A Preflight Planner for Succesful Missions of Unmanned Aerial Vehicles

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***Abstract*—This paper investigates the flight planning for unmanned aerial vehicles. It proposes a prototype of preflight planner for different models of unmanned aircrafts. The planner is able to take 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 images quality. An overview of the prototype is reported and some significant test results are discussed in order to show its features.**

Keywords-UAV; flight planner; payload management; NIIRS.

I. INTRODUCTION

An Unmanned Aerial Vehicle (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. Recent advances in UAVs' technology allowed the emergence of a wide range of applications, such as military operations [1], disaster management [2], and urban terrain surveillance [3]. Without the need of an onboard pilot, a vehicle may be designed to accomplish the D-cube (dull, dangerous and dirty) missions [4]. 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. Nevertheless, tedious and repetitive tasks relating also to mission preflight operation (such as the design of the flight path) could relieve the remote pilots if they were autonomously performed and could provide a formal guarantee of the mission success.

Indeed, 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 designed 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. Indeed, the proposed PFP is able to take into account various mission constraints for the planning, such as 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; an integrated insertion of emergency and termination routes; the verification of the performances and the constraints for the achievability of the waypoints and the mission objectives.

In the following sections, the background, an overview of the prototype and some significant test results are discussed.

II. BACKGROUND

An 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:

1. **UAV Activities Management** – Software to manage the different activities of UAV fleets and related projects at business level, maintenance plans and pilots work. Different platforms providing such services are going to be developed in Europe.
2. **Flight Management** – Software allowing the execution of the flight from take-off to landing. Such class 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 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.

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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 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 [5]. 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 [6]. The KopterTool is the ground software for the platform MikroKopter [7], whereas OpenPilot is an open platform [8]. 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 [9]-[19].

3. **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.
4. **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 elaborate the cartographic data, and APSCheck for the check of the UAV shoots. It also allows to validate and classify the collected data [20]. Pix4D from Pix4D Switzerland (a spin-off of Swiss university, born in 2011) 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 ([21],[22]) 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 [23]. Cloud services for UAV (like REDcatch GmbH [24], Agribotix [25], and the Maps Made Easy project [26]) 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.
5. **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.

In this paper, we will refer to the strategic planning allowing the mission controller to plan (edit), validate and then upload the flight plan to the UAV. Research has focused on the identification of approaches and optimization algorithms obtaining 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. 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. The purpose of this work is to extend the capabilities of a UAV mission planner by proposing a solution of an offline flight plan validated against aspects related to mission objectives and data link coverage.

A. Images Quality Metrics

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 [27]. 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 a scale. It was formerly defined for intelligence and military use and extended to civilian use later on. The general approach is to use image exploitation tasks to indicate the level of interpretability for imagery basing on the detection

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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 exploitation 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 I.

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 literature, many tools to predict NIIRS have been proposed. This work addresses a possible approach for a quantitative assessment of the NIIRS index.

TABLE I. NIIRS LEVELS [28]

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.

III. THE UAV PREFLIGHT PLANNER

The PFP is a Java software prototype that 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.

A. *Software Architecture*

The PFP operation has been structured in three main phases: the setup phase, which allows for the configuration of all the mission parameters that are required for the planning; the planning phase, which is in charge of the route design by means of the waypoints positioning; analysis, which allows for the necessary checks in order to approve the designed plan.

The software structure of the PFP is split into five modules: User Database (setup phase); Mission Data (setup phase); Route Planner (planning phase); Analysis (analysis phase); Export. The data flow diagram of the PFP is shown in Figure 1.

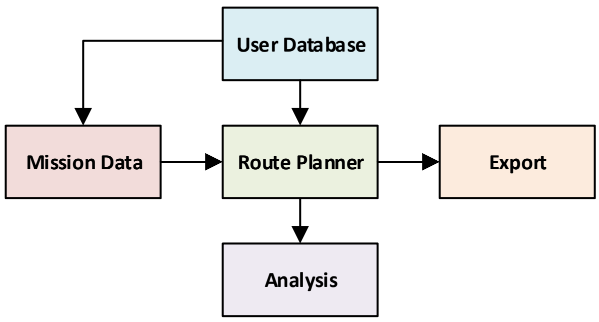

Figure 1. Data flow diagram of the PreFlight Planner.

