An Automated Emergency Airport and Off-Airport Landing Site Selector

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***Abstract*—We present a novel landing site selector capable of selecting suitable landing sites (airport and off-airport) for emergency landings. In a first step, information from several databases which includes, for instance, elevation data, is gathered by our system. Then, this information is processed in order to create a list of potential landing sites ranked according to several factors, such as the characteristics of the runway, the type of emergency or the current weather. A generic scenario and case studies have been defined in order to test the landing site selector, ultimately leading to a series of trajectories—generated with an emergency trajectory generator presented in previous publications—safely leading the aircraft to one of the landing sites chosen by our system.** [1]

Keywords—Aircraft emergency planning; Safety; Landing Site Selection; Automation

I. Introduction

Nowadays, emergency trajectories for airliners in a degraded flyability mode do not exist except for engine loss situations in SIDs (standard instrumental departures), for which airliners have to specifically design the corresponding flight procedure. The current process of defining emergency trajectories and landing sites remains completely manual and fully relies on the capabilities of the pilot for situation analysis. In emergency situations, an automated support to the pilot could suppose a clear advantage by providing a trajectory to safely bring the aircraft from the location where the emergency takes place until a safe and appropriate landing site.

We can observe in history several cases of successful landings with very degraded aircraft capabilities—e.g., the U.S. flight 1549, ditching in the Hudson river after a double engine failure caused by bird strike—in which, thanks to a good situation analysis of the aircraft crew, the safety of the passengers and integrity of the aircraft structure were preserved. However, in other situations the consequences were fatal and, even if the outcome is positive in some cases, having an automated emergency trajectory generator and landing site selector could help to ensure avoiding compromising the safety of the operation in abnormal situations.

In this work, we present a novel system to automatically select landing sites suitable for emergency landings. Both airport and off-airport landing sites are taken into account by our system. In addition, different factors are considered when analyzing the suitableness of each landing site; for instance, the emergency type, the current weather in the landing sites or the services available on ground. Our system gathers information from several databases in order to be able to make the best possible choice and to ensure the safety of the operation. This information involves, for instance, elevation data, weather data (e.g., thunderstorms) or geographical data (e.g., terrain type). This system is intended to work together with the algorithms presented in references [1] and [2], which deal with the generation of the trajectory leading the aircraft from the location where the emergency occurs to the landing site. Ultimately, the outcome of this work is to bring a support to the pilot—in both flight management and decision making—in emergency situations with degraded aircraft capabilities, where emergency trajectories together with their corresponding destination landing site would be injected within the flight management system (FMS).

Extensive research has been made recently focusing on the identification of safe landing sites, specially in the field of unmanned aerial vehicles (UAVs). For instance, in [3], the authors proposed an offline semi-automated approach for finding emergency landing sites in the shape of a rectan-

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gular runway to be used in pre-flight contingency planning. Their approach introduced a total of five emergency landing measures and a surface type estimation, which were applied to the identified emergency landing site candidates for their safety assessment. Landing sites were ranked according to their level of safety. Another approach was presented in [4], where the authors proposed a system to select a safe landing site by combining images gathered by the UAV with an on-board camera and machine-learning algorithms to determine whether the landing site was safe or not. Other authors [5] proposed similar solutions relying on cameras but focusing on aircraft. The authors proposed a safe emergency landing site detection system consisting of different modules. First, an image is acquired by on-board cameras, each of them pointing at different directions. Then, all the images are combined together and are gathered into a panorama, which is enhanced by a non-linear retinex image enhancement method in order to improve their sharpness and contrast. Finally, the potential landing site regions are identified and shown to the flight crew. Other authors [6] investigated the possibility of identifying safe landing sites by using publicly available databases, both airport and off-airport sites. They prioritized roads as the safest landing sites after conventional aerodromes, and their objective was to apply this system together with cameras (which would be used for final identification of transient obstacles and local area details not modeled in a database).

To the best of the authors' knowledge, although there are many works dealing with the identification of safe landing sites for emergency situations, they mostly focus on UAVs. Furthermore, works focusing on conventional aircraft do not consider all the constraints that could affect the safety of the operation when landing on a given landing site. The methodology proposed in this paper follows a similar approach to the one proposed in [6], but a greater amount of elements are considered when selecting the potential landing sites, gathering and processing information from several public and private databases.

II. System Overview

In this section, we present an overview of the whole system in charge of choosing the potential landing sites and generating the emergency trajectories.

Our current setup to generate emergency trajectories from the moment the emergency occurs until a safe landing site is divided mainly in two modules or systems:

- **Landing site system**: this module is in charge of selecting a set of potential landing sites by considering different factors, such as the current weather, terrain and the type of emergency. In Section III, we will focus on the description of this module.
- **Trajectory generation system**: this module is in charge of generating an emergency trajectory that safely leads the aircraft to the chosen landing site, avoiding all the obstacles in the way. The algorithms involved to generate the emergency trajectory were described in references [2] and [1]. Basically, we use a combination of the optimal version of the rapidly exploring random tree (RRT*) and Dubins paths in order to generate the lateral path, while we use trajectory prediction algorithms to generate the vertical profile.

