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Besada, J., Campaña, I., Bergesio, L. et al. Drone flight planning for safe urban operations. Pers Ubiquit Comput 26, 1085–1104 (2022). https://doi.org/10.1007/s00779-019-01353-7

Noname manuscript No.
(will be inserted by the editor)

Drone Flight Planning for Safe Urban Operations

UTM Requirements and Tools

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Received: date / Accepted: date

Abstract This paper describes the requirements of a flight planning tool for safe urban operations, which may be used to design operations considering flight constraints and limitations. This system is designed to work in coordination with an unmanned traffic management system in charge of distributing available very low level airspace resources among different operations and authorizing them, and of monitoring compliance of actual flights with flight authorizations. Representative examples of flight planning are described, as calculated by a prototype flight planning tool following this requirements.

Keywords drone · fleet management · unmanned traffic management system · UTM

1 Introduction

The market of civilian drone applications will be growing extremely fast in the next years [1], being the use of a drone as a mobile aerial sensor a key enabler of many new applications [2]. A specially demanding application is that of e-commerce and delivery (see, for example [3], from Amazon). Also, air taxies may