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Autonomous planning and replanning of a single Unmanned Aerial Vehicle: strategies and simulations

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ABSTRACT

The aim of this paper is to define and elaborate the main features of an Unmanned Aerial System (UAS) in order to make it as autonomous as possible. In this context, the authors would propose and verify possible strategies for an autonomous replanning of a route in case out-of-nominal situations would happen. In the first part of the paper, a general methodology to perform an autonomous replanning is proposed, with a particular attention to the techniques already proposed and studied by other research teams [1, 2]. This activity can be seen as a preliminary study to create an algorithm able to propose alternative routes in case replanning actions would be required. In this context, it was necessary to define how many and what kind of critical conditions the UAS has to recognize and correct autonomously. All these critical conditions were separated in different scenarios. With the aim of studying the replanning algorithms for each scenario, the earlier phase of this work leads with the definition of the logical processes that stand behind them. The most important purpose of this activity is to define the main requirements and all the logical processes required to allow the mission planning and replanning. All these evaluations would be a guideline for the generation of a code able to autonomously propose in real-time replanned routes, like those proposed in literature [3, 4]. The second part of the work deals with the simulations of the possible mission scenarios using a specific software called STK (Systems Tool Kit, previously Satellite Tool Kit). This tool is employed in the simulation of planned and replanned routes, in order to verify the respect of the scenario constraints (e.g. flight within the boundaries of a segregated area) and the aircraft performances. In conclusion, the paper would like to highlight some peculiar aspects of an autonomous replanning in order to enhance the efficiency and efficacy of an Unmanned Aerial System. This is considered as a fundamental step to develop and simulate replanning solutions for a fleet of Unmanned Aerial Vehicles (UAVs).

1 INTRODUCTION

Unmanned Aerial Vehicles are becoming even more popular, and they are even more required for monitoring and surveillance purposes. Nowadays, for safety reasons, the space in which they are allowed to operate is strictly compliant with national rules and temporary permissions. Indeed, UAV can only fly inside segregated areas, entailing a limit to their employment, but there are many studies trying to create fleets able to autonomously operate within the civil airspace. In order to reach an increase of the level of autonomy of this kind of vehicles and to widen the operational capabilities, each UAV should be able not only to follow a planned route, but also to rapidly change its trajectory in case one or more legs would not be feasible. For a manned aircraft, this problem is strictly related to its handling qualities, while in case of unmanned aircraft proper avionic system equipment (both airborne and on-ground) should be designed. Complementary, replanning strategies should be in-depth studied.

Within this context, this paper addresses viable strategies for planning and replanning missions intended to be performed by UAVs. In particular, the major attention has been devoted in the identification of possible mission scenarios in which replanning actions are required.
The activity presented in this work has been performed within the framework of SMAT F2, an Italian project in which Politecnico di Torino is involved. SMAT (Sistema di Monitoraggio Avanzato del Territorio – Advanced Territory Monitoring System) is a project funded by Regione Piemonte and Fondo Europeo di Sviluppo Regionale (F.E.S.R.), now at its second phase, that studies and demonstrates an advanced monitoring system able to comply with planned tasks (e.g. traffic monitoring, pollution monitoring, plantations observation and measurements, etc.) and to prevent and monitor different types of emergency events (e.g. floods, fires, landslips, etc.).
At first, Section 2 is intended to offer an overview of the previous and current studies about planning and replanning strategies. Moreover, in this section, possible monitoring scenarios in which replanning could be required are listed and described. Then, Section 3 describes the methodology employed in the definition of replanning strategies. Finally, in Section 4 the reader can discover the tools that have been used and relative applications.

2 PLANNING AND REPLANNING STRATEGIES

2.1 Previous and current research on planning and replanning strategies

Many studies have been conducted by teams of experts concerning planning and replanning strategies. The research in this particular field is focused both in civil and in military applications, and various are the reasons that could entail the rerouting of aircraft, like hijackings, failures, weather hazards, variations of the scheduled mission.
In the military field, an important study has been carried out by Cook and Smallman [1]. The authors have conducted a cognitive task analysis interviewing four UAV operators of the Navy's VC-6 Squadron. The research was focused on the challenges and issues of unmanned vehicles rerouting. Replanned routes are cause of new constraints and different hazards, like as instance, weather changes or new enemy air defences. The consequences are the increment of pressure and stress levels on UAV operators and the introduction of new threats on the mission and on the vehicle. From this cognitive study, the researchers have understood the importance of the introduction of new display tools and aids able to provide the operators useful information during the rerouting, like airspace availability and clearance, position and identification of other aircraft, terrain overlay and weather conditions.
In [2] the authors have considered the hazardous event of civil airplanes hijacking. The proposed replanning method should be able to generate alternative routes in real-time in order to avoid aircraft collisions with buildings and critical infrastructures placed on the trajectory. This methodology, based on strategies of direct multiple shooting optimization, operates independently, bypassing the pilot authority.

