Resilient Drone Mission Management and Route Optimization in Drone Delivery Context

RESILIENT DRONE MISSION MANAGEMENT AND ROUTE OPTIMIZATION IN DRONE DELIVERY CONTEXT

Giuseppe Tomasicchio
Telespazio, Via Tiburtina 965, 00156, Rome, IT, giuseppe.tomasicchio@telespazio.com
Antonello Cedrone
Telespazio, Via Tiburtina 965, 00156, Rome, IT, antonello.cedrone@telespazio.com
Federico Fiorini
Telespazio, Via Tiburtina 965, 00156, Rome, IT, federico.fiorini@telespazio.com
Laura Esposito
Telespazio, Via Tiburtina 965, 00156, Rome, IT, laura.esposito@telespazio.com
Giovanna Scardapane
Telespazio, Via Tiburtina 965, 00156, Rome, IT, giovanna.scardapane@telespazio.com
Francesco Filipponi
Telespazio, Via Tiburtina 965, 00156, Rome, IT, francesco.filipponi@telespazio.com
Marco Rinaldi
Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, IT, marco_rinaldi@polito.it
Stefano Primatesta
Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin IT, stefano.primatesta@polito.it

Abstract

The last two decades were characterized by a rapidly increasing of innovative solutions in the microelectronic field, having therefore a significant impact on a huge set of applicative scenarios. This aspect allows the development and improvement of new solutions, giving the possibility of growth and development of new markets, such as the drones ones. Actually, in the unmanned field we have seen an exponential growth of the market, given not only from the increased computing capabilities, but also by a more efficient developed hardware, thus leading to the definition of innovative uses, service paradigms and applications. The latter span in several different areas, from agriculture monitoring to society's services including the **Package Delivery** which immediately plays a strategic role in the modern society. These types of applications took place mainly in an urban environment, highlighting therefore new rules, needs and management system in order to accommodate the mission's achievement guaranteeing at the same time a high degree of resilience, citizen safety and risks minimization. Furthermore, to assist these types of operations, T-DROMES, a **RPAS** (Remotely Piloted Aerial Systems) fleet and mission management solution, was developed allowing to scale-up the use of drones in complex operations from a geographical and mission point of view, in different applicative scenarios. The paper aims therefore to presents the tools capabilities and how the developed architecture is able to manage the entire mission for any context scenario and how the developed platforms and tools can be a valid framework for developing new operative working models.

1. Introduction

The recent years are characterized by a significant growth in a huge set of technological fields, by the improvement of the knowledges and research activities. This is directly reflected in the robotics fields, and in particular in the aerial one, where unmanned vehicles are largely used. Their applications span from social to law enforcement helping the human on their actions. This lead us to define new operational uses and service paradigms in an **Urban Environment** in order also to improve the quality of life and also to maintain the innovation technological stream that characterize the modern society. One of these applications is the **Package Delivery via Drones** which immediately plays a strategic role acquiring then the interest of companies and institutions. The high complexity of the Urban Scenario, as well known is not only characterized by a strongly dynamicity, but also by signal propagation problems (causing e.g. the so called **Urban Canyon**) which requires an assisted, precise and continuous management of the entire flight missions, from the initial phases (Flight planning) up to the *package delivery.* By means of an integrated platform the involved operators are assisted to perform their assigned tasks **minimizing the risks and receiving a resilient communication with the drones**; this represents the focal point to facilitate the growth of package delivery applications.

For this purpose, the platform T-DROMES has been developed and this paper aims at describing it highlighting all its capabilities and services that actively support the entire flight mission, with a high degree of resilience and service availability. This is possible since the platform is able to handle **different communication channels**, but also to manage a set of **alternative navigation methods**, added to the one already present in the drone control system, which allow to safer perform the task in any adverse conditions, having a continuous conformance monitoring and control of the executed flight planning status.

This paper describes, then, how T-DROMES services guarantee a continuous and valid support in particular in a Package Delivery via Drone scenario in an Urban Environment, depicting the developed platform features and architecture, and how it harmonically works in different flight mission phases. In the following sections are reported the achievements of some real Use-Cases, the simulation results and the planned future works, that can enhance the drone usages harmonizing them with already developed infrastructures.

