following specific cases: RTH activation, No-Fly Zone violation, and the detection of critical battery levels. In all three cases, messages appear on both the headset and CAS interfaces. The Figure 10 shows: on the left, the UAV status interface attached to the left controller, that displays correctly both critical battery level and No-Fly-Zone violations. On the top, a portion of the wall-mounted display. And the various trajectories: violet for drones and light blue tubes for fixed wing aircraft. The three geofences are also highlighted in red. Details on the wall-mounted display are shown in Figure 11.

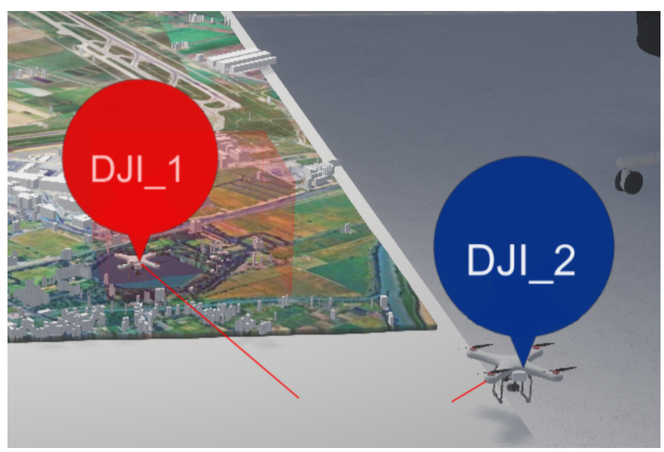

Figure 8. No-Fly-Zone crossing is signaled by a change of the colour of the label from to red.

The interactive map widget showed to correctly display the correct positions and routes of the drones in real time from telemetry data along with the integration of geofences and restricted areas in the map, which are displayed with colored outlines (Figure 10).

The collision risk management system correctly warned the operator of the risk of a possible collision both during the mission planning phase and in real-time, highlighting the two drones close to collision with a colored sphere (Figure 9).

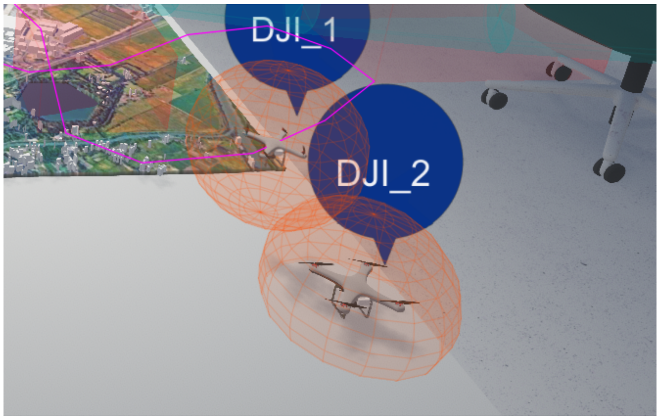

Figure 9. Real-time visual warning of an imminent possible collision between two aircraft.

To validate the Primary Flight Display (PFD), the graphical indicators were compared with aircraft attitude and altitude data directly from the simulation. The run-time display of this data demonstrated good latency.

The XR interface's graphical elements proved responsive and fluid. Features like simulation state management, such as the ability to pause and resume the simulation, were also tested. Regarding orientation in the immersive space, teleportation was chosen over the initial choice of 3D physical movement, since it was observed that it could cause motion sickness over time, given that frequent movements and changes in perspective can be necessary during a single mission.

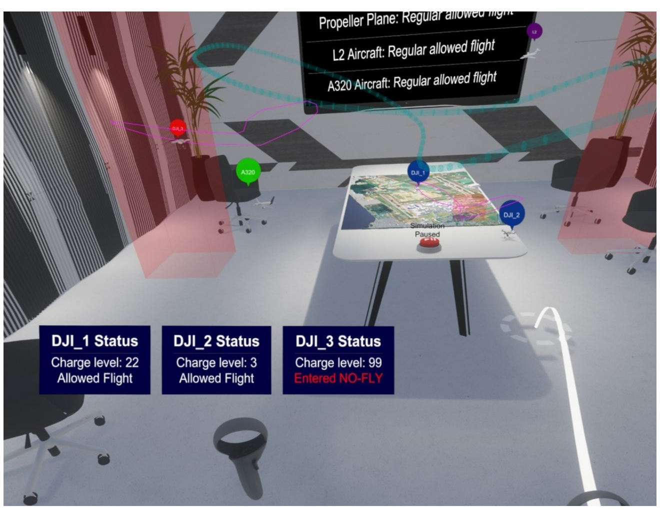

Figure 10. UAV status display, geofences, wall-mounted display and aircaft trajectories.