2.2 Monitoring activities performed by UAVs

This research is focused on the employment of UAVs in civil operations. The use of UAVs instead of manned vehicles is more suitable in missions considered dull and repetitive, like surveillance and territory monitoring (planned tasks), and in dangerous situations, as in case of emergency. Scheduled missions concern the monitoring of vehicular traffic, air pollution and coastlines and the observations and measurements of plantations. Furthermore, the UAS should prevent different types of emergency events, like river floods, fires, landslips, sea pollution. For these reasons, civil UAVs of this study are equipped with EO/IR cameras, Synthetic Aperture Radars (SAR) and Hyperspectral sensors.

2.3 Scenarios description

The starting point of this research is the definition of the number and the typology of critical conditions that the UAS should autonomously identify and correct. As a consequence, four scenarios are identified, describing the following critical conditions:

- *Weather phenomena (No Fly Zone or NFZ) and Permanent No Fly Zone Avoidance*. The event of a weather phenomenon, which could entail hazardous conditions for the UAS, could be the origin of a temporary NFZ. In addition, many other reasons and needs could bring to the creation of a NFZ, causing a route replanning. The aim of the airplane in this scenario is to fly the planned route up to the intersection of the leg (i.e. a segment route between two waypoints) with the temporary NFZ. Then, the UAS shall autonomously replan the route, avoiding entering in the restricted area, and minimizing the difference of flight time between the scheduled route and the new one.
- *New Targets/New Waypoints from SSC.* This scenario takes into account the possibility of the change of the flight plan route by the SSC ("Stazione di Supervisione e Controllo", i.e. ground control station for mission support) once the vehicle is airborne. The UAS should independently modify the course depending on the new assigned targets or waypoints, respecting the replanned route constraints. The logic of the new route planning should minimize the time difference with the original route.
- *Vehicle Failure/Payload Failure after that require to land.* After a vehicle or payload failure, the UAV should abort the mission, start an emergency descending, and point to the closest landing area or termination point. The failure could affect, as instance, an engine or a vital sensor, causing the impossibility of completing the scheduled mission. This scenario should provide two alternatives. The first one concerns the selection from a database of the nearest area suitable for an emergency landing, while the latter refers to the return to the base. However, in case of excessive degradation of the performances due to the failure, the vehicle could be unable to reach the nearest landing zone. In this case, for safety reasons, the UAV should head towards a termination point, which should have been scheduled prior the take-off, within a segregated area.
- *Vehicle Failure and Payload Failure that degrade the overall mission.* Differently from the previous scenario, in this case the vehicle or payload failure is supposed not to force the abortion of the mission. This situation is related to the critical condition of a minor fault, like a failure of a secondary sensor. The reduced performances cause only a scheduled mission modification, as the bypass of certain waypoints because no longer relevant after the failure.

It is important to underline that, in every scenario, the system should be able to replan the route autonomously and complying with the vehicle performances. Moreover, the modification of the scheduled mission introduces new constraints that the UAV should take into account.

3 SYSTEM ENGINEERING METHODOLOGY FOR REPLANNING STRATEGIES DEFINITION

The most important objective of this work is the study of algorithms for UAVs autonomous rerouting.
Starting from each scenario described in the previous section, a Systems Engineering methodology is employed with which, thanks to its iterative and recursive characteristics, it is possible to evaluate the logical sequence of actions that must be accomplished during the planned and replanned missions. In this paper, the realization of a Functional Flow Block Diagram (FFBD) is proposed, whose aim is to illustrate the logical and chronological sequence of functions performed by the system during the route replanning. At the end of the methodology, a list of top-level requirements is derived, which should be matched for the fulfilment of the mission. In this section, an overview of the entire methodology is presented, especially with regard to the phases of the Functional analysis and of the Concept of Operation definition.

