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Optmized Preflight Planning for Successful Surveillance Missions of Unmanned Aerial Vehicles

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Abstract—**This paper investigates the flight planning for surveillance missions of unmanned aerial vehicles. It proposes a prototype of preflight planner for different operative scenarios. The planner is able to provide an optimized route planning taking into account several constraints (e.g., the vehicle dynamics, the no fly zones, the endurance, the feasibility of the mission objectives, the terrain separation, etc.). It also provides a quantitative estimation of the air data link coverage and of the National Imagery Interpretability Rating Scale (NIIRS) index for the image quality. An overview of the prototype and of the planning approach is reported and some significant test results are discussed in order to show its features.**

Keywords-UAV; surveillance mission; optimal flight planning; payload management; NIIRS.

I. Introduction

This paper is an extended version of [1]. Compared with the previous work, here we provide a detailed survey of the background for the surveillance missions of Unmanned Aerial Vehicles (UAVs) and we add the design of a new functionality of the Route Planner module implementing the optimal allocation strategy of the sequence of targets.

UAVs are suitable to accomplish the D-cube (dull, dangerous and dirty) missions [2]. Dull operations are too monotonous or require excessive endurance for human occupants. Dirty operations are hazardous and pose a health risk to a human crew. Dangerous operations could result in the loss of life for the onboard pilot.

The D-cube terminology was originally defined within the military field, but is also applied to the civil sector. Examples of military applications include ISTAR (Intelligence, Surveillance, Target Acquisition and Reconnaissance) missions, such as visual detecting of enemy tanks and troop movements and surface-to-air missile launcher suppression. Civil applications include investigation in post-disaster areas for search and rescue operations and monitoring of environmental phenomenon in harsh scenarios (e.g., monitoring nuclear radiation). Moreover, recent advances in UAVs' technology allowed the emergence of a wide range of applications, such as for military operations [3], for disaster management [4], for urban terrain surveillance [5], and for agricultural surveillance [6].

A UAV is an aircraft with no human pilot onboard. It is the central element of an Unmanned Aerial System (UAS), which is the set of the aircraft and all the other elements supporting its service, including the Ground Control Station (GCS) and the payload.

Nowadays, UAVs are mostly Remotely Piloted Vehicles (RPVs) since their operations are performed by large teams of human operators, who remotely pilot the aircraft and control its actions. For RPVs, ground operators must be endowed with the proper expertise and this represents a substantial constraint, especially concerning costs. Dull missions particularly stress the training requirements. These considerations push the necessity to extend aerial platform capability related to autonomous flight. Therefore, one the main objectives of UAV research is to reduce the reliance on human operators in order to make UAVs a more economical and scalable technology. Indeed, tedious and repetitive tasks could relieve the task load of the remote pilots if they were autonomously performed and could provide a formal guarantee of the mission success. This approach would reduce the operators' workload with regard to system specific tasks, that are usually detailed and monotonous. Besides, it would allow the operator to focus on global situation awareness and emergency decision-making actions and it would limit their fatigue and lack of attention. A reduction of operational costs would also be achieved since the number of necessary members of the ground human team would be minimized.

This is also true for the tasks relating to mission preflight operation, such as the design of the flight path. In general, an integral part of UAV operation is the design of a flight path that attains the mission objectives. Flight planning shall ensure that the UAV operates in a safe and efficient way. Moreover, the mission effectiveness shall be ensured by verifying that all the required objectives are fulfilled by means of the design route.

This work deals with an offline flight planner, named PreFlight Planner (PFP), wherein the mission objectives concern the proximal sensing of geographical targets. The PFP is a Java software prototype, which is in charge of the 4D flight planning for different samples of UAVs. The 4D flight planning problem is concerned with finding a path that links a specified initial state and several goal states. These states are four-dimensional (three spatial and one time dimension). It is also a constrained problem. Thus, the proposed PFP is able to take into account the vehicle dynamics, the no-fly zones, the endurance, the data link coverage, the feasibility of the mission objectives, the terrain separation, etc.

The proposed software is an innovative UAV flight planner since it permits:

- a planning that is jointly based on the mission targets and the payloads;
- the insertion of emergency and termination routes;
- the verification of performances and constraints complying with surveillance mission objectives;
- an optimal allocation of the sequence of targets to cover.

The rest of this paper is organized as follows. Section II discusses the background. Section III provides an overview of the prototype and its software architecture. Section IV addresses a detailed analysis of the approaches for the flight plan verification. Section V details the approach for the route planning. Section VI presents some significant test results.

II. Background

This section provides some essential introductive concepts for the description of the PFP, such as the surveillance missions of UAVs, the related planning, the possible support tools and the image quality metrics for the evaluation of surveillance tasks.

A. Surveillance Missions of UAVs

A UAS is made up of [7]:

- **Airframe** – It is the mechanical component of the vehicle. It consists in the propeller(s) and the servos that actuate the control surfaces.
- **Flight Control System** (FCS) – It collects aerodynamic information by means of a set of sensors and controls the propulsion system and the servos.
- **Payload** – It is the specific equipment to accomplish a given mission. It may include cameras, infrared sensors, synthetic aperture radars, etc.
- **Ground Control Station** (GCS) – It is a network of computer systems on the ground, which monitor and control UAS operation.
- **Communications infrastructure** – It is the set of data links enabling communication between the aircraft and the GCS.
- **Launch and recovery systems** – They are special means to launch and recover the vehicle.

One of the most common applications of UAVs are surveillance missions or observations missions, which employ the UAS as an observation platform in order to locate a target entity within a Region of Interest (ROI). Thus, the UAS has to scan a given area, to track a fixed or mobile entity, to detect a predefined event and to monitor its evolution, etc. The surveying and reconnaissance capabilities of the vehicle depend on the sensor payload features.

A typical surveillance mission of a UAV includes a mission scenario with a number of geographically distributed targets in a given ROI. Hence, the UAV is in charge of visiting these targets and to perform the needed manoeuvres and the sensing activities for their observation, according to the requirements of the specific surveillance mission. Each target shall be observed for the UAV to accomplish the mission.

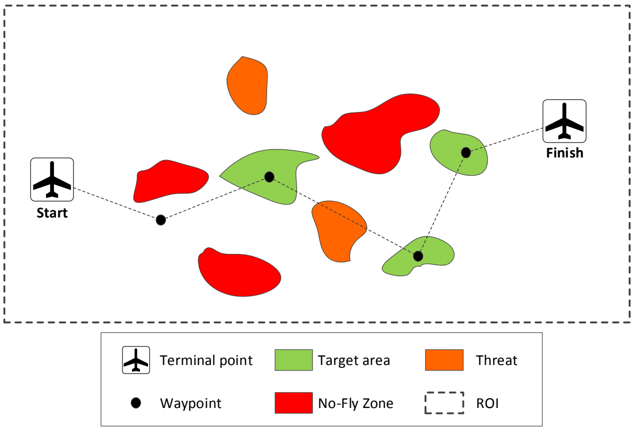

Figure 1. Two-dimensional graphical representation of a UAV surveillance mission.