Figure 1 depicts a general diagram of the system, where both the landing site and trajectory generation modules are shown.

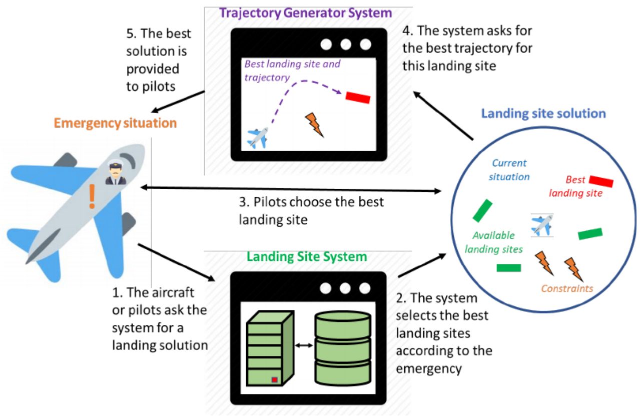


Fig. 1. System diagram

The landing site system has a set of pre-computed landing sites and up-to-date dynamic constraints—such as weather information—in order to respond as fast as possible to the emergency situation. When the flight crew triggers the landing site system, a selection of the best landing sites is made. The current state of the aircraft (including performance), the kind of emergency and the current state of dynamic constraints (e.g., weather information) are taken into account in order to make the choice. The best landing sites are classified according to their characteristics to maximize landing safety.

Once the best landing site(s) are selected, their data and associated constraints are sent to the trajectory generator system so that a trajectory is generated leading the aircraft safely to the landing site(s).

Finally, the best solutions (landing sites and associated trajectories) found for the emergency are provided to the flight crew.

III. Methodology

In this section, we will describe the methodology proposed to select a set of potential landing sites in case of an emergency.

The aim of the landing site system is to provide more assistance to the flight crew in case of an in-flight emergency situation by providing a set of landing solutions where multiple factors are taken into account. The objective is to find the best compromise between limited on-ground damages and maximum survival chances for the aircraft passengers. In order to answer to this need, the envisioned management process for landing sites consists of two distinct modules:

- **Data compilation**: it is used to integrate system world-wide data from multiple sources. More precisely, the

purpose of this module is to gather in a pre-flight database a list of possible landing sites (airport and off-airport) to be used in case of emergency. The result of this process is a master database of landing sites and constraints (e.g., terrain elevation data). This database must cover the entire planet and must include enough landing sites to be able to give a solution in every situation. The data compilation module is described in more detail in Section III-A.
- **Data exploitation**: it is used to provide on-board assistance to the pilot crew in an emergency situation. It operates during the flight and is in charge of selecting the best landing sites and the relevant constraints for the flight crew. The landing sites are selected from the master database created before the flight by the data compilation module. In order to abstract the implementation of the functionalities for system users, the data exploitation module will take the form of a web service. The service will be available to clients or tools in charge of triggering the selection process in case of emergency. The data exploitation module is described in more detail in Section III-B.

The process of generating and selecting the landing sites is described in Section III-C. Both modules (i.e., data compilation and exploitation modules) are used in such a process.

A. Data Compilation Module

The goal of the data compilation module is to aggregate heterogeneous data from various sources into a single database. It is based on the architecture depicted in Figure 2. The inputs

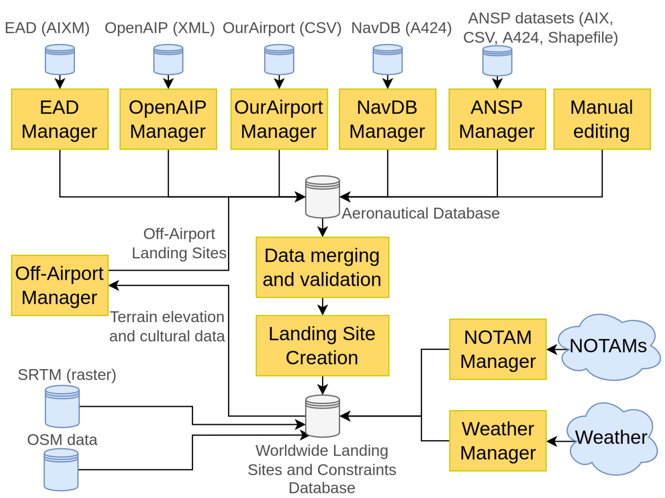


Fig. 2. Architecture of the data compilation module

required for the data compilation module are divided into static and dynamic, depending on whether the data changes or not during the flight:

- **Static**:
  - **Geographical databases**: these databases gather information necessary to find off-airport landing sites such as buildings and other obstacles to be avoided, terrestrial traffic lanes (highways, roads...), terrain types with usage, natural features (vegetation, hydrography, relief) or waterways. **OpenStreetMap (OSM)** is the database chosen in this case.
  - **Terrain databases**: these databases gather terrain altitude information through digital elevation model (DEM) files. The terrain elevation is used by the data compilation module in order to find flat terrains for off-airport landings. It is also used to identify obstacles by the trajectory generation module. Terrain data was obtained from the **Shuttle radar topography mission (SRTM)** developed by NASA.
  - **Aeronautical databases**: these databases gather the static aeronautical features necessary for the system such as:
    - ∗ Aerodromes, with associated features (e.g., runways and thresholds).
    - ∗ Radio Navigation aids: location, name, frequencies and channels.
    - ∗ Existing approach procedures and the associated landing minima, if any.
    - ∗ Airspace and route names, geometries and constraints.
    - ∗ Obstacles name and position.