2. T-DROMES service and concept architecture

T-DROMES is an integrated *digital platform* based on an efficient complex combination of *procedures, operations, software tools* and *hardware payload* that can guarantee a resilient and efficient constant support, to the Drone Operators, in all flight mission phases providing also the interface with a local UTM\U-SPACE service provider, in order to manage the flight authorization process and design the flight plan in accordance with aeronautical restrictions.

In Figure 1 the entire T-DROMES product architecture is reported, where the offered capabilities are the result of a combination of several building blocks.

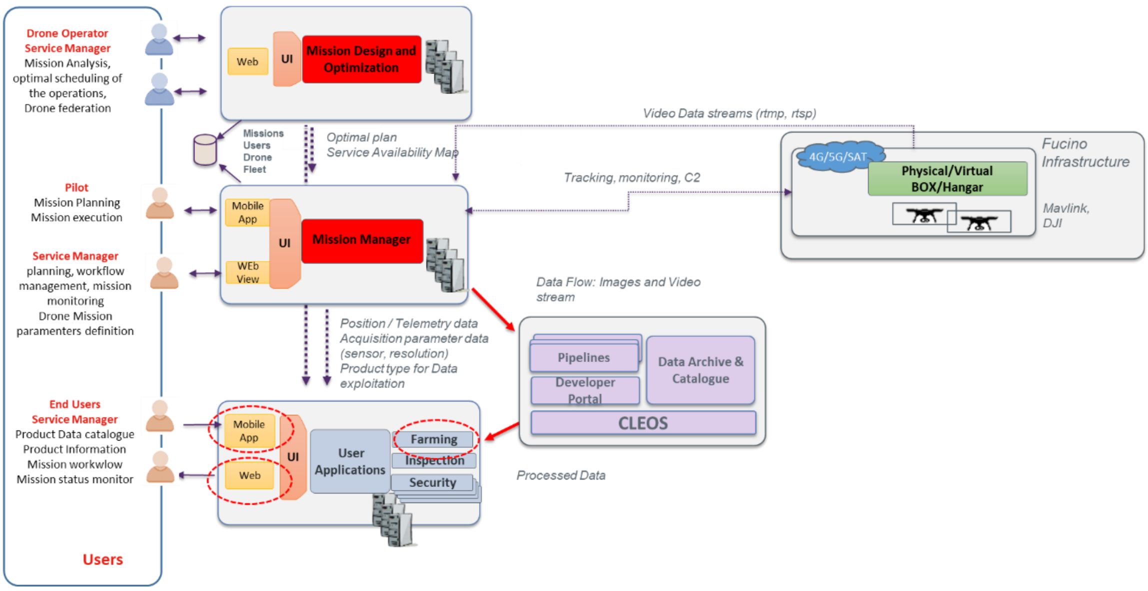

Figure 1: T-DROMES Architecture

In all drone mission context, and more in detail in the **Package Delivery** ones, T-DROMES is a valid assistant that can support the *Drone Operator* in the different mission phases providing all the additional features that permit it to manage also the most critical scenarios. In particular we can distinguish two supporting phases:

- **Pre-flight** *phase*: providing an enhanced flight planning algorithm to calculate the route with less impacts ground risk.
- **On-flight** *phase*: providing a *resilient connectivity* with both **LTE** and **SATCOM** (Iridium) with the drone with different telemetry sources as GNSS, Beacon and Visual navigation and traffic detection.

More in details, the ***Pre-flight*** *phase* is a strategic stage of the entire mission, where all the flight plans and operations are defined in accordance with system capabilities and flight area restriction and criticality. For these reasons **T-DROMES MDO** (Mission Design and Optimization) has been developed and focused on risk and energy optimization of payload pick-up and delivery with UAVs. The tool consists of **two interconnected components**:

- **Safe Path Generator**: it works according to a two-stage procedure: firstly, a risk map is generated assessing the ground risk in the operational area; secondly, a risk-aware path planning (developed using RRT* algorithm) seeks the minimum risk path, in the risk map, with the minimum flight time, as Figure 2 shows.