Figure 1 graphically illustrates a two-dimensional description of the required mission.

Actually, the considered surveillance mission is an exploration mission since the UAV shall cover all targets once. Other instances of surveillance mission exist, such as the persistent surveillance mission (wherein all targets shall be continuously visited) and the coverage mission (wherein a certain ROI shall be completely covered). Anyway, the solution approach for the exploration mission may be easily extended to the other instances of surveillance mission.

In order to partially automatize the preflight operation for a surveillance mission of a UAV, an offline planner shall be introduced. Generally speaking, a planner is an abstract and explicit deliberative process that chooses and organizes actions by anticipating their expected outcomes. This process aims to achieve some predefined objectives as best as possible. Then, the planning of a surveillance mission of a UAV needs to generate a surveillance strategy for the vehicle that fulfills the requested mission objectives in an optimal way.

The planning of a surveillance strategy shall usually process two types of plans [8]:

- the flight plans, that allow the vehicle to reach the targets requested by the operator and to perform the manoeuvre for the successful sensing of the targets;
- the activity plans, that allow the boarded payloads to execute the necessary activities on a target for the successful fulfilment of the mission.

The proposed problem should be stated as an optimization problem since the planning is expected to produce plans which somehow maximize the mission effectiveness, accruing an utility and optimizing a convenient cost function. This optimization problem has to be constrained because the plans shall respect a set of constraints, which may be explicit (i.e., related to the mission definition) or implicit (i.e., related to the operative scenario, such as the configuration of the vehicle and the external context). Constraints may be further classified in:

- mission constraints, that are related to mission objectives;
- system constraints, that are related to the system configuration and state (the adopted vehicle model, the ground control station, the payloads, etc.);
- path constraints, that are related to the features of the region of interest (e.g., no fly zones).

Concerning the targets allocation for the flight planning, different approaches may be used. The spatial queue approach treats the target allocation problem as "customer" representing spatially distributed demands. Formally, spatial queues assume that a model of the exogenous component of the process exists, such as a stochastic model of the spatio-temporal distribution of the arrivals of customers. The graph theoretic approach, instead, represents the allocation problem as a search of the optimal path on the graph.

B. *Support Tools for UAVs Missions*

A UAV mission may be divided in two main parts: the flight and the fulfillment of the assigned objectives. Objectives are reached by means of onboard payloads. A typical UAV mission starts with the assignment of the objectives, goes on with the definition of the flight plan to reach them and the execution and control of the flight from take-off to landing, and it ends with the post flight analysis of collected data.

All such phases are supported by different types of software, that may be categorized in:

- **UAV Activities Management** – Software to manage the different activities of UAV fleets and related projects at business level, maintenance plans and pilot workload. Different platforms providing such services are going to be developed in Europe.
- **Flight Management** – Software allowing the execution of the flight from take-off to landing. This includes both Ground Control Station (GCS) software and onboard guidance, navigation and control software (autopilot). The autopilot works according to the flight plan and by means of sensing and actuating. The typical UAV ground control software receives telemetry data from the UAV and sends telecommands to it. It allows the aircraft operator to communicate the flight plan to onboard autopilot and/or to remotely control the UAV. It may support First-Person View (FPV) equipment to enhance the situational awareness of the remote pilot. In these fields, much research effort has been focusing on relevant aspects such as the perceptual and cognitive issues related to the interface of the UAV operator, including the application of multimodal technologies to compensate for the dearth of available sensory information. GCS software products usually allow to manage one UAV and they are combined to the UAV autopilot. For example, APM (ArduPilotMega) is the GCS of all UAVs with ArduPilot, a 3D robotics autopilot. Paparazzi GCS is the software employed in projects using the UAV Paparazzi platform [9]. It allows the design of the flight plan as well as the system configuration by means of a TCP-IP aircraft server. DJI provides a PC ground station for multi-rotor UAVs and manages the no-fly zones by means of a global list with a safety margin of 8 km [10]. The KopterTool is the ground software for the platform MikroKopter [11], whereas OpenPilot is an open platform [12]. Currently, it is possible to find commercial GCSs for multi-UAV systems ranging from the advanced proprietary and closed solution by Boeing for the X-45, Parrot SDK systems of PrecisionHawk, Draganfly, and Aeryon to open source solutions as QGroundControl Station and others [13]-[23].
- **UAV Payload Management** – Software enabling the management of the onboard payloads during the flight. This class allows the fulfillment of the assigned mission objectives. Payload management products may be integrated into ground control software or not. They strictly depend on the payload model and type. The payload usually provides its own control software.
- **UAV Post Flight Analysis** – Software producing evidences on the basis of data collected by the UAV during the flight. In the photogrammetry domain, companies such as Erdas or Inpho have been proposing solutions for UAV. APS from Menci Software has been one of the first platforms for UAV in Italy. It provides some additional functionalities, such as StereoCAD and Terrain Tools to enhance the cartographic data, and APSCheck for the check of the collected images. It also allows to validate and classify the collected data [24]. Pix4D from Pix4D Switzerland (a spin-off of Swiss university) provides Pix4Dmapper Capture App, which allows to display on tablets or smartphones the images from commercial UAVs, like the DJI Phantom. ENSOMosaic Suite and PIEneering ([25], [26]) offer different and integrated solutions from flight planning software to post flight photogrammetric analysis, including 3D models. The PhotoScan platform from Agisoft proposes the SFM (Structure For Motion) innovative approach. PhotoScan Professional and Standard Edition products are cheap and are open enough to accomplish the growing needs from applications [27]. Cloud services for UAV (like REDcatch GmbH [28], Agribotix [29], and the Maps Made Easy project [30]) may support UAV not only for planning, but especially for post flight elaboration of geo data. Additionally, a transversal category may be considered regarding the 3D modeling and vision digitalizing to realize 3D model and advanced visualization applications.

- **UAV Flight Planning** – Software implementing: the strategic planning, which occurs before take-off and takes a priori information about the environment and the mission goals to construct an optimal path for the given objectives; the tactical planning, which involves re-evaluation of the flight plan during flight.

Table I summarizes the types of support tools for UAVs missions and the related examples.

TABLE I. SUPPORT TOOLS FOR UAVS MISSIONS

Category	Tools Description
Activities Management	Management of the UAVs fleet
Flight Management	Execution of the flight from take-off to landing (APM, Paparazzi, KopterTool, OpenPilot, QGroundControl Station)
Payload Management	Management of the onboard payloads
Post Flight Analysis	Production of evidences on the basis of collected data (APS, Pix4D, ENSOMosaic Suite, PIEneering, PhotoScan, REDcatch GmbH, Agribotix, Maps Made Easy)
Flight Planning	Strategic and tactical planning of the UAV flight

Such software enables each UAV to properly flight followed by its own GCS, but two point seems to need further studies:

- to guarantee a successful mission, what about the flight plan and the clear sight of the targets associated to mission objectives?
- to guarantee the UAV flight according to airworthiness requirements, which ground station will cover the UAV?