    Two groups of data sources are used to generate the aeronautical database, according to their priority. Air navigation service provider (**ANSP**) databases, navigation databases (**NavDB**) and European AIS Database (**EAD**) have the highest priority. **OpenAIP** and **OurAirports** databases are also used, but just when data is not duplicated with that obtained from databases with the highest priority.
- **Dynamic**:
  - **Weather data**:
    - ∗ **Navigational constraints**, in a 4D-grid format, including temperature, pressure and wind speed/direction.
    - ∗ Navigational obstacles, including significant meteorological (**SIGMET**), **icing** and **lightning cells**. SIGMET reports the occurrence and/or expected occurrence of specified en-route weather phenomena over time.
    - ∗ Landing site selection related data, including meteorological aerodrome reports (**METAR**), **pseudo-METAR** and automatic terminal information service (**ATIS**). METAR is a routine observation made at an aerodrome throughout the day. METAR observations are made at intervals of one hour or, if determined by regional air navigation agreements, at intervals of half an hour. Pseudo-METAR is a METAR information extracted from the global forecast system (GFS) by the national oceanic and atmospheric administration (NOAA). Finally, ATIS is a continuous broadcast of recorded aeronautical information (such as current weather information, active run-

ways or available approaches) in busy terminal areas.

All weather data was provided by *MetSafe* [7].

– Notice to air missions (**NOTAMs**): used to ensure the aircraft can safely perform a landing on the selected airport.

The data compilation module aggregates the aforementioned inputs in order to generate the following databases (i.e., output of the process):

- A **worldwide landing site database**, gathering a raw list of theoretical landing sites (airports and off-airports) all around the world independently from constraints such as weather and independently from aircraft information. The landing sites described in this database already have a ranking information, giving an indication on their usability by an aircraft. This ranking information only depends on the physical characteristics of the landing site such as the surrounding environment, the soil type, etc. More information regarding the landing site classification can be found in Section III-C.
- A **worldwide static constraint database**: gathers theoretical static constraints depending on the static data information. These constraints can be, for example, terrain obstacles or prohibited airspaces. These constraints are later transferred to the trajectory-generation module.

The process is run whenever new data is available in order to keep the system databases up-to-date. The operation is performed on the ground before the beginning of the flight. The databases produced by the data compilation module are then loaded into the aircraft to be used during the flight by the data exploitation module.

B. Data Exploitation Module

The objective of the data exploitation module is to select the landing sites around the aircraft during a flight and to select the relevant constraints necessary for the trajectory generation module. The landing sites and constraints are stored in the database created by the data compilation module.

The data exploitation module is divided into four main submodules and its architecture is depicted in Figure 3:

- The **landing site selector** responsible for the selection of the best landing site available around the aircraft. It uses the list of landing sites compiled in the on-board database as well as information about the weather on the landing site using METARs and pseudo-METARs.
- The **weather manager**, in charge of downloading weather (dynamic) data.
- The **NOTAM manager**, in charge of downloading the NOTAMs.
- A **web service** responsible for the connection of the data exploitation module with external processes. The web service expects a request with the position of the aircraft and the type of emergency and returns a list of landing sites suitable for the emergency situation. It also returns the weather and constraints needed by the trajectory generation module to generate the emergency trajectories. Currently, a simulator is under development in order to issue requests to the data exploitation module and to connect this module with the trajectory-generation module.

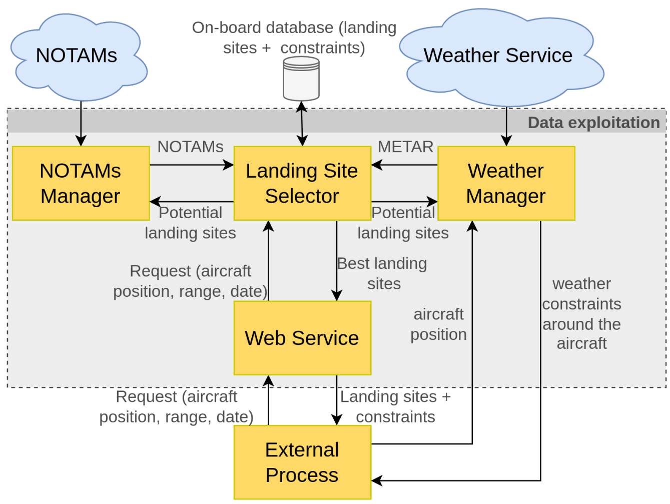


Fig. 3. Architecture of the data exploitation module

C. Landing Site Generation and Selection Mechanism

Landing sites are split into two categories: airports and off-airports landing sites. Airports are the most common and preferred choice, having been built for the purpose of landing aircraft. In the case of an airport, one landing site will correspond to one runway direction. For instance, an airport such as LFBO (Toulouse), with 2 runways, leads to 4 landing sites.