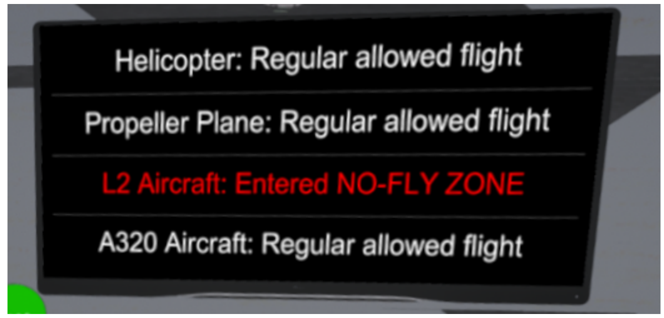

Figure 11. Detail on wall-mounted display, that alerts user about a No-Fly-Zone violation from L2 aircraft.

CONCLUSIONS

The test results demonstrated overall good performance from both interfaces, both in terms of the fluidity, promptness, and consistency of information, as well as the correct functioning of the various controls.
Overall, the user experience of an operator seeking intuitive, agile, and comprehensive control of an entire fleet of UAVs integrated into a shared airspace was satisfactory and effectively proved to increase situational awareness.

However, during testing of this system, several critical issues arose, suggesting potential system modifications. Regarding the XR system's user experience, one critical issue concerned motion sickness. As mentioned, it was noted that long monitoring missions such as these for an MVMS involve numerous movements that can cause motion sickness. The initial movement solution was replaced with the idea of teleporting the user, triggered by a joystick command. This method also allows for faster movement in the 3D environment than physical movement. Another critical issue concerns the methodologies for positioning the information displays in the XR system. The initial solution of consolidating all the information indiscriminately on a single wall-mounted display was discarded in favor of separating the displays for the fleet's drone status into a second interface, which for convenience was placed on the left control panel. However, after testing, this solution proved to be poorly scalable because it was too cumbersome, especially when there were more than a dozen drones in the fleet. Another issue also concerned the size of the aircraft, which were initially scaled with the map. However, for large maps, they were so small that they were unrecognizable. Therefore, a larger, non-scale size was chosen, especially for the quadcopter drones. As for the wall-mounted display, it is convenient, but when facing away from the viewer, the information is lost. Tests revealed that an arrow or indicator indicating a new CAS message would be helpful, or a viable alternative could be to replace the wall-mounted screen with a semi-transparent HUD (Head-Up Display). Another improvement identified during the testing campaign concerns the limited interaction with aircraft, for which detailed information could be viewed simply by clicking on them or approaching them.

FUTURE DEVELOPMENTS

Following the system's development and testing campaigns, several ideas and suggestions for future developments emerged.

One of the most promising developments is the integration of physical drones, testing a Hardware-In-The-Loop (HITL) version, both through a traditional transmission system and possibly through a 4G infrastructure. This also includes the integration (both simulated and real) of available real traffic data.

A second future development concerns communication between drones, aiming to create a decentralized or hybrid architectures.

Furthermore, with a view to creating a system potentially suitable for managing an entire airspace, the possibility of adding multiple pilots and control instances (i.e., multiple Ground Stations) managing the same fleet or joint fleets could be explored. This could have several interesting implications in multiple scenarios, civil and military, both for real operational scenarios and for training purposes when combined with the simulation environment. This solution ensures also redundancy for an improved fleet safety.

Consistent with the system's intrinsic modularity and scalability, it is possible to add various modules, thus enriching it with new features. These could include, for example, computational modules that implement different path planning algorithms tailored to different use cases.

Currently, the two interfaces are intentionally kept separate, designed for the cooperation of two operators, each with different tasks. It is possible, however, to explore the integration of the two interfaces (XR and widget-based) in a single VR environment, but this would in any case exclude the HOTAS component and its interface from the integration.

As emerged from the test campaign, the need to customize the XR environment's 3D control room depending on the size of the airspace to be controlled is crucial. For large spaces, a tactical table that is too small would result in excessive miniaturization of the landscape and aircraft.

Further future developments, emerged from the operator's experience during tests, may involve also the implementation of advanced interactions with virtual reality subjects. As mentioned, interactions with aircraft, to gain rapid insight into their status and route, but also interaction with the aircraft's routes themselves, for example, directly moving the trajectories of the various UAVs, through a direct manual interaction.

Finally, a final future development could involve the possibility for the operator to also opt for an AR (Augmented Reality) environment instead of VR (Virtual Reality), in which the interface adapts completely to the (real) room in which it operates.

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