A careful study of the market and of the existing products shows that very few products combine these aspects.

C. Images Quality Metrics

As regards the mission objectives, the first issue in devising a surveillance planner is to agree what it means to do a good surveillance job and to define a surveillance performance requirement. In particular, in any application where proximal sensing on a specific target is required, a variable that plays an important role is the quality of the set of pictures. Many image quality metrics have been proposed in the recent years [31].

The quality of images is expressed by several technical parameters, such as ground sampling distance (GSD), modulation transfer function (MTF), signal to noise ratio (SNR) and National Imagery Interpretability Rating Scale (NIIRS). However, these parameters may partially address interpretability. GSD is related to the spatial resolution of images and is probably the most popular parameter. This is not the ultimate parameter to describe quality of images. For example, images with a same GSD may have very different interpretability. MTF and SNR may specify some aspects of image quality.

For this reason, the NIIRS index has been proposed as a measure of image quality in terms of interpretability criteria. It has been applied with multiple types of imagery and offers a robust approach to developing an evaluation scale. It was formerly defined for intelligence and military use and extended to civilian use later on. The general approach is to use image analysis tasks to indicate the level of interpretability for imagery based on the detection of the object. The scale is defined so that when more information may be extracted from the image, the NIIRS rating increases. A set of standard image analysis tasks or “criteria” defines the levels of the scale. The NIIRS consists of 10 graduated levels (0 to 9), with several interpretation tasks or criteria forming each level. These criteria indicate the level of information that may be extracted from an image of a given interpretability level. All NIIRS rating levels are described in Table II.

TABLE II. NIIRS LEVELS [32]

Rating Level	Description
0	Interpretability of the imagery is precluded by obscuration, degradation or very poor resolution.
1	It is possible to: distinguish between major land use classes; detect a medium-sized port facility; distinguish between runways and taxiways at a large airport; identify large area drainage patterns by type.
2	It is possible to: identify large fields; detect large buildings; identify major road patterns; detect ice-breaker tracks; detect the wake from large ships.
3	It is possible to: detect large area contour ploughing, individual houses in residential areas, trains or strings of rolling stock; identify inland waterways navigable by barges; distinguish between natural forest and orchards.
4	It is possible to: identify farm buildings as barns, silos or residences; detect basketball or tennis courts in urban areas; identify individual tracks, rail pairs and control towers; detect jeep trails through grassland.
5	It is possible to: identify individual rail wagons by type; detect open bay doors of storage buildings; identify tents at recreational camping areas; distinguish between coniferous and deciduous trees during leaf-off conditions; detect large animals in grasslands.
6	It is possible to: identify cars as saloon or estate types; identify individual electricity or telephone posts in residential areas; detect footpaths through barren areas; distinguish between grain crops and row crops.
7	It is possible to: identify individual railway sleepers; detect individual steps on a stairway; detect tree-stumps and rocks in forest clearings and meadows.
8	It is possible to: identify vehicle grille detailing and/or the license plate on a truck; identify individual water lilies on a pond; identify the windscreen wipers on a vehicle; count individual lambs.
9	It is possible to: identify individual barbs on a barbed-wire fence; detect individual grain heads on small grain crops; identify an ear tag on livestock.

Because of different types of imagery support different types of interpretation tasks, individual NIIRS indexes have been developed for four major imaging types: Visible, Radar, Infrared, and Multispectral. It provides a simple, yet powerful, tool for assessing and communicating image quality and sensor system requirements and it has been used for our purposes to provide a direct criterion to validate the waypoint and the relative legs associated to mission targets objectives. In other words, a target will be considered successfully acquired or observed if the related payload image exhibits at least the requested NIIRS value.

III. High-Level Description of the UAV PreFlight Planner

This section provides a high-level description of the PFP, by detailing the concepts behind the prototype and the software architecture.

A. PFP Concepts

This work concerns the PFP, that is a strategic planner allowing the mission controller to plan (edit), validate and then upload the flight plan to the UAV. It proposes a solution of an offline flight plan validated against aspects related both to mission objectives (acquisition of targets) and path constraints (such as no fly zones) and system constraints (such as data link coverage). The effectiveness of the acquisition of targets is enabled by a quantitative assessment of the NIIRS index. The PFP does not include the planning of payload activities.

Research has focused on the identification of approaches and optimization algorithms which select the best route to guarantee the feasibility according to the vehicle performances, the compliance with the safety objectives, the endurance, the ability to return to base, and the terrain profile.

The problem of flight planning is an instance of the generic path and motion planning problem, regarding the synthesis of a geometric path from a starting position to one or more targets and of a control trajectory along that path that specifies the state variables in the configuration space of a mobile system. The adopted approach for the optimal targets allocation is graph theoretic.

B. PFP Software Architecture

The PFP is a Java software prototype which allows to plan a mission of a UAS, namely, to identify the mission objectives and to design the mission path to observe them. Furthermore, the PFP ensures the success of the planned mission. The success assurance of the mission is attained by guaranteeing the following properties for the designed plan:

- the dynamic feasibility from a 4D point of view by means of the selected vehicle;
- the terrain separation;
- the compliance with the no-fly zones, i.e., the 3D regions that shall not be entered by the UAV;
- the compliance with the safe zones, i.e., the 3D regions that are reserved for the UAV flight and that shall not be left by the UAV;
- the endurance, which requires that the boarded fuel level is enough to accomplish the mission;
- the air data link coverage at any point of the route;
- the visibility of the targets at the related route points.

The preflight verification of these properties is necessary to avoid potential and expensive mission aborts due to neglected offline checks. In particular, the visibility check of the targets is profitable in order to avoid online changes of the UAV flight plan for the achievement of the mission objectives. In this way, the PFP provides a flight plan that is entirely verified and approved to guarantee the success of the designed mission.

In detail, the PFP operation has been structured in three main phases, as shown in Figure 2:

- the setup phase, which allows for the setting of all the configuration data that are required for the planning;
- the planning phase, which identifies all the mission parameters and the actual route taken by means of the waypoints positioning;
- analysis, which allows for the necessary checks in order to verify and approve the designed plan and shows the related numerical results and diagrams.

Moreover, the software structure of the PFP is split into five modules:

- **User Database**;
- **Mission Data**;
- **Route Planner;**
- **Analysis**;
- **Export**.

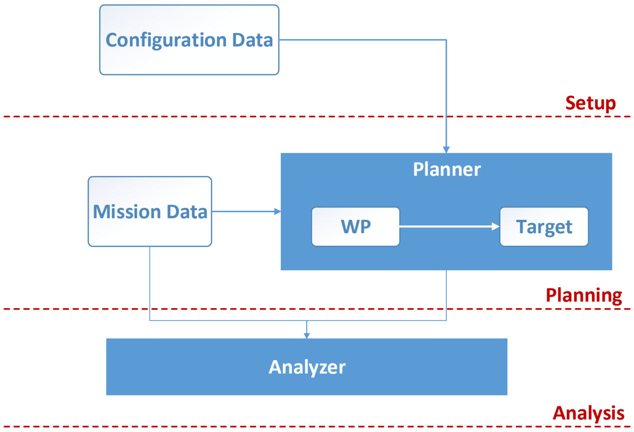

Figure 2. Operation phases of the PreFlight Planner.