On the other hand, off-airport landing sites are meant to be used when no airport can be reached by the aircraft due to a particular emergency situation. An off-airport landing site is extracted from the compilation of geographical data and terrain elevation data, is modeled by a strip of land and, thus, shares some similarities with a runway. The features included for each landing site (for both airports and off-airports landing sites) are the following: identifier, name (e.g. runway name), airport name, country code, landing site class, landing site surface, landing closed (if runway is closed), elevation, position (latitude and longitude), last point of the trajectory, length, width, heading and source (databases used to obtain the landing site data).

For the particular case of off-airports, a terrain with the following characteristics needs to be identified:

- The **terrain** must be **flat** enough to ensure the aircraft will not crash into an abrupt slope or fall into a ravine. The precision of the elevation data must be as thin as possible to identify even small obstacles that may damage the aircraft. The flatness is assessed using a terrain roughness index (TRI), proposed in [8]. The TRI is defined to evaluate the heterogeneity of the roughness of the terrain, in a grid format. It is computed by comparing a central pixel with its neighbors, taking the absolute values of the differences, and averaging the result. The TRI gives a quantitative measure for the roughness of the terrain. For the sake of an emergency landing, a level terrain or nearly level terrain surface is considered (TRI values up to 116). Figure 4 shows in red the TRI computed from a terrain elevation of an area in the south of Toulouse. The zones in red correspond to a higher TRI and, thus, rougher terrain. On the other hand, areas in white/pale red correspond to flatter terrain.

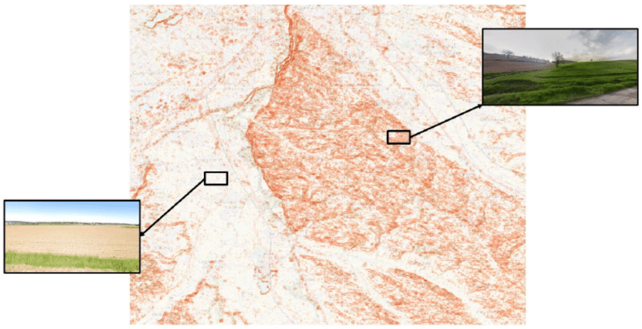


Fig. 4. Relationship between TRI and the actual terrain flatness (south of Toulouse)

- The **type of terrain** must be taken into account for two main reasons:
  - The terrain must not damage the aircraft and endanger the passengers.
  - The forced landing must not threaten the lives of people on ground.

  As specified in Section III-A, the data compilation module extracts geographical data from the OSM database. From this database, it is possible to select areas safe for landing, including, for instance, natural areas (e.g., wetlands or grasslands), some land-use areas (e.g., farmlands or meadows) or aerodromes. On the other hand, areas that involve an unsafe landing involve buildings, and some land-use areas (e.g., factories or warehouses). Each terrain can be color coded to create a map of land-use like the one depicted in Figure 5; yellow represents arable lands (which might be a good choice for an off-airport landing site) and red represents towns and villages, that need to be avoided at all costs.
- The selected **terrain** needs to be **long and wide** enough for a safe landing. The terrain is represented with a polygon format, extracted according to the terrain type.
  In order to ensure the polygon is large enough, the off-airport generator tries to fit a rectangle of at least a length of 1500m and a width of 100m. The algorithm used to find these rectangles is an adapted version of an algorithm that seeks for the largest rectangle in a given polygon, as described in [9].

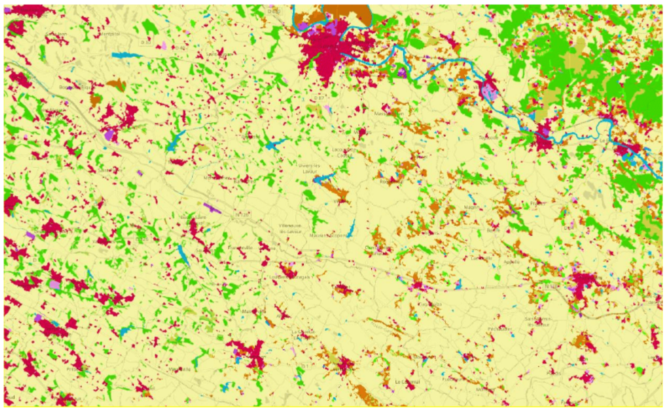


Fig. 5. Land-use color map

- The **path** leading to the off-airport has to **cross an area clear of obstacles**. In order to find this path, a safety horizon distance is used, corresponding to a distance from the ground that can be safely crossed in a straight flight (direction and constant slope) by an aircraft. The value of the horizon is either the maximum distance remaining before encountering an aeronautical constraint, or the distance limiting the obstacle analysis of the method. The main output of the dichotomy algorithm used for this purpose is a 3D polygon (i.e., safe sector) from the landing point with the safe horizon as the distance available before intersecting an obstacle from the landing point.
  In this work, the surface helps to protect the approach on a slope at 3 degrees for at least 10NM from the threshold of the landing site. The algorithm creates surfaces defined by the threshold of the runway, the slope to protect, the width of the surface near the threshold and the width of the surface at 10NM in the direction of the heading of the landing. An example of the result obtained by the algorithm is depicted in Figure 6. In this example, the target point, in Grenoble, is surrounded by mountains. Each polygon defines a slope protected of the terrain. Hence, bigger polygons correspond to the preferred approach direction in case of an emergency landing because no terrain is intercepting the slope angle for a longer distance. In this particular case, the preferred approaches are from the south-west and north-east.