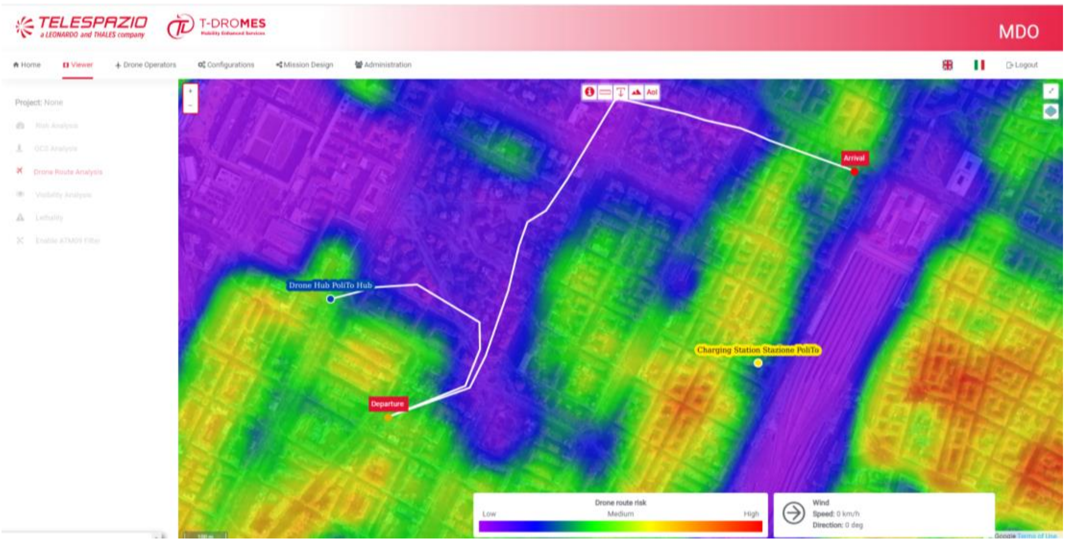

Figure 2: T-DROMES MDO – Planned safe Route in Urban Environment

- **Task Scheduling:** The task scheduling software is implemented using a market-based task strategy: *(i)* assigning the orders to the fleet of drones; *(ii)* optimizing UAVs' flight speed such that the orders are delivered on time and the UAVs' energy consumption is minimized; *(iii)* allocating battery re-charge tasks to the UAVs in order to ensure that the UAVs do not run out of battery during task execution; *(iv)* optimizing UAVs' flight speed such that the idle time represented by battery re-charge is minimized.

The ***On-flight*** *phase,* instead, encloses all those operations that can be considered active during the tasks executions and therefore require a high level of service availability and robustness. In fact, this phase is mainly related to the **flight *management and monitoring*** that require, by definition, a certain degree of resilience and support to involved Drone Operators. To assess these requirements, T-DROMES infrastructure provides an integrated solution that guarantees a continuous and robust system, by the exploitation also of usage of an engineered hybrid communication network.

In addition to this, an ad-hoc module has been developed, the **T-DROMES MMA** (Mission MAnager), in order to make the users acquire the capability to contemporary manage and control a huge set of drones, involved in many different flight missions and context scenario and with a strong degree of interoperability, enabling also new operative concept, as for example the *one-to-many missions*.

2.1. T-DROMES Mission MAnagement (MMA)

The User, that can be a Drone Operator, a Pilot or a Service Manager, uses the T-DROMES MMA by defining the mission from the initial **planning phases**, thus determining the mission geometry, the execution time horizon and also the operation typology (such that Inspection, **Urban Delivery**, Mapping, Monitoring etc.). At the end of this process, T-DROMES MMA allocates each task to the most suitable aircraft, in accordance to UAS capabilities and task characteristics. Considering the above aspects, the users can also choice to *plan and schedule periodic flight missions*, performed completely without human intervention, based on the possibility of T-DROMES to autonomously manage different type of **drone hangar**, allowing then to **increase the automation** degree of the operations. These are very important aspects also for the modern concept of *Package Delivery via Drones*, because permit to increase the automatization of the procedures and minimize humans' errors in all the flight mission phases.