The User Database and the Mission Data modules are employed in the setup phase, the Route Planner is used in the planning phase and the Analysis module performs the analysis phase.

Figure 3 shows a block diagram of the software architecture of the PFP. It also graphically depicts the data flow amongst the different modules.

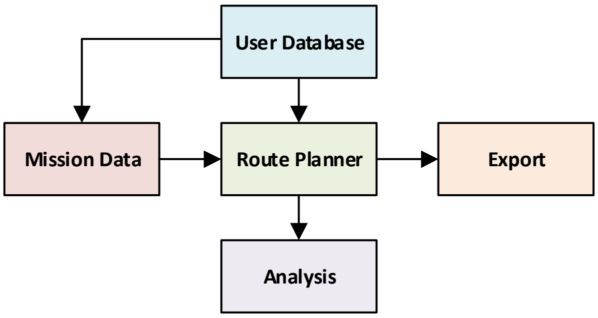

Figure 3. Data flow diagram of the PreFlight Planner.

1) User Database Module

The User Database is the module for the management of the database of the reusable data. Such data refer to objects that are used for the planning of a mission, but are not specific of a single mission. On the contrary, they may be defined and reused without modification in order to simplify the operator throughout the generation of a mission plan.

Some of the reusable entities are: aircrafts; airports; payloads that may be boarded; point targets, i.e., mission objectives without a significant size; area targets, i.e., mission objectives with a significant size; user waypoints, which are defined by the user; standard waypoints, which are standard aeronautic waypoints; air data links, i.e., the transmission/reception instruments that may be boarded; no-fly zones and safe zones; patterns, i.e., waypoint sequences that define significant route segments; contingency routes, i.e., standard routes that may be reused in case of failure in the air data link.

The databases used are described in Table III.

TABLE III. DESCRIPTION OF THE DATABASES

Database	Description
Aircraft	Database of the vehicles.
Payload	Database of the sensors that may be boarded on the vehicle.
Point Target	Database of the punctual targets, i.e., the mission objectives of interest that do not have a significant extension.
Area Target	Database of the extended targets, i.e., the mission objectives of interest that have a significant extension.
User Waypoint	Database of reference waypoints that are defined by the user.
Standard Waypoint	Database of reference aeronautical waypoints.
Map	Database of georeferenced images, which may be displayed in overlay on the map during the mission planning.
Air Data Link	Database of transmission/reception devices that may be boarded on a vehicle.
Data Link Station	Database of transmission/reception devices that may be used in the GCS.
No Fly Zone	Database of the regions that mark prohibited airspace for the flight of a vehicle.
Safe Area	Database of the reserved areas for the flight of a vehicle and from which the exit is prohibited.
Pattern	Database of waypoint sequences, which define reference route segments that may be reused for different missions.
Contingency	Database of standard routes, which have to be used in case of failures of the radio link between the vehicle and the GCS.
Airport	Database of the airports.

In detail, the Aircraft database contains the models of the vehicles that may be used for a mission. These models allow to verify that the planned route belongs to the flight envelope of the selected vehicle. The parameters of the models are grouped for homogeneous classes, which define the vehicle performances throughout the different flight phases: acceleration, cruise, climb, descent, take-off and landing.

The acceleration parameters describe the vehicle performances during the transition from a flight condition to another one (e.g., during a turn or during the passage from an altitude level to another one). Table IV reports the acceleration parameters of an aircraft model.

The cruise performance model includes a set of parameters which define the behaviour of the vehicle during the levelled flight phase. Table V reports the cruise parameters of an aircraft model.

TABLE IV. ACCELERATION PARAMETERS OF AN AIRCRAFT MODEL

Parameter	Description
Turn Rate	Turn rate of the vehicle in a levelled and coordinated turn.
Pull Up	Orthogonal acceleration with respect to the motion vector, which is used during a flight transition from a levelled flight or a dive to a nose-up.
Push Over	Orthogonal acceleration with respect to the motion vector, which is used during a flight transition from a levelled flight or a nose-up to a dive.
Roll Rate	Change rate of the bank angle of the vehicle during a turn.
Pitch Rate	Change rate of the pitch angle of the vehicle during a manoeuvre.
Yaw Rate	Change rate of the yaw angle of the vehicle during a manoeuvre.

The cruise performance model includes a set of parameters which define the behaviour of the vehicle during the levelled flight phase. Table V reports the cruise parameters of an aircraft model.

TABLE V. CRUISE PARAMETERS OF AN AIRCRAFT MODEL

Parameter	Description
Ceiling Altitude	Maximum altitude for the vehicle to hold up a levelled flight without resorting to accelerations.
Default Altitude	Cruise default altitude of the vehicle.
Minimum Speed	Minimum cruise speed (true airspeed), with the related fuel consumption.
Maximum Speed	Maximum cruise speed (true airspeed), with the related fuel consumption.
Maximum Endurance	Cruise speed (true airspeed) that allows for the maximum endurance of the flight, with the related fuel consumption.
Maximum Range	Cruise speed (true airspeed) that allows for the longest path of the flight, with the related fuel consumption.

Table VI reports the performance parameters of a vehicle for the climb flight phase and the descent flight phase.

TABLE VI. CLIMB/DESCENT PARAMETERS OF AN AIRCRAFT MODEL

Parameter	Description
Airspeed	Vehicle speed (true airspeed) in the climb/descent phase.
Altitude Rate	Altitude rate of climb/descent of the vehicle.
Fuel Flow	Fuel consumption during the climb/descent manoeuvre.

Table VII reports the performance parameters of a vehicle for the landing flight phase.

Table VIII reports the performance parameters of a vehicle for the take-off flight phase.

TABLE VII. CLIMB/DESCENT PARAMETERS OF AN AIRCRAFT MODEL

Parameter	Description
Airspeed	Vehicle speed (true airspeed) that is kept during the descent path towards the landing track.
Ground Roll	Covered on-ground distance until the stop.
Fuel Flow	Fuel consumption during the landing manoeuvre.

TABLE VIII. CLIMB/DESCENT PARAMETERS OF AN AIRCRAFT MODEL

Parameter	Description
Airspeed	Vehicle speed (true airspeed) during the taxiing.
Ground Roll	Covered on-ground distance until the take-off.
Departure Speed	Vehicle speed (true airspeed) at the take-off.
Climb Angle	Climb angle at the take-off.
Acceleration Fuel Flow	Fuel consumption during the acceleration for the take-off.
Departure Fuel Flow	Fuel consumption at the take-off speed.

As regards the point targets, they are generally objects (natural or artificial structures), with a negligible extension or non influential for the purposes of the planning. These targets shall be acquired by means of one or more payloads that are boarded on the vehicle. Table IX reports the parameters of a point target.