Landing sites are classified in 6 classes, as shown in Table I. The following characteristics are taken into account to do the classification: runway length, runway type (e.g., concrete, grass, gravel...), approach type (e.g., precision approach type), ATC available, security concern (e.g., landing site in war zone) and passenger accommodation available (e.g., medical assistance on ground).

The system supports 3 types of emergencies, which are used to select the best landing sites for each situation:

- **ANSA** (at nearest suitable airport): in this situation (e.g., medical emergency or loss of one engine), the pilot has

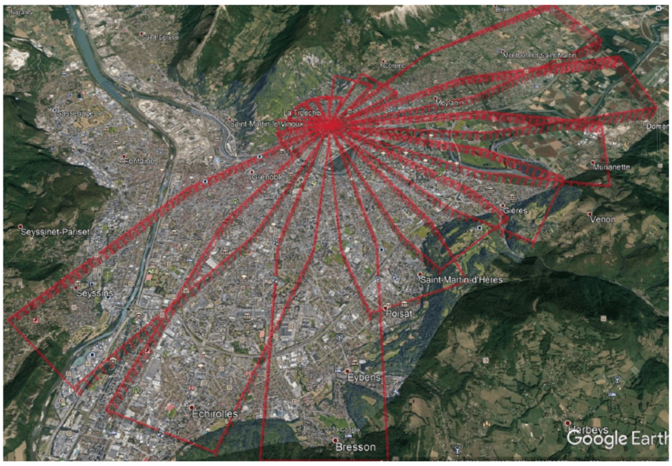


Fig. 6. Safe sectors for Grenoble airport

TABLE I
LANDING SITES CLASSES

Class	Type	Characteristics
1	Airport	• Length of the runway > 2700m • Airport in navdatabase • IFR approach with at least 200ft minima or lower • ATC • Fire assistance • No security concern • Passenger accommodation available
2	Airport	• At least one runway > 2200m for big aircraft • Not necessarily included in navdatabase • At least an IFR non-precision approach procedure • At least one remote ATC or traffic information
3	Airport/runway/concrete strip	• At least one concrete runway with length greater than the average landing distance for the aircraft category • Not in the aircraft navdatabase • No IFR approach procedure • At least remote ATC
4	Airstrip	• At least one runway with no solid obstacle in a 1200m radius after the touchdown area • Not in the navdatabase • No IFR approach procedure
5	Ditching	• Open sea or river • Within reachable distance to a place where emergency services are available
6	Forced landing	• Flat or almost-flat area with no obstacles • One direction identified providing the longest landing strip • With reachable distance to a place where emergency services are available

enough time to select a major airport. The passenger safety is not directly in danger but an extended flight beyond the nearest suitable airport is not recommended. Airports of class 1 and 2 are considered in this case.

- **ASAP** (as soon as possible): this situation (e.g., loss of electrical power) forces the pilot to land the aircraft on a runway in the shortest amount of time possible. In this situation, the landing site must be a runway, corresponding to landing sites of class 1 to 4.
- **TEFO** (total-engine flameout): in this case, the aircraft has a limited range, which might mean that landing sites of classes 1 to 4 might not be available. Thus, in this case, landing sites of class 1 to 6 are considered suitable for landing.

The data exploitation module uses a range value to filter potential landing sites (Figure 7), which is computed by the trajectory generation module by taking into account the current aircraft performance and weather. Once the reachable landing sites are determined, they are ranked according to their suitableness for performing a safe landing. The following steps are performed:

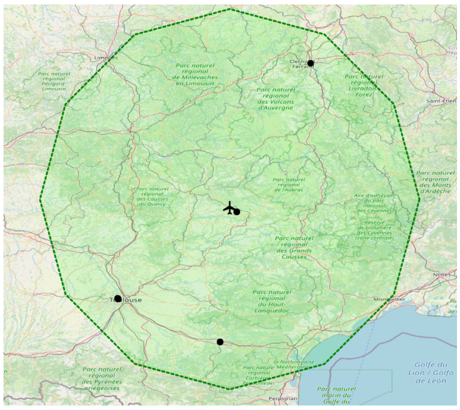


Fig. 7. Range and potential landing sites for TEFO situation

- Landing sites are ranked according to their class (Table I).
- Landing sites belonging to a same class are ranked, by taking into account, by order of importance, the distance from the landing site to the aircraft, the weather in the landing site and the contamination of the runway.