The main characteristic offered by MMA, as anticipated before, is the possibility to *contemporary* **handle multiple UAV systems.** In fact, according to their profile privileges, Users and Pilots can access at the same time to multiple UAV telemetries, **monitoring and controlling** them with the support of the platform services, independently from the drone manufacturer and the UAV communication protocol (e.g. DJI or MAVLink based drones). The latter aspect is itself a strength of T-DROMES MMA that provide an adaptation layer between UAV system and User, allowing him to be independent by the drones tasked to the specific mission. This is a very innovative and important aspect that allow the management of a large scalability to huge drone fleets also composed by heterogeneous systems, in terms of manufacturer or communication protocols.

So, relying also on the developed resilient infrastructure, **T-DROMES MMA** allows the tracking and Real-Time monitoring of drone positions, sensors' status and also to perform a conformity check of the executing flight path with respect to the planned flight route in a resilient way. In particular there exist the Tracking & Monitoring Service and the important capabilities to internally managing multiple connectivity such as Satellite and LTE. In fact, T-DROMES architecture provides ad-hoc interfaces with the Telespazio COM-BOX HW permitting therefore to handle not only VLOS flights, but also **BVLOS** missions, that mainly characterize the **Urban Delivery via Drone** missions.

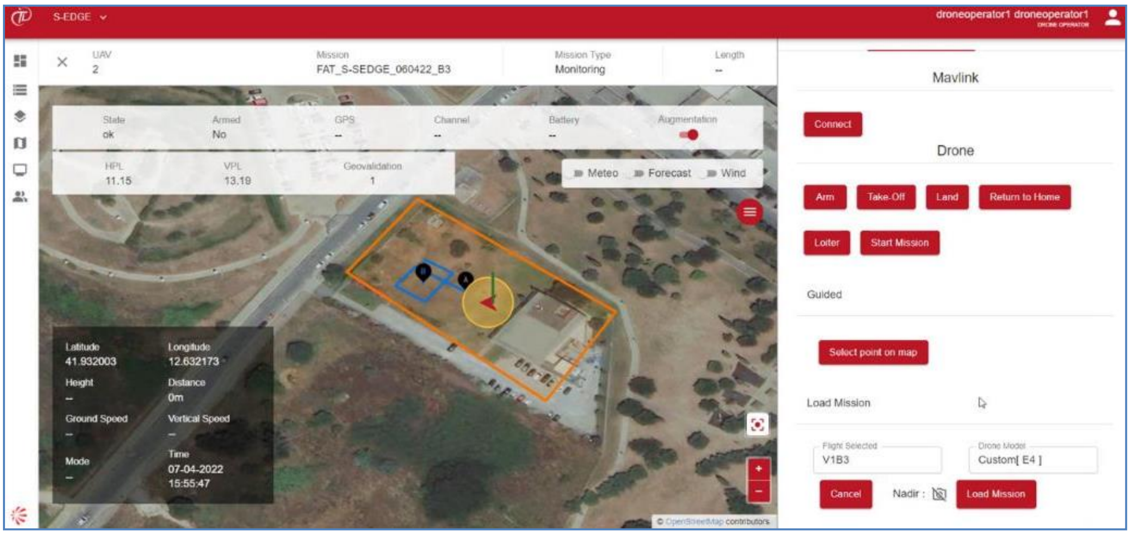

Figure 3: T-DROMES C2 & Telemetry management

Installing the COM-BOX on board the drone or on Ground Control Station, is possible to create a secure and direct connection with T-DROMES platform, bringing a massive added-value to the entire mission assets improving also the mission resilience and consistency. Moreover, the usage of high-performance GNSS positioning systems and additional satellite connectivity, provide an higher degree of reliability and resilience that is the focal point for Command & Control (C2) aspects, but also permit the management of a ***Real-Time*** *data flow*, as the **video streaming**. Also, the latter is an important aspect that highlight again the capacity of the platform. In fact, the received video streaming is displayed in different manner, and then can be viewed the raw video provided by the optical sensor on board the drone, but also can be displayed with additional data provided by AI algorithms, permitting at the operator to consult the video with an important added value, minimizing also in these cases the analysis time.