TABLE IX. PARAMETERS OF A POINT TARGET

Parameter	Description
Latitude	Target latitude.
Longitude	Target longitude.
Altitude	Target latitude.
NIIRS Level	Requested minimum NIIRS for the target acquired image by the sensors.
Date From	Starting validity date of the target.
Date To	Ending validity date of the target.
Info	Description of the target.

Besides, the managed waypoints are compliant with the ARINC (Aeronautical Radio INCorporated) 424 standard, which is the international standard file format for aircraft navigation data.

2) *Mission Data Module*

The Mission Data carries out the management and the insertion of the set of data that characterize a given mission throughout the planning phase. The module is invoked both for the creation and for the change of a mission.

It collects the following data from the user:

- the mission vehicle;
- the mission payloads;
- the air data links for the mission;
- the fuel level;
- the start time;
- the safe zone;
- the ground control stations that are active.

The Mission Data receives the contents of the following databases from the User Database: aircraft, safe area, payload, airport and data link station. and sends its own data to the Route Planner. The data that the operator submits by means of the Mission Data module are then sent to the Route Planner module in order to allow for the creation for the mission scenario.

3) *Route Planner Module*

The Route Planner is the module that accomplishes the flight planning (or route planning) phase. In the following, flight planning and route planning will be used with the same meaning.

Moreover, the Route Planner module performs the following functions by means of the interaction with a georeferenced 2D map:

- insertion of a new waypoint, both as a last waypoint of the route and as an intermediate waypoint between two preexisting waypoints;
- change of a the position and/or of the attributes of a previously inserted waypoint;
- removal of a previously inserted waypoint.

The crossing order of the waypoints may be also modified.

Each waypoint may be related to one or more targets, which shall be observable (i.e., shall exhibit a minimum specified NIIRS) along the route section between two consecutive waypoints. The user may request that a target is observable by means of one or more payloads within the set of boarded payloads.

Besides, every waypoint may be optionally related to one or two contingency routes, that shall be selected within the User Database. One contingency route may be defined as emergency route, whereas the other may represent a termination route: the former is the route to follow if the air data link is lost along the course starting from the chosen waypoint, while the system is waiting for the link recovery; the latter is the route to follow if the air data link is lost along the course starting from the chosen waypoint and it cannot be recovered. Hence, the match between a waypoint and the contingency routes is static.

During the insertion and the change/removal of the waypoints, the Route Planner executes some validity checks in order to ensure that the following two conditions always hold:

1. the vehicle is able to perform the necessary manoeuvres to reach the waypoints;
2. there are no ground impacts (i.e., collisions with the terrain).

If the first condition is violated, the system does not agree to the proposed modification of the route. If the second condition is violated, the system signals the problem to the user, who may also continue the planning without automatic modifications to the route. The module also handles a 3D view of the Earth, that may be invoked anytime and allows a realistic visualization of the mission execution.

Section V deepens the approach for the route planning.

4) Analysis Module

The Analysis module is in charge of the analysis of the flight (or route) plans as a function of the mission objectives. It verifies that all the mission constraints are fulfilled and ensures the success of the plan.

In detail, the following properties of the computed plan are checked:

- the vehicle never leaves the coverage region of the air data links, which is computed by taking into account the positions of the GCSs and the land orography;
- the targets are always visible along the route sections, by taking into account the boarded payloads and the land orography and by envisaging a minimum level of quality of the captured image; if some variable confocal optics are boarded, the visibility check is carried out with four different focal lengths, namely, minimum, 1/3 of the maximum, 2/3 of the maximum and maximum;
- the vehicle never leaves the safe zone, if this is included in the mission planning;
- there are no ground impacts; a minimum distance with the terrain is guaranteed for each point of the route along vertical, frontal and lateral directions;
- the boarded fuel is enough for the accomplishment of the whole flight plan.

The checks are performed starting from the data of the aircraft (i.e., its model parameters), of the payload and of the mission. The results of each check may be displayed both on a 2D map and on a 3D view, by highlighting the route segments wherein the test has passed and the ones wherein the test has failed.

The approach for the flight plan verification carried out by the Analysis module is examined in depth in Section IV.

5) Export Module

The Export module exports one or more planned missions in order to upload them in the Flight Management System (FMS) of the reference UAV.

The interchange format is based on XML (eXtensible Markup Language) and has been implemented by a configurable XML schema.

IV. FLIGHT PLAN VERIFICATION IN THE UAV PREFLIGHT PLANNER

Section III reports the high-level requirements of the Analysis module for the verification of a flight plan.

In detail, the coverage limit of the air data link is computed starting from the link budget equation, i.e.

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} \,, \quad (1)$$

wherein P_{RX} is the power of the signal that arrives at the receiver, P_{TX} is the transmitted power, G_{TX} is the gain of the transmitter antenna, L_{TX} is the transmitter loss, L_{FS} is the loss due to the signal propagation in space, L_M is the safety link margin, and G_{RX} is the gain of the receiver antenna. All these parameters are known and are stored as data of the air data links in the User Database, except L_{FS}. The latter depends on the distance R that is covered by the wave and the wave length λ, which is derivable from the frequency of the transmission channel (also stored in the User Database). In detail, the relation between L_{FS}, R and λ is

$$L_{FS} = 20\ \ln \frac{4\,\pi\,R}{\lambda} P_{RX} \,. \quad (2)$$

In order to receive a signal, the condition $P_{RX} > 0$ must hold. This condition is equivalent to

$$20\ \ln \frac{4\,\pi\,R}{\lambda} < P_{TX} + G_{TX} - L_{TX} - L_M + G_{RX} = \alpha \,, \quad (3)$$

wherein α is equal to $P_{TX} + G_{TX} - L_{TX} - L_M + G_{RX}$.

Hence, the maximum coverage distance R_{MAX} is

$$R_{MAX} = \frac{\lambda}{4\pi} e^{\frac{\alpha}{20}} \,. \quad (4)$$

As regards the NIIRS quantitative assessment, the first step is the computation of the GSD, which is the dimension of the ground projection of a sensor pixel. If we assume the pixels to be square with dimension d and the acquisition to occur with an elevation angle that is different from $\pi/2$, the ground projection of the pixel is distorted in a rectangle. Starting from Figure 4, the following equations hold

$$x = \frac{d \cdot r}{f} \,, \quad (5)$$

$$y = \frac{d \cdot r}{f \cdot \sin elev} \,, \quad (6)$$

$$\mathrm{GSD} = \sqrt{x \cdot y} = \frac{d \cdot r}{f \cdot \sqrt{\sin elev}} \,. \quad (7)$$

The expected NIIRS may be computed as

$$\mathrm{NIIRS} = A + B \cdot \log_{10}\mathrm{GSD}, \quad (8)$$

wherein A and B are two constants, whose values have been set as $A = 10.251$ and $B = -3.32$ [33].