The ordered list of landing sites is sent to the trajectory generator module so that a trajectory safely leading the aircraft to the best possible landing site is computed. In addition to the landing sites, elevation data, weather data (i.e., obstacles such as SIGMET, icing and lightning cells + wind/pressure/temperature), geographical data and NOTAMs are also provided to the trajectory generation module.

IV. RESULTS

This section presents the results obtained in this work. Section IV-A presents the scenario and case studies, while Section IV-B focuses on the different generated trajectories with their corresponding landing sites.

A. Scenario and Case Studies

Let us assume an Airbus A320 cruising at FL350 over France (latitude=44.232 degrees, longitude=0.615 degrees), with a speed equal to Mach 0.77 when an emergency occurs. At this moment, the trajectory generation module computes a range value depending on the emergency, current aircraft performance and weather. Thus, the landing site system can filter the reachable landing sites in the vicinity of the aircraft and rank them. Finally, the trajectory generation module computes a trajectory that safely brings the aircraft from the cruise phase to a given *final point* (which will depend on the emergency type) close to a safe landing site.

Four types of emergencies are considered: TEFO with and without fuel on board, ASAP and ANSA corresponding, respectively, to profiles 1, 2, 3, and 7b (which were previously described in [2] and whose trajectory phases and intents are detailed, respectively, in Tables II, III, IV and V). The different aircraft intents that are considered in the profiles have the following meaning: ALT, maintain a constant altitude; MACH, maintain a constant Mach number; CAS, maintain a constant calibrated airspeed (CAS); ACC, accelerate at a given acceleration or with a given load factor; DEC, decelerate at a given deceleration or with a given load factor; THR, keep a given throttle setting. For the ACC and DEC cases, we have used the energy share factor value proposed by the base of aircraft data (BADA) [10], which varies for acceleration and deceleration and depends on the flight phase (descent or climb). The green dot speed (for the Airbus A320) is the minimum operating speed in managed mode and clean configuration, being approximately the best lift-to-drag ratio speed. V_{F1} is the target speed for flaps deployed in configuration 1, while V_{app} is the approach speed, which is the final approach speed when the flaps/slats are in landing configuration and the landing gear is extended. MMO and VMO are, respectively, the maximum operating Mach and CAS. Finally, FAP/FAF stand for the final approach point/final approach fix.

TABLE II
PROFILE 1: TEFO + FUEL ON BOARD

Phase	a/c intent #1		a/c intent #2	
(Above FL200) Deceleration/ acceleration to relight speed	ALT	Current altitude	THR	IDLE
CAS descent	CAS	Relight speed	THR	IDLE
(Below FL200) Deceleration to green dot	ALT	Current altitude	THR	IDLE
CAS descent	CAS	Green dot	THR	IDLE
Acceleration to increase rate of descent	ACC	-	THR	IDLE
Descent at higher speed to increase rate of descent	CAS	CAS_n	THR	IDLE
Deceleration to V_{app}	DEC	-	THR	IDLE

B. Emergency Trajectories

In this section we show the several trajectories and chosen landing sites for each of the case studies defined in Section IV-A.

Once the emergency occurs, a list of potential landing sites is generated by the landing site module by taking into account the range computed by the trajectory-generator module. This range is wider for both the ANSA and ASAP cases, as engines are still available. On the other hand, in the TEFO case, engines are not available and the range is shorter. Furthermore, it is important to highlight the fact that in the ASAP case, even if the range is the same as in the ANSA case, the potential landing sites considered are different, as discussed in Section III-C. In this particular scenario, the aircraft is flying over France when the emergency occurs, which means that a great amount of class 1 and 2 landing sites are available.

Figure 8 depicts the vertical and lateral profiles for the TEFO case with fuel on board. In this case, Toulouse airport (LFBO) is chosen as the best landing site. The aircraft accelerates first to the relight speed; this speed is maintained until FL200, altitude at which the aircraft decelerates to green dot in order to maximize the range. Finally, when approaching the airport, the aircraft follows a VMO profile. As it can be observed in Figure 8(b), the aircraft performs a holding pattern once it reaches the vicinity of the airport. The rationale

TABLE III
PROFILE 2: TEFO + NO FUEL ON BOARD

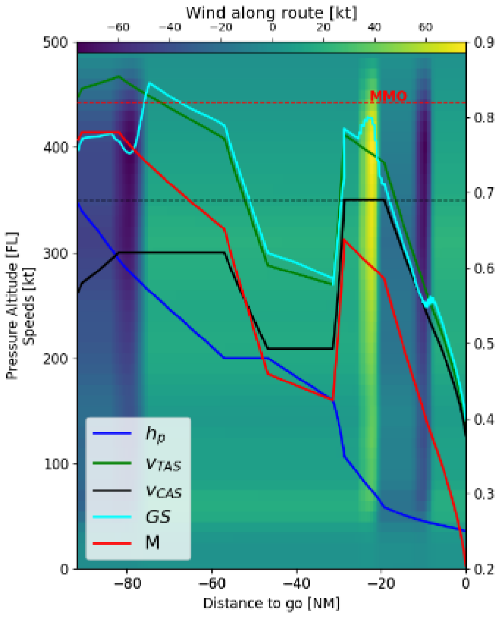
Phase	a/c intent #1		a/c intent #2	
Deceleration to green dot	ALT	Current altitude	THR	IDLE
CAS descent	CAS	Green dot	THR	IDLE
Acceleration to increase rate of descent	ACC	-	THR	IDLE
Descent at higher speed to increase rate of descent	CAS	CAS_n	THR	IDLE
Deceleration to V_{app}	DEC	-	THR	IDLE