The User Database is the module for the management of the database of objects that may be applied for different missions (e.g., vehicles, no-fly zones, safe areas, etc.). These objects may be defined and reused without modifications in order to simplify the operator throughout

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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 remarkable route segments; contingency routes, i.e., standard routes that may be reused in case of failure to the air data link. The managed waypoints are compliant with the ARINC (Aeronautical Radio INCorporated) 424 standard.

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, payloads and air data links; the fuel level; the start time; the safe zone; the ground control stations that are active. The Mission Data receives the list of user entities from the User Database and sends its own data to the Route Planner.

The Route Planner is the module that accomplishes the planning phase. Moreover, it performs the following functions by means of the interaction with a 2D map: insertion of a new waypoint; change of a previously inserted waypoint; removal of a previously inserted waypoint. 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 conditions always hold: the vehicle is able to perform the necessary manoeuvres to reach the waypoints; there are no ground impacts. If one of these conditions is violated, the system does not agree to the modification of the route. The module also handles a 3D view of the Earth, that may be invoked anytime.

In more detail, the Route Planner 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 computer at any given time. Moreover, this module provides a software geometry engine that accurately illustrates dynamic objects.

The Analysis module is in charge of the analysis of the flight plans as a function of the mission objectives. It is examined in depth in the following section.

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.

B. Flight Plan Verification

The Analysis module verifies that all the mission constraints are fulfilled and ensures the success of the plan. In detail, the following properties 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.

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

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

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

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

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

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

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 2, the following equations hold

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

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

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

The expected NIIRS may be computed as

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

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

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 [29]. 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 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 [29].

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), that 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.

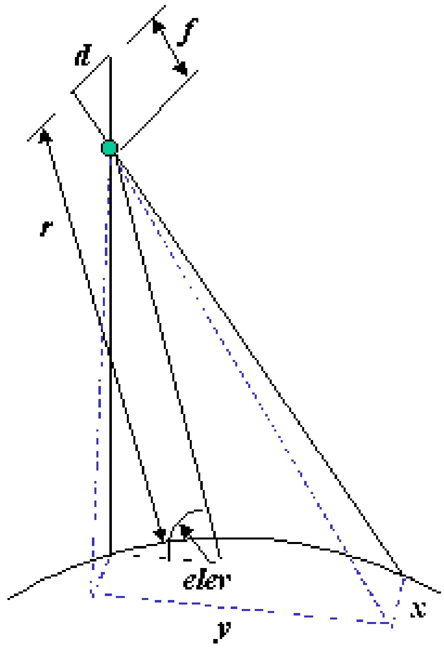

Figure 2. NIIRS quantitative estimation in the PreFlight Planner.

C. 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 3. 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 3, 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 4, 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 formally 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.

IV. 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 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.

In addition, the verification of data link coverage encourages future enhancements by considering a fleet of UAVs with different GCSs. Other possible improvements cannot overlook the research issues concerning the waypoints scheduling optimization.