The structure of eq. (8) and the values of A and B are coherent with the General Image Quality Equation (GIQE). The GIQE is an empirical formula for calculating the image quality that is expected for a given optical system [33]. It is a model that was developed using statistical analysis of imagery analyst responses.

The coefficients A and B and the logarithmic structure were obtained by regression to fit the results of an image evaluation study. In detail, the logarithmic structure of eq. (8) embodies the notion that NIIRS changes by 1.0 for each factor of two in the spatial resolution is equivalent to one unit on the NIIRS scale, namely, a change of ±1 of the NIIRS is equivalent to halving or doubling the distance between the sensor and the observation point. This relationship was confirmed by visual observations [33].

More broadly, the GIQE predicts the NIIRS value as a function of other parameters in addition to the GSD (which is directly related to the spatial resolution). These supplementary parameters are: the Relative Edge Response (RER), which is indirectly associated to the point spread function and that estimates the effective slope of the imaging system's edge response; the SNR and the system post-processing noise gain, which quantify the noise in the post-processed imagery; the system post-processing edge overshoot factor, that measures the amount of edge ringing resulting from post-processing. Within this work, we consider only the spatial resolution (i.e., the GSD) as a parameter for the NIIRS estimation, whereas the other criteria are not considered since they are related to the post-processing phase and the aperture configuration.

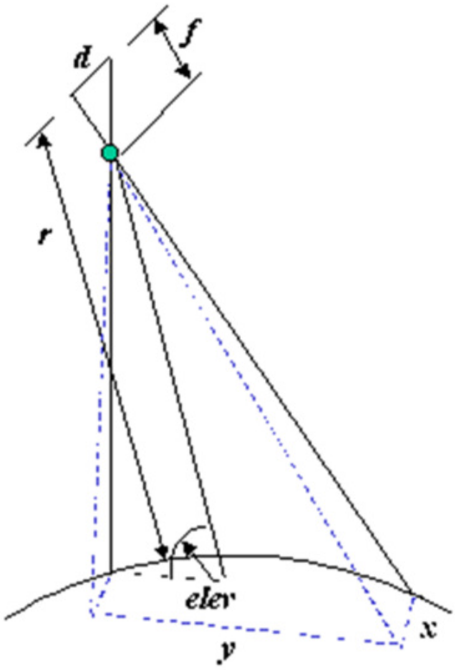

Figure 4. NIIRS quantitative estimation in the PreFlight Planner.

V. Route Planning in the UAV PreFlight Planner

As stated in Section III, the problem of flight planning has to be stated as a constrained optimization problem, whose solution is generally challenging from a computational point of view. A possible solution of this issue is the adoption of a hierarchical decomposition. Indeed, the original problem is a monolithic planning problem, namely, it consists of a single large problem and may be solved only by means of a single large algorithm, which examines all the factors at once. By contrast, a hierarchical decomposition splits the monolithic problem into smaller sub-problems, which are arranged in a hierarchical fashion. The decomposition is usually performed by reducing the degree of detail or the range of the single problems, which is named problem horizon. For instance, the top-level sub-problems may consist of the whole problem range with a small degree of detail, whereas the bottom-level sub-problems may have a small horizon with a high degree of detail. The hierarchical decomposition of the original problem in sub-problems is established by fixing a criterion for the problems horizon (i.e., the range of the single problems). Common horizons are temporal or spatial, wherein the problem is broken down by units of time or distance.

In our case, we use a temporal hierarchical decomposition for the partition of the joint mission planning problem. Therefore, a root planning problem is provided for the planning over the entire mission time and it acts over the total temporal horizon, but with a coarse degree of detail. Instead, the child sub-problems work on shorter temporal horizons and supply accurate plans. As regards the coordination of the hierarchical decomposition, given that the planning problem has to be stated as an optimization problem, we employ the multilevel optimization principle [8] in order to ensure that the system-wide objectives and constraints are respectively optimized and satisfied along the hierarchy.

In particular, the global optimization problem is broken in simpler problems, which are independently solved. Moreover, the upper levels coordinate the solutions of the decoupled problems of lower levels. In our case, the flight planning problem for the surveillance mission of a UAV is decomposed in the following sub-problems:

- the task planning problem, which works over the whole temporal horizon and aims at an optimal scheduling (assignment and ordering) of the targets to cover and at the generation of an optimal high-level (i.e., with a coarse degree of detail) trajectory;
- the trajectory planning problem, which works over a small temporal horizon and consists in the actual flight planning (i.e., the real trajectory) of the vehicle.

In the case of PFP, the trajectory planning problem has to generate a trajectory that allows the aircraft to reach the targets safely and on schedule. This problem is solved by the Route Planner module, which carries out the computations of the flight plan for the specific aircraft. It employs the performance model of the aircraft in order to ensure the realistic and optimized route. The performance model includes some well-known characteristic parameters, such as cruise airspeed, climb rate, roll rate, etc. The route is modeled by means of a sequence of curves and the state of the vehicle may be analytically computed at any given time. Moreover, this module provides a software geometry engine that accurately illustrates dynamic objects.

The Route Planner module is based on the STK (Systems Tool Kit) product of AGI (Analytical Graphics Inc.). It is a physics-based software geometry engine that accurately displays and analyzes dynamic objects in real or simulated time. It models moving objects and the dynamic relationships of those objects in space. Moreover, it provides the platform and tools for solving system level problems of motion and time.

Instead, as regards the task planning problem, it may be seen as a task allocation problem. Indeed, it produces the selection and the ordering of the waypoints (i.e., the reference points for navigation) for the mission accomplishment and it establishes the optimal ordered sequence of targets to cover. The produced list of waypoints is the reference input for the trajectory planner.

By taking into account the constraints that are handled by the PFP, the stated problem about the task planning for a UAV surveillance mission is surely NP-hard. Indeed, the Travelling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP) are known to be NP-hard [34] and they may be regarded as a special case for the surveillance task planning.

Hence, we firstly make the following further assumptions to enable an approximate resolution: the UAV moves only in a plane (i.e., at a constant altitude); the targets always coincide with a single waypoint; the durations of an acquisition activity on a target by means of the payloads are left out. Under these assumptions, the stated task planning problem is a topological planning problem is a topological planning problem [35]. Here, the landmarks and the gateways are represented by the targets and some distinctive points for the no fly zones, such as their polygonal vertices. The search space may be built by orientation regions, which are defined by landmark pair boundaries. Every landmark pair boundary is a link between two landmarks and it partitions the world into orientation regions. Then, orientation regions are conceptually similar to neighbourhoods and typify the search space as a graph.

Figure 5 shows a graphical depiction of the topological view for task planning problem of a surveillance mission by means of a UAV.