3.1 Methodology overview

The methodology starts with the Mission Analysis, in which the mission statement first, and then the primary objectives and constraints are defined.
The mission statement declares the aim of the project. In this particular case, the purpose is:

"To define general algorithms in order to make an Unmanned Aerial System able to perform replanning activities guaranteeing a certain level of autonomy to the Unmanned Aerial Vehicle"

The primary objectives and the constraints derive from the mission statement. The primary mission objective of this study is to perform replanning activities, while the constraint is to guarantee a minimum level of UAV autonomy.
Once the Mission Analysis is performed, the methodology proceeds with the Stakeholder Analysis [5], in which the main actors of the mission (e.g. customers, sponsors, operators and end-users) and their needs are identified. From the study of these needs, secondary objectives (e.g. *"To perform control and monitoring activities"*) and constraints are derived.
Then, the designer has to identify the main actions that should be performed by the system and the components that constitute the product. These results are obtained during the Functional analysis (see Section 3.2) thanks to the employment of three tools: the Functional Tree, the Functions/Products Matrix and the Physical/Functional Block Diagram. From this type of analysis, the functional requirements are derived.
The Functional Analysis is followed by a preliminary Concept of Operations (ConOps) definition (more details in Section 3.3). The ConOps aims to underline all the Stakeholders' expectations, requirements, and the architecture of the project [6]. A connection between the Functional Analysis and the Concept of Operation is represented by the Functional Flow Block Diagram (FFBD), which shows the sequential relationships among all the functions of the UAV rerouting.
During the entire design process, the requirements are derived and divided following the classification proposed in [6].

3.2 Functional analysis

As previously mentioned, the Functional analysis is a method aimed to the physical definition of the system architecture and to the description of the relations among all the elements, based on the functional architecture of the product.
The Functional analysis starts from the definition of all the actions that must be accomplished in respect of the top-level requirements. Then, the obtained functions are decomposed and allocated to the lower levels of the product breakdown structure. Finally, the interfaces between all the elements of the system are defined.
During the Functional analysis, three main tools are useful. The first one is the Functional Tree, which shows all the functions that should be accomplished at System of System (SoS), Segment (i.e. ground or flight segments), System and Sub-system levels.
An example of Functional Tree is reported in **Figure 1**, concerning the top-function "*To perform replanning activities"*. The top-function has to be derived directly from the mission statement.
The second tool that is useful during the Functional Analysis is the Functions/Products Matrix. The object is to select the appropriate components necessary to perform the functions defined before with the Functional Tree.
An example of Functions/Products Matrix, considering only the Segment level, is reported in **Figure 2**. Through this particular tool it is possible to obtain the list of components required for the analysed mission. In this case, at Segment level a Ground Segment and a Flight Segment are defined. The Ground

Segment is composed by all the fixed or portable on ground elements that are able to track a particular mission and its communications. The Flight Segment is considered as a group of flying elements that are able to accomplish a particular mission.