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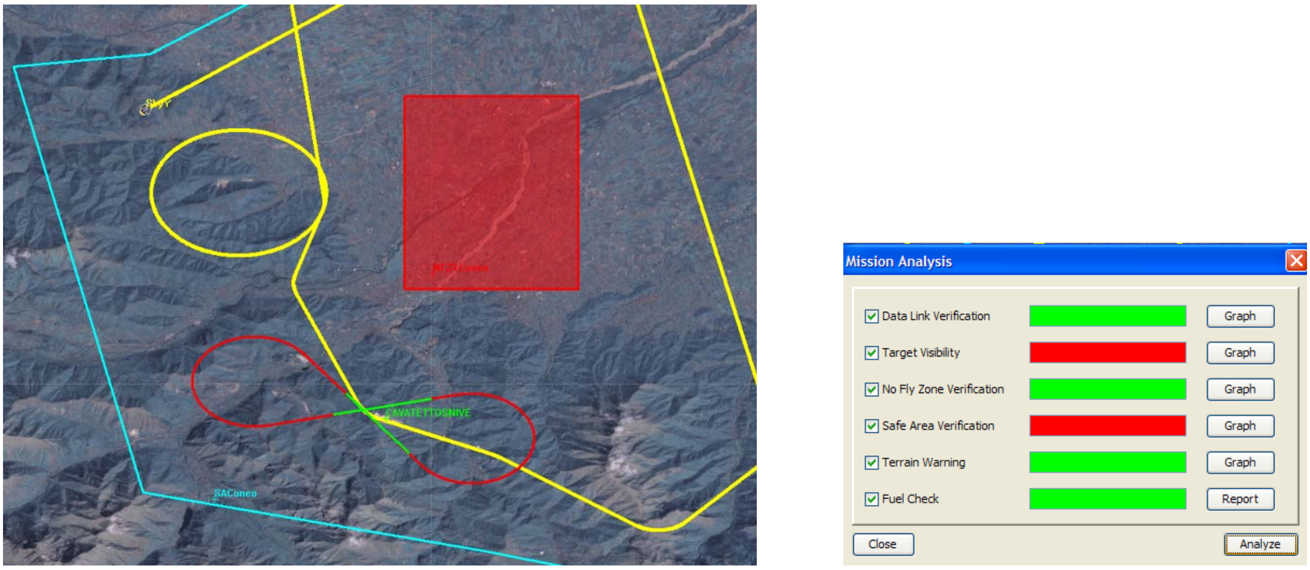

Figure 3. Results of the first test.

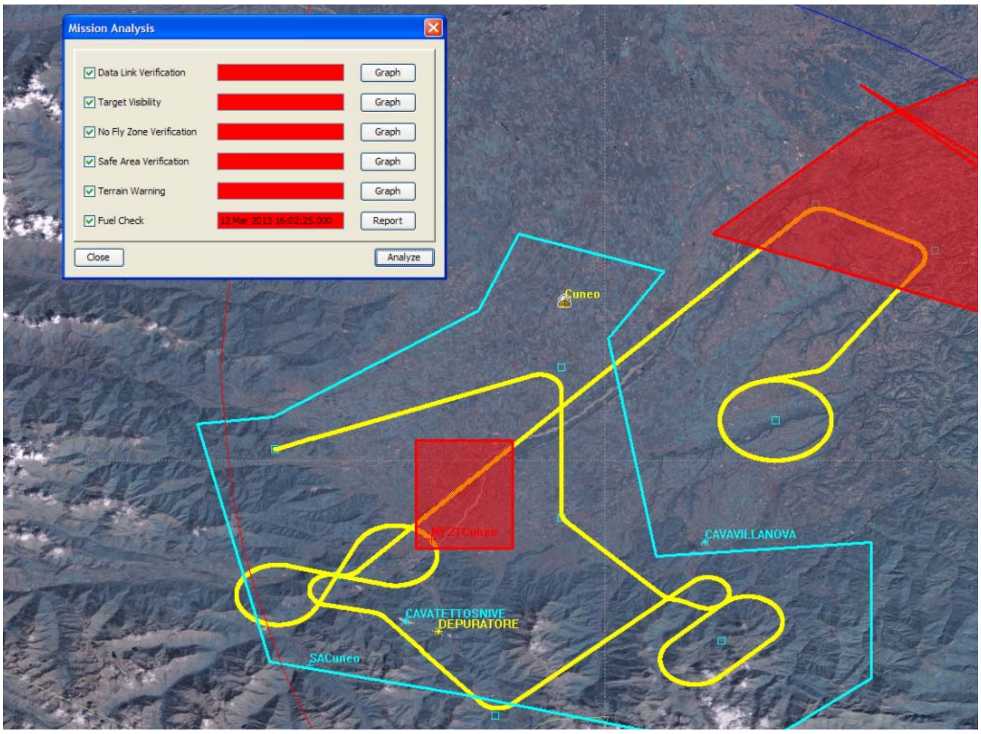

Figure 4. Results of the second test.