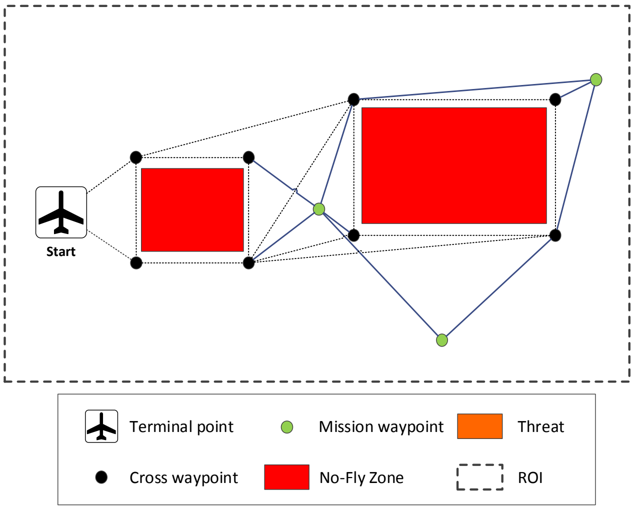

Figure 5. Topological view of the task planning problem for a surveillance mission of a UAV.

In light of these reflections, the total cost of a surveillance itinerary $\boldsymbol{\tau}$ will be related to the assessed time T_τ for its completion. The itinerary $\boldsymbol{\tau}$ is a sequence of allocated tasks (i.e., waypoint) for the UAV and can be described as an ordered sequence of points in the space domain (i.e., the region of interest) W that are assigned to the vehicle, i.e.,

$$\boldsymbol{\tau} = \{\boldsymbol{\tau}_0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \dots\}, \quad \boldsymbol{\tau}_i \in W, i \in \mathbb{N} \,. \tag{9}$$

The single points may coincide with the target areas and may be scheduled for their visitation or may be used for the avoidance of no fly zones. Furthermore, the times to targets are a decision variable and they should be coupled with the itinerary points $\boldsymbol{\tau}_i$. We ignore this and we assume that the UAV moves at a constant speed. Thus, the times to targets are only a consequence of the itinerary scheduling.

The task planning problem for the surveillance mission of a UAV may be formally stated as the search of a surveillance itinerary $\boldsymbol{\tau}_{opt}$ such that

$$\boldsymbol{\tau}_{opt} = \underset{\boldsymbol{\tau}}{\operatorname{argmin}}\ T_{\boldsymbol{\tau}} \,. \tag{10}$$

Each itinerary may be described by a structure with the following attributes: the sequence of the traversed waypoints; the temporal cost T_τ. The behaviour of the planning algorithm has been designed with an iterative approach. At every step, the target with the shortest time to reach (from the current planned position) is selected as a next candidate for the itinerary. If more targets have the same shortest time to reach, they are all selected and an alternative itinerary is processed for each of them.

A new itinerary is computed for every candidate target with the shortest time to reach by invoking the same algorithm with different inputs, which plans an itinerary starting from the current candidate target. The pseudo-code for the task planning algorithm is the following:

```
function task_planning(route_id, residual_scans, start_visit_times, M)
root ← null
do
  if root ≠ null
    route_id ← root.id
    start_visit_times ← root.start_visit_times
    residual_scans ← root.residual_scans
    root ← root.next
  end
  next_targets ← findTargetsWithShortT(start_visit_times)
  start ← last(route_id)
  for k=1 to size(next_targets)
    current_next_target ← next_targets(k)
    route_to_current_target ← Dijkstra(start, current_next_target, M)
    new_start_r_times ← update_visit_times(start_visit_times)
    new_route_id ← update_route_id(itineraries, route_id)
    update_itineraries(route_id, route_to_current_target)
    if residual_time > 0
      new_root.route_id ← new_route_id
      new_root.start_visit_times ← new_start_visit_times
      new_root.residual_scans ← residual_scans – 1
      if root = null
        new_root.next ← null
      else
        new_root.next ← root
    end
while root ≠ null
end
```

The $route\_id$ variable is the identifier of the local route into the planned itineraries set and start_visit_times is the array of targets local visit times. If there are some residual scans (residual_scans) to schedule, the planning strategy schedules the execution of a child process (planning spawns), which will look for an itinerary starting from the current candidate (i.e., the local next target). The candidates are saved on a linked list implementing a stack. The $route\_id$ needs to be updated because the planning could overwrite the current itinerary or could allocate a new itinerary depending on the number of candidates for the spawn point. Besides, the itinerary update involves the update of the related costs. The route for the next target is processed by the Dijkstra algorithm, which operates according to the adjacency matrix M of the topological graph.

The adopted search strategy is:

- best-first, because every spawn selects the next candidate among the most promising targets (the ones with the shortest time to reach);
- breadth-first, because the graph structure is explored starting from the current root node and by inspecting its neighbour nodes (the targets with the shortest times to reach).

The function may be used also in case of re-planning by updating the matrix M.

VI. Test Results

We have conducted a series of tests to verify the correct implementation of the software. The main entities have been tested by creating, modifying and deleting records in different databases and also checking their correct visualization during the planning process. The verification of the analysis has required the creation of a number of flight plans to test the software behavior on different situations. In the following, two test cases are reported.

The first test and the related check results are depicted in Figure 6. The flight takes place in a segregated area (the azure line), the route (the yellow line) consists of eight waypoints, three of which are loiter. The no-fly zone is reported in red. There is a single GCS, but the link coverage is not visible because the area of operations is much less extensive. Two targets are associated to loiter waypoints. As shown by the right side of Figure 6, the flight plan validation fails on two aspects: the targets visibility and the boundaries overcome of segregated flight zone. The PFP analysis module is able to provide other graphic evidences: the non compliance with safety objectives, the issues on target visibility (highlighted red path) and the report on the fuel consumption.

In the second test, the flight plan of the first test has been modified in order to violate the data link coverage, the fuel consumption and the terrain obstacles on a linear target. The outcomes of the analysis are shown in Figure 7, which provides: the evidence that the flight plan is not feasible due to the overcoming of all the considered constraints; finally, the evidence of the link coverage analysis, the problems of visibility on the linear target (a river).

It may be noted that the previous test cases have been discussed in order to highlight the verification and the analysis capabilities of the PFP. Indeed, the checking phase of the PFP is able to verify the compliance of the computed flight plan with all the reference constraints and to guarantee the success of the designed mission. However, some of these constraints are previously taken into account by the Route Planner, which processes the actual flight plan in order to reach the prescribed waypoints by means of the selected aircraft (i.e., the related dynamic model). Clearly, the other constraints are not considered in the planning phase since they do not directly involve the trajectory elaboration. Thus, they may be only evaluated by means of the PFP checks.

As regards the route planning algorithm, some specific tests have been performed in order to exclusively solicit it and to evaluate the time required for the processing of a route plan. The Arduino MEGA 2560 has been used as testing platform. It is a microcontroller board, based on the ATmega2560 microcontroller, with 16 MHz clock speed, 8 kB of SRAM and 2560 kB of flash RAM. Different scenarios have been used, with an increasing number of targets. Table X reports the test results of the route planning algorithm.