TABLE IV
PROFILE 3: ENGINE(S) OPERATIVE + ASAP + IFR + FULLY MANEUVERABLE

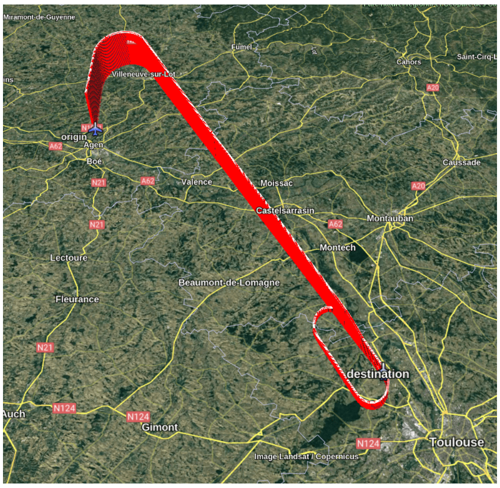
Phase	a/c intent #1		a/c intent #2	
Acceleration to descent Mach	ACC	-	THR	IDLE
Mach descent	MACH	MMO	THR	IDLE
Flight at crossover altitude	CAS	VMO	ALT	Crossover altitude
CAS descent	CAS	VMO	THR	IDLE
Deceleration to V_{F1}	DEC	-	THR	IDLE
Level-off to intercept FAP/FAF	CAS	V_{F1}	ALT	FAP/FAF altitude

TABLE V
PROFILE 7B: ENGINE(S) OPERATIVE + ANSA + IFR + FULLY MANEUVERABLE

Phase	a/c intent #1		a/c intent #2	
Acceleration to higher Mach	ALT	Current altitude	THR	MCT
Cruise	MACH	MMO	ALT	Current altitude
Mach descent	MACH	MMO	THR	IDLE
CAS descent	CAS	CAS_x	THR	IDLE
Deceleration to V_{F1}	DEC	-	THR	IDLE



(a) Vertical



(b) Lateral

Fig. 8. TEFO with fuel on board

behind this decision is to—by maximizing the section in which the aircraft flies at green dot—ensure the aircraft reaches the landing site at a sufficiently high altitude in order to maximize the safety of the operation and make sure the landing site will be reached in case the situation worsens.

In the TEFO case without fuel on board, the aircraft decelerates directly to green dot in order to maximize the range; then, when approaching the airport, it follows an MMO/VMO profile. It is important to highlight the fact that our framework can also propose different alternative trajectories safely leading the aircraft to an appropriate landing site. In this particular case, trajectories are generated to the airports of Toulouse (LFBO), Bordeaux (LFBD) and Tarbes (LFBT). The lateral and vertical profiles are shown, respecitvely, in Figures 9 and 10.

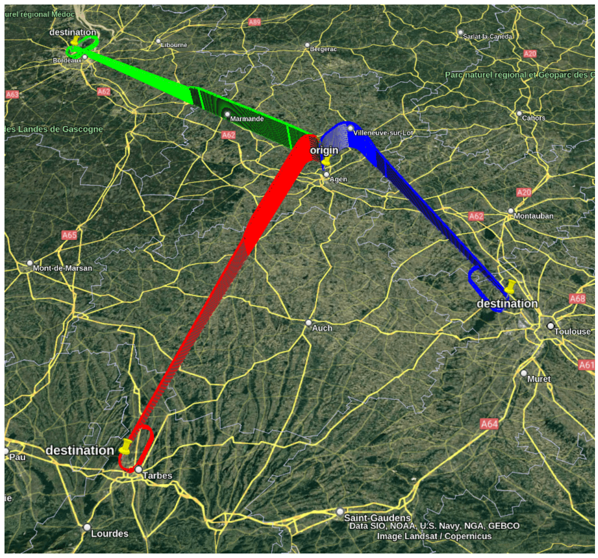


Fig. 9. TEFO with no fuel on board (lateral) - LFBT (red), LFBO (blue), LFBD (green)

Finally, in the ANSA case, the aircraft accelerates to MMO while in cruise. Then, it follows an MMO/VMO profile. In the ASAP case, the aircraft flies at constant altitude at the crossover altitude, where true airspeed is maximized. The vertical profile for ANSA and ASAP cases is shown in Figure 11. In both cases, the chosen airport was Tarbes (LFBT).

Not only the evolution of speed and altitude is shown in the vertical profiles for each case study, but also the current wind along the route followed by each trajectory. Both the ANSA and ASAP trajectories follow a south-west direction, with predominant tailwind. For the TEFO trajectory with fuel on board, the aircraft follows a south-east direction, with tailwind for the most part of the route. Finally, for the TEFO trajectory without fuel on board, tailwind is observed for the trajectories leading the aircraft to LFBT and LFBO, while headwind is observed when the aircraft flies to LFBD.