2.2. T-DROMES Mission Design and Optimization (MDO)

Regarding the Mission Design and Optimization tool used in the Pre-flight phase, we adopted the architecture shown in Figure 4. As previously stated, this strategic phase consists of two main components, i.e., Task Scheduling and Safe Path Generation, that jointly interact one each other to design and optimize the mission of a fleet of drones considering the available system capabilities.

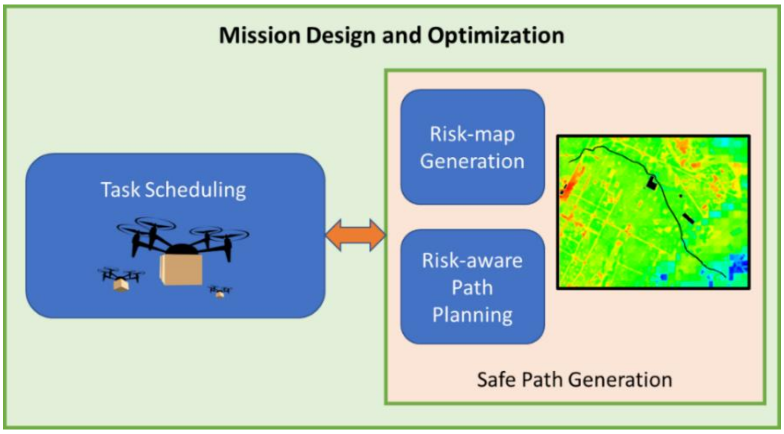

Figure 4: The main architecture of the Mission Design and Optimization tool

The Safe Path Generation aims at computing the safe path for a drone in a specific urban area minimizing the ground risk to the people on ground and the flight time [1]. The Safe Path Generation is performed with a two-stage process: the generation of a risk-map, and the risk-aware path planning.

Specifically, the risk-map is generated to assess the ground risk of flying over the urban area considering a specific drone and the delivered payload. The risk map is a two-dimensional map in which each element of the map is associated with a specific location and has a specific risk value [2]. The risk value is defined as the expected frequency of fatalities after a ground impact accident and is computed using a probabilistic approach, [3], considering the drone parameters and its payload. In particular, a multi-layer framework has been developed to compute the risk-map, in which each layer contains data required to compute the risk or to define no-flyable areas. Specifically, the multi-layer framework considers: Population density layer, Buildings layer, Sheltering factor layer, Meteo layer and GNSS layer.

Once the risk-map is generated, the safe path is computed using a risk-aware path planning algorithm minimizing the overall risk of the risk-map and the flight time [1]. In particular, the adopted algorithm is based on RRT*, a well-known sample-based algorithm able to compute asymptotically optimal solutions even in high dimensional search space.

As far as the Task Scheduling solution is concerned, the addressed problem consists of allocating parcel delivery tasks with time deadlines to the available fleet of heterogeneous UAVs, minimizing the total energy consumption. On the other hand, UAV's battery discharge is one of the main limitations to the execution of either medium-to-long range tasks or multiple short-to-medium range tasks. For this reason, the problem of scheduling battery re-charge tasks is also addressed with the aim of minimizing the impact on the delivery process. A delivery task is defined as the transportation of a payload mass from pick-up to delivery location, while a charge task is defined as a target location to be reached by the unloaded UAV such that the battery is charged. The UAV's battery re-charge time is the sum of the battery re-charge time (interpolated from the UAV's residual battery) and the UAV's flight time needed to reach the assigned re-charging station.

The sequential single-item and the multiple-item action-based task assignment strategies proposed in [4], allocate the delivery orders and the re-charge tasks to the UAVs, respectively. The energy consumption model related to aerial logistics with drones defined in [5] is minimized through a sequential unconstrained optimization method [6] such that the optimal velocity of task execution is computed for each task. The safe path's lengths computed by the Safe Path Generation element are given to the Task Scheduling as parameters for estimating the energy consumption and the flight time related to each task-UAV pair.