TABLE X. Test results of the route planning algorithm

Number of Targets	Planning Time [μs]
5	90728
10	195136
15	299200
20	366048
25	427223

VII. Conclusion and Future Work

This work proposes some new perspectives on UAV preflight panning by pursuing the idea that a flight plan should not only guarantee a successful flight, but also a successful mission. It analyses the typical UAV surveillance missions where proximal sensing is requested and their main requirements. Here, the quality of images is a critical aspect and an approach for its measurement is implemented in the PFP as a criterion to validate the flight plan. Once assured the achievements of the mission targets, the inclusion of other kind of constraints such as the link coverage, the no fly zones avoidance, the evaluation of the emergency and termination routes, etc., guarantees the safety of the produced plan.

The integration of the task allocation optimization in the Route Planner module enables the capability to support the operator in the waypoints identification.

Future enhancement will consider the planning of the route of a fleet of UAVs jointly cooperating to perform a surveillance mission.

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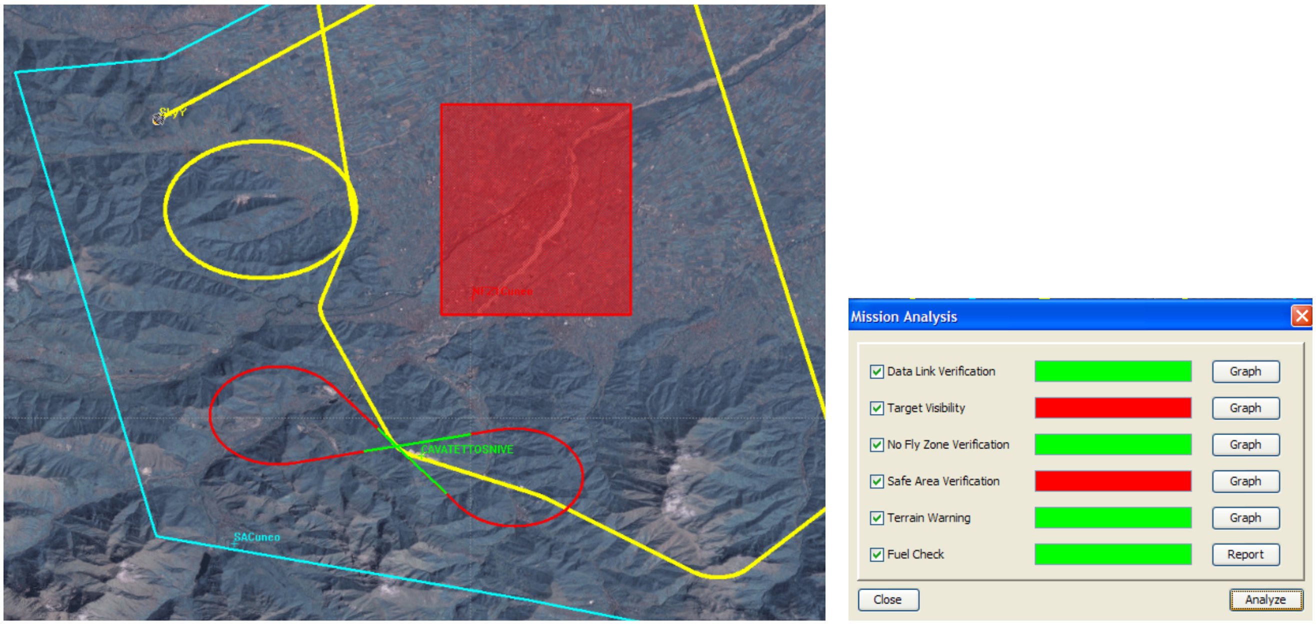

Figure 6. Results of the first test on the PFP.

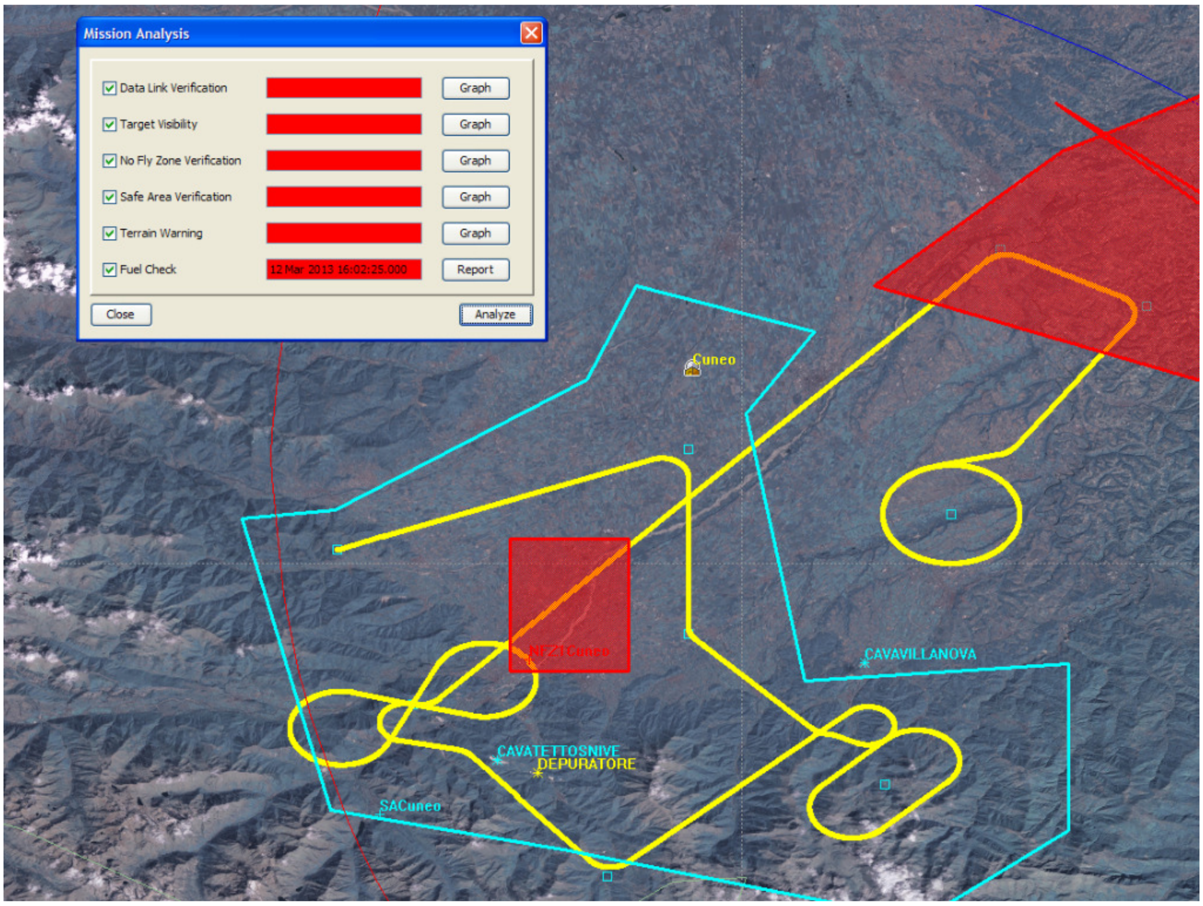

Figure 7. Results of the second test on the PFP.