V. Conclusions

In this paper, we described a novel system used to select safe landing sites (airport and off-airport) for emergency situations, by taking into account several factors and by gathering data from several databases. This system works together with the algorithms described in references [1] and [2], which were used in this paper to generate trajectories to the landing sites chosen by our system.

In the future, we are planning to study more case studies—under a different set of conditions/locations and also real case studies that happened in the past—to better assess the viability of our framework.

Acknowledgments

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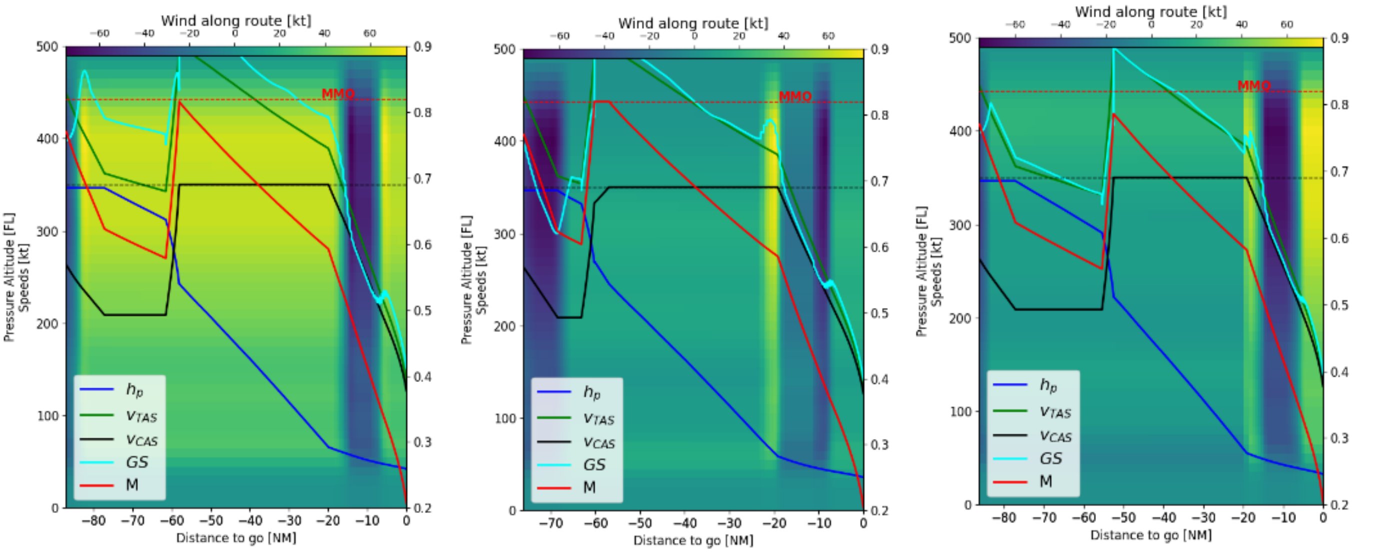
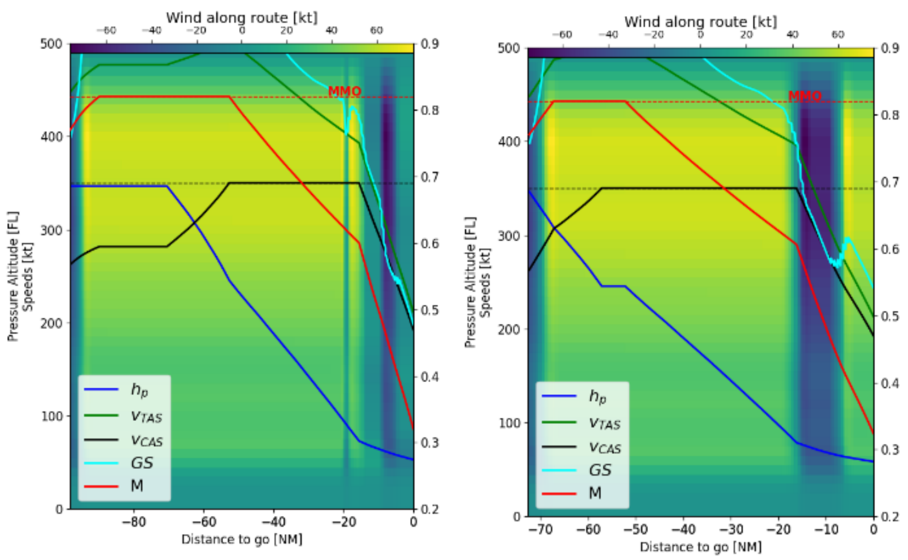


(a) Trajectory to LFBT (red path in Figure 9) (b) Trajectory to LFBO (blue path in Figure 9) (c) Trajectory to LFBD (green path in Figure 9)

Fig. 10. TEFO with no fuel on board (vertical)



(a) ANSA (b) ASAP

Fig. 11. ANSA and ASAP trajectories (vertical)

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