3. Simulative Results

This Section describes an example of mission planning of a package delivery application using the T-DROMES MDO.

Table 1: Main characteristics of the fleet used in the example scenario

Model	Mass [kg]	Max payload [kg]
DJI Mavic 2	0.7	0.1
DJI Phantom 4	1.4	1.2
DJI Matrice 300	3.3	2.7

Table 2: List of delivery tasks to complete in the drone delivery application

Task ID	Start [lat, long]	End [lat, long]	Weight [kg]
TKA1	[38.110, 13.316]	[38.135, 13.290]	1.5
TKA2	[38.111, 13.315]	[38.120, 13.294]	0.8

The reference scenario assumes the use of a fleet consisting of three heterogenous drones listed in Table 1. The objective of the mission is to complete two delivery tasks with different starting and ending locations, as well as the packages to be delivered have a different weight as detailed in Table 2. The operational area identified in a portion of the city of Palermo, Italy, is illustrated in Figure 5, where drones are initially located in the drone hub.

Once the operational scenario is defined through the graphical interface of T-DROMES, the MDO allocates each task to the most suitable drone by using the task allocation and planning method described in Section 2.2. As result, Task TKA1 is allocated to the DJI Phantom 4, while the Task TKA2 to the DJI Matrice 300. On the other hand, the DJI Mavic 2 is not used since it has insufficient payload capacity to perform the tasks considered. As previously stated, the task scheduling allocates tasks to drones by optimizing the total energy consumption.

An interesting aspect of the results concerns the routes computed by the Safe Path Generation. Figure 6 shows both the risk maps of the operational area and the safe paths to accomplish the tasks. We can observe that the resulting paths pass thought areas with the minim risk (in purple) and, in any case, minimize overflights on high-risk areas (in red).

Figure 5: The operational area located in the city of Palermo, Italy, assumed in the delivery application of example. The fleet is initially located in the Drone Hub.