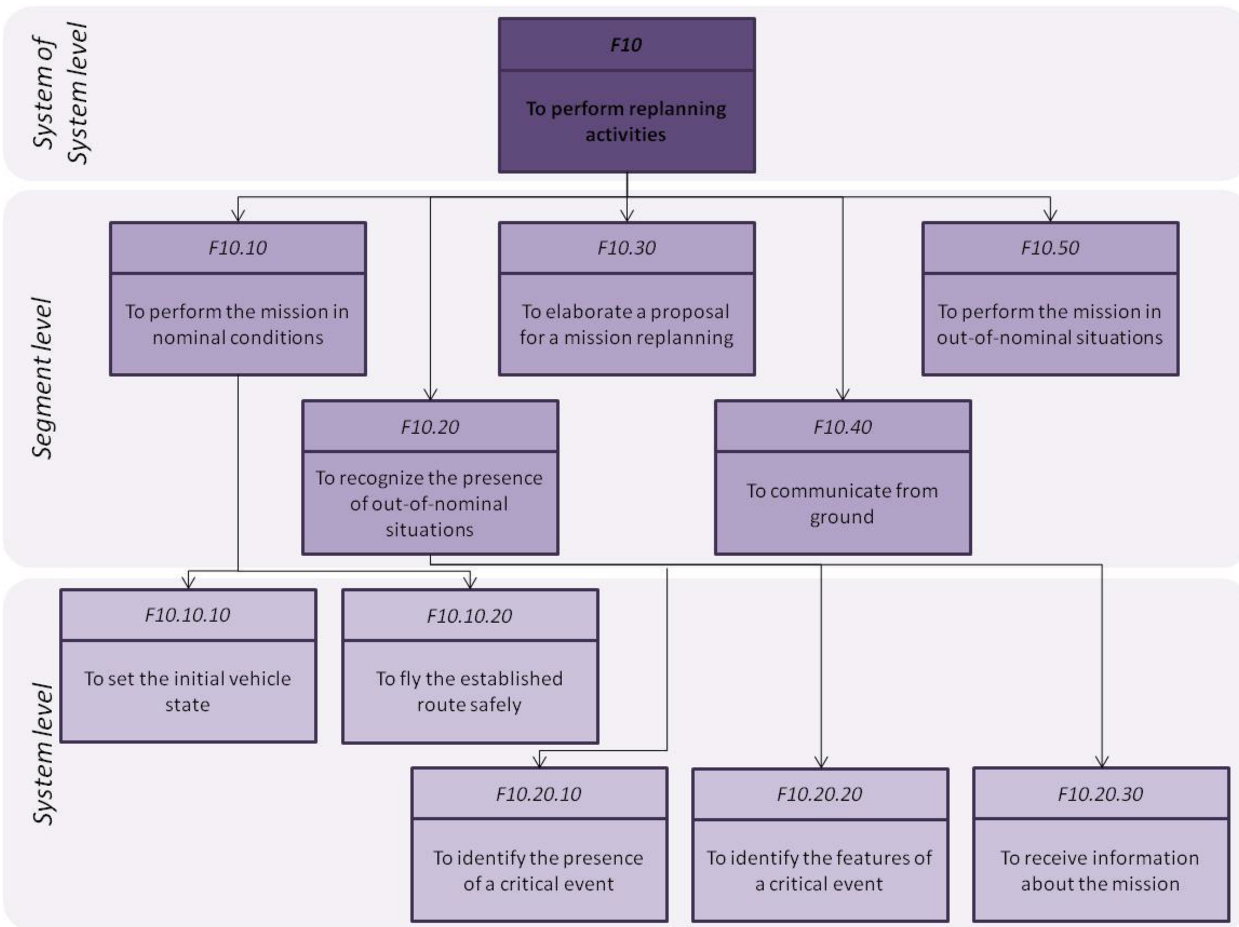

Figure 1: Functional Tree at System Level

SEGMENT LEVEL		SEGMENTS: Ground Segment	SEGMENTS: Flight Segment
F10.10	To perform the mission in nominal conditions		X
F10.20	To recognize the presence of out-of-nominal situations		X
F10.30	To elaborate a proposal for a mission replanning		X
F10.40	To perform the mission in out-of-nominal situations		X
F10.50	To communicate from ground	X	

Figure 2: Functions/Products Matrix at Segment Level

Finally, the last tool used during the Functional analysis and here proposed is the Physical/Functional Block Diagram. Its aim is to define all the relationships and interfaces between the physical elements selected before. In the Physical/Functional Block Diagram, three types of interfaces are considered: mechanical, data exchange and memory allocation. The tool shows the category and the direction of the links among the products, but information about internal relationships is not provided. In **Figure 3** Physical/Functional Block Diagrams at system and segment level are reported.

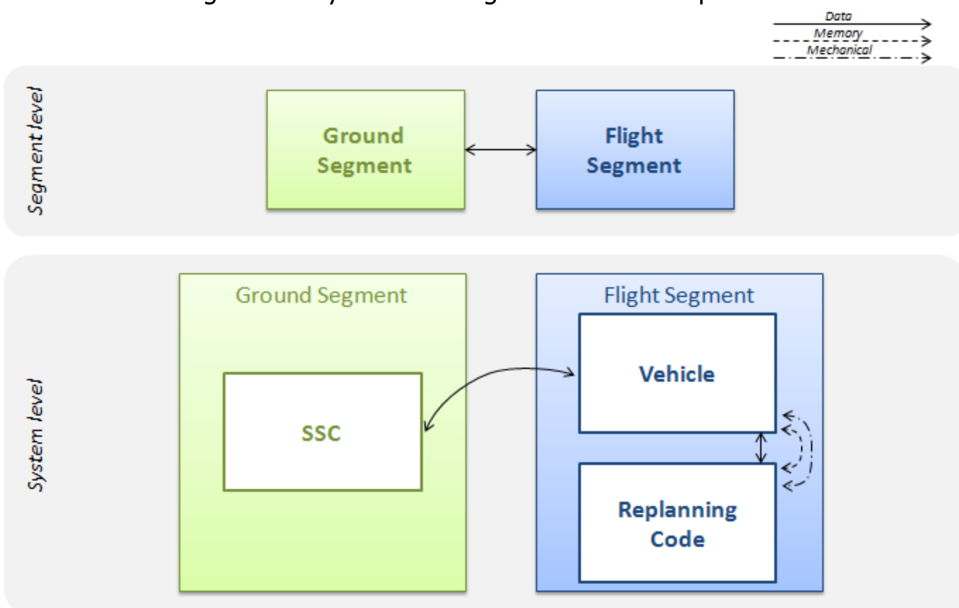

Figure 3: Physical/Functional Blocks Diagram

3.3 Concept of Operations

A description of the system operation during the whole life cycle as expected by the stakeholders is provided by the Concept of Operations. This document describes the characteristics of the product from the users' viewpoint. It should consider all aspects of operations including integration, test, and mission definition from its start though the system disposal.

A connection tool between the Functional Analysis and the ConOps is represented by the Functional Flow Block Diagram (FFBD), whose an example of representation is given in **Figure 4**, which derives from flow charts like the one shown in **Figure 6**. The FFBD illustrates the logical sequence of functions that should be performed by the system.

In the Concept of Operation, a unique mission phase is studied: the cruise phase, which is divisible in two Mission Scenarios. The first one is the nominal cruise, in which no critical events are considered and the route is performed as scheduled. The latter is the out-of-nominal cruise, in which an alternate route should be hypothesized and executed, due to the occurrence of a critical condition or a rerouting. Five Modes of Operations, which are defined establishing which subsystems and equipment are active or not, are identified in the two Mission Scenarios. In both the types of cruise, the following modes are considered:

- Communication Mode: used for data transmission and receiving;
- Waiting Mode: used in the flying phases, when only communication is allowed and the replanning code has to interrupt other activities;

- Evaluation Mode: used comparing data and constraints.

During the out-of-nominal scenario, other two Modes of Operations are considered:

- Saving Mode: used for save and load new data;
- Elaboration Mode: used for the calculation of new data.

Finally, analysing the mission features here described through the logical sequence of action required (FFDB) and the actual organization of the products between them (Physical/Functional Blocks Diagram) and in the mission performed (ConOps), list of significant parameters for the route replanning has been identified. The identification and the study of these parameters is important in order to consider a propter organization for a future replanner.

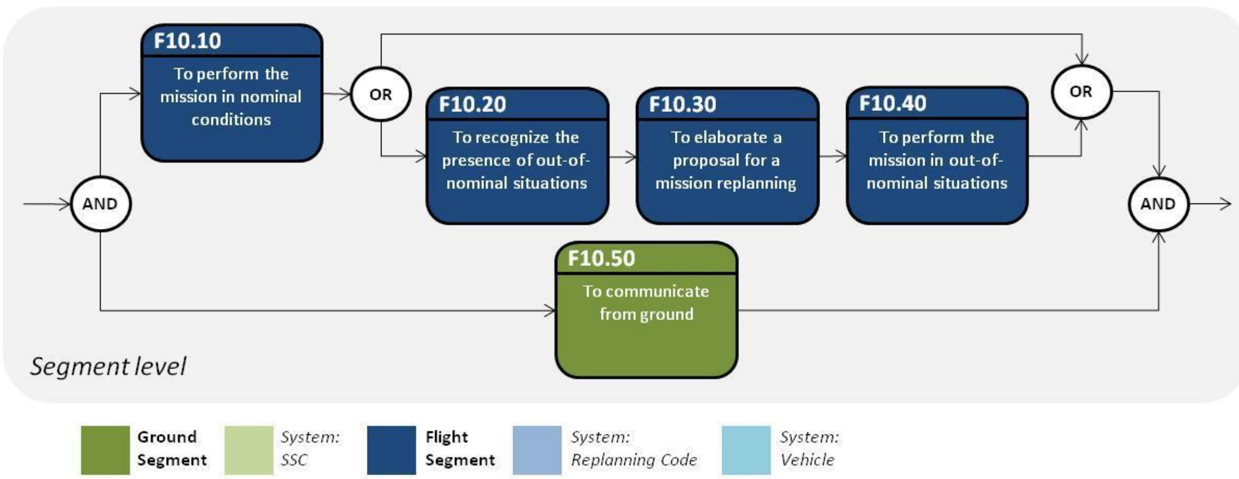

Figure 4: Functional Flow Block Diagram

4 CASE STUDY

4.1 Main objectives

In this section, a case study is proposed, as example of the methodology previously presented and of the achievable results.

A mission located in the first scenario, "*Weather phenomena (No Fly Zone or NFZ) and Permanent No Fly Zone Avoidance*", is considered. The sequence of actions that the replanner should perform is depicted in a flow chart, and the top level requirements are derived. From these results, new waypoints are determined, tracing a new route that is simulated by the tool STK. All the obtained results are reported and discussed.

4.2 Scenario description

The proposed test case is implemented in the first scenario (see **Figure 5**), where a permanent (in blue – prismatic shape) and two temporary (in red – cylindrical shape) NFZs are present.

The preliminary scenario description is reported hereafter:

> *"The MALE UAV has a planned route through many waypoints. Inside the Area of Operations* (AoO) (white line) *there is a permanent NFZ* (blue line) *above the city of Cuneo. In the moment when the vehicle is flying over the waypoint F02 (08:01:22 UTC) data regarding the formation of a weather area, dangerous for vehicle performances, are transmitted. The same happens after waypoint F08: a cylindrical NFZ* (red line) *that interferes with the*

planned route (particularly among WP F12 and F13) is generated. The vehicle will then be able to re-plan the route in order to avoid every NFZ, considering its performances (fuel consumption etc.).”

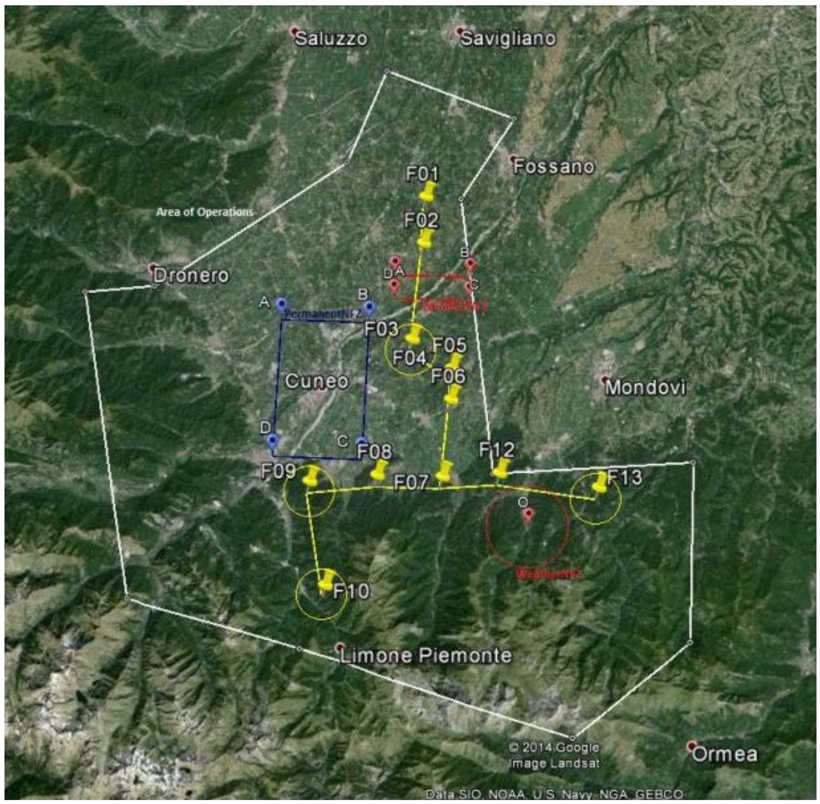

Figure 5: Critical events in the first scenario

4.3 Pre-processing activities

Once the scenario is introduced, the logic process at the base of the replanning algorithms is described, obtaining two results. The first one is described through the definition of the FFDB. For simplicity a flow chart describing only the logical sequence for the analysed scenario is reported in **Figure 6**, in which the logical sequence of the actions that should be performed by the system are depicted. The latter is represented by the top-level requirements that are derived from the logical analysis. A list of requirements is hereafter reported as example:

- The system shall identify the new avoidance route’s WPs.
- The system shall compute the new route in TDB seconds.
- The system shall compute the distance through the starting and the ending WP in the new avoidance route.
- The system shall compute the time over every WP.
- The system shall compare the replanned route features with the vehicle performances.

The results achieved from this functional analysis are used in the hypothesizing route that could result from the autonomous code, in respect of every constraints of the scenario (e.g. terrain morphology, NFZs, segregated area) and taking into account the performances of the vehicle.

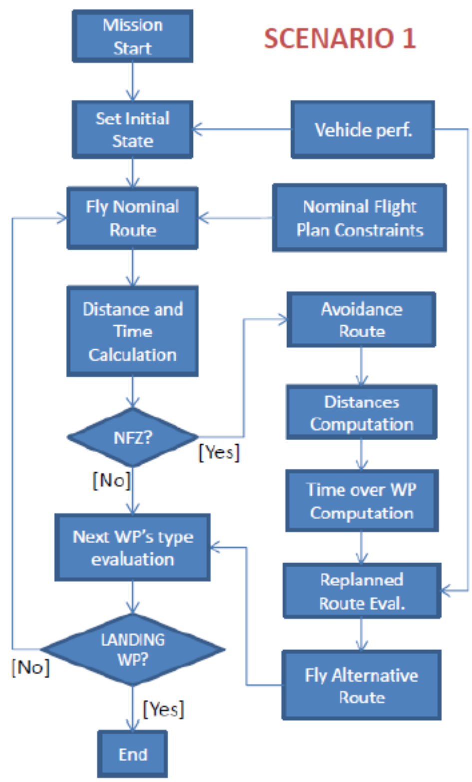

Figure 6: Flow chart of the first scenario

4.4 Processing activities

After the replanned route with the new waypoints is obtained, the results are simulated in STK, a physic-based tool developed by AGI (Analytical Graphics, Inc.) since 1989. It is used in complex analyses on ground, sea, air and space assets. In the beginning, STK was employed in the study of satellites orbiting around the Earth, but nowadays it is used in many other fields of application, like the aerospace.
The software is able to determine not only the asset, the attitude, the dynamic position in the geographical space and in the time. It also defines the existing relationships among the objects modelled including possible relationships (i.e. accesses) taking into account a certain number of simultaneous constraining conditions.
STK is chosen in order to:

- Verify the mission feasibility according to the configuration of the geographical area where the mission has to be performed;
- Visually verify the replanned route features, comparing them with the initial route;
- Verify the accuracy of the results that have been obtained through the route replanning, according to the assumption made (e.g. optimization of mission duration);
- Evaluate the time required to perform the mission, both for the planned and replanned routes;
- Calculate the access: STK is able to compute the exact location and time of the critical situation. For example, in the first scenario STK is able to calculate when and where the UAS would have entered the NFZ if it could not replan the route.

The model in STK is composed by the UAV performing the original route and by the UAV flying above the new waypoints, with the same characteristics given as output by the autonomous replanning code. The

permanent and temporary NFZs are modelled within the scenario, as described in Section 4.2. Moreover, a 3D map with altitude information is added to the model, in order to verify the geographical collocation of every route. Furthermore, STK is able to estimate the flight time in both planned and replanned routes, pointing out the duration difference between the two missions.
The results obtained through the software are presented and discussed in Section 4.5.

4.5 Analyses of the outputs

The results obtained through the simulation in STK are shown in **Figure 7**. The UAV is planned to fly on the scheduled route described in Section 4.2, which is represented with the yellow line. Due to the two temporary NFZs caused by hazardous weather, the vehicle is supposed to autonomously change its waypoints to ensure safe conditions. For this reason, the replanner code should be able to respect all the constraints present within the scenario. The new route should be planned outside the permanent NFZ around the city of Cuneo and within the limits of the AoO (white line) and it should minimize the flight time difference with the scheduled route. A hypothetical replanned route is represented by the red line. STK software estimates a duration increment of the new mission of nearly 1 minute and 26 seconds.
The simulation in the STK environment allows a visual check of the replanned route. From 3D views, terrain avoidance and respect of NFZ, AoOs and corridors (i.e. zones connecting airports and AoOs in which the aircraft has only a transit task) are controlled. Furthermore, the respect of vehicle constraints, like available fuel and performances, is verified, and the observation of assigned targets is confirmed.

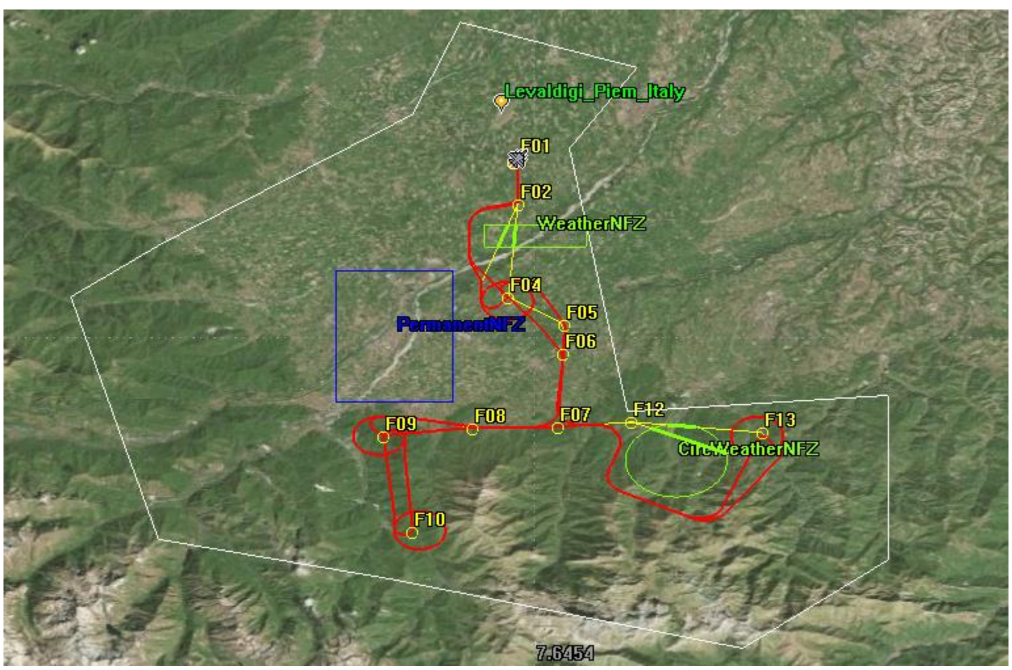

Figure 7: Replanned route simulated in STK

5 CONCLUSION

Various research teams [1, 2] have highlighted the importance of aircraft autonomous replanning. Different are the reasons at the base of this necessity, as obstructing hijackings in civil aviation [2], or alleviate pressure and stress levels on UAVs operators [1].

In this research, strategies about autonomous planning and replanning were proposed, considering the particular case of the employment of UAVs in civil applications, like territory monitoring and intervention in case of emergency (e.g. floods, fires). All the possible criticalities were divided in four possible scenarios: 1) the route is diverted because of permanent or temporary No Fly Zones (NFZ); 2) the scheduled mission is modified by the ground control station; 3) a major failure forces an immediate landing (or the descent to a termination point); 4) the mission is downgraded (some waypoints are skipped) in case of a minor fault.
The study is the preliminary design of a replanning code able to autonomously generate new routes, in accordance with the mission scenario constraints and the vehicle performances. A methodology based on a Systems Engineering approach was proposed and it was used to define the logical process that lies behind the code. With this method, a Functional Flow Block Diagram able to describe the chronological sequence of actions that should be performed by the UAS was depicted. Moreover, a list of top-level requirements, which must be matched by the vehicle in order to fulfil the mission, was derived.
Finally, a cased study of the proposed methodology was presented. The results were used in the identification of an alternative route, which was simulated and verified through STK software. This test case has validated the replanning strategies proposed in the paper. Future work will study the implementation of these algorithms within codes for autonomous real-time replanning, which could be applied to a fleet of UAVs.

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