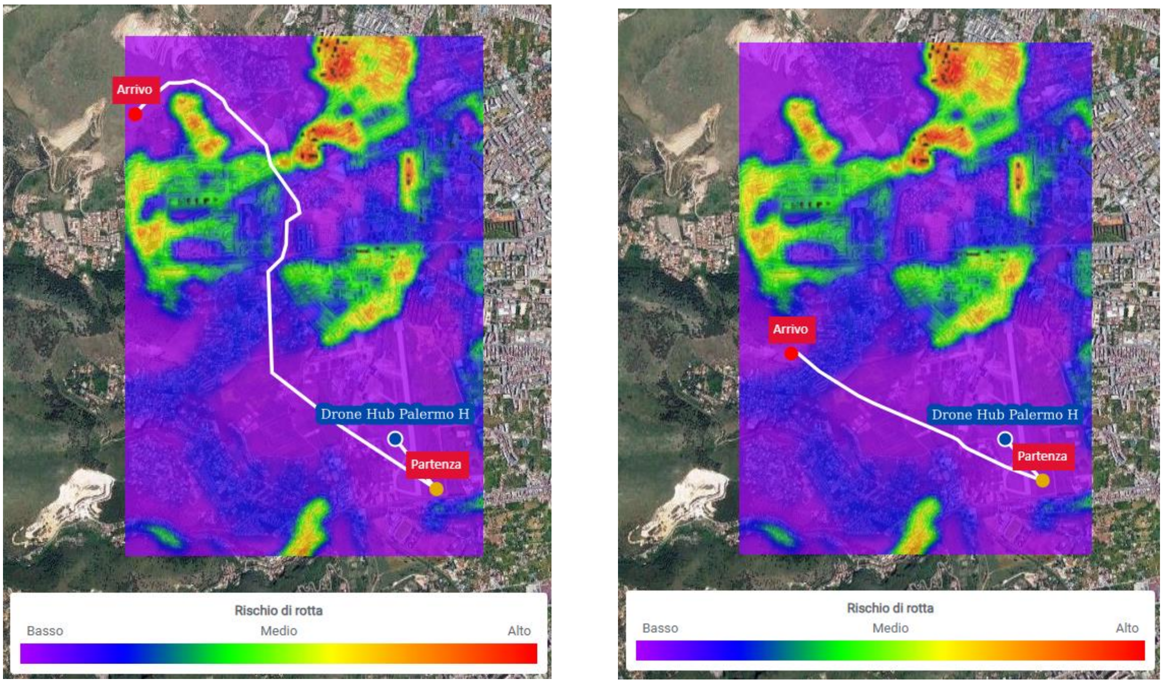

Figure 6: On the left, the risk map and the minimum risk path of the task TKA1 performed by the DJI Phantom 4. On the right, the risk map and the path of the task TKA2 performed by the DJI Matrice 300.

These results demonstrate that the MDO tool is able not only to adequately allocate tasks to suitable drones, but also to provide optimal routes with risk minimization for the execution of safe flights even in urban environments. It can be noted that the example shown is particularly simplified by the greater clarity of the results.

Finally, the same tool has been used also for scenarios with larger fleets and more tasks.

4. Conclusions and future works

The drone applications field is constantly growing highlighting new problems and needs, also in terms of procedures and flight safety management, also given by the new concepts and mission scenarios born in recent years. To assess the drones' market request and increase the usage of these strategical assets, T-DROMES and all its modules was developed, in order to guarantee a unique user-friendly and **resilient drone mission management and route optimization platform** that plays an important role in all flight mission phases.

Then, starting from **flight plan** design, through the combination of the T-DROMES MDO and MMA tool;s is possible to generate a safe and reduced risk flight route that takes into account drone characteristics and environmental aspects, performing also optimization analysis in terms of energy consumption. This not only maximizes both the overall system efficiency and the tasks requirements satisfaction, but also representing a projection to the Sustainable Development Goals. Afterwards, accessing to the T-DROMES Mission **Monitoring, Management** and **Tracking**, is possible to directly manage the active drone in the various mission context, accessing to its capability, viewing the Real Time video streaming also with AI processing layer, and performing conformances checks regarding the integrity of the executed flight path with respect the planned one, having the possibility to handle different alternative positioning system inserted in the system loop as expected by T-DROMES architecture.

All these aspects make the T-DROMES platform an enabler of new applications and new operative mission concepts, permitting also a rapidly and safer development of Package Delivery via Drone missions.

In the future the T-DROMES platform will enclose new capabilities, such as the possibility to provide 3D planning support taking into account environmental constraints and the integration with UTM systems, also handling collisions avoidance during the planned tasks execution. The additional functionalities are planned in a development roadmap, in consideration always of the most recent market demands, and therefore guaranteeing a fundamental support role to all the actors involved with drone missions, always guaranteeing a high degree of resilience regarding the aspects managed by T-DROMES.

References

[1] Primatesta, S., Cuomo, L. S., Guglieri, G., & Rizzo, A. An innovative algorithm to estimate risk optimum path for unmanned aerial vehicles in urban environments. Transportation Research Procedia, 35, 44-53, 2018.

[2] Primatesta, S.; Rizzo, A.; la Cour-Harbo, A. Ground risk map for unmanned aircraft in urban environments. Journal of Intelligent & Robotic Systems, 97(3), 489-509, 2020.

[3] Dalamagkidis, K.; Valavanis, K.P.; Piegl, L.A. On unmanned aircraft systems issues, challenges and operational restrictions preventing integration into the national airspace system. Progress in Aerospace Sciences, 44, 503-519, 2008.

[4] Rinaldi, M.; Primatesta, S.; Guglieri, G.; Rizzo, A. Auction-based task allocation for safe and energy efficient uas parcel transportation. Transportation Research Procedia, 65, 60-69, 2022.

[5] Aiello, G.; Inguanta, R.; D'Angelo, G.; Venticinque, M. Energy consumption model of aerial urban logistic infrastructures. Energies, 14, 5998, 2021.

[6] Byrne, C. Sequential unconstrained minimization algorithms for constrained optimization. Inverse Problems, 24, 015013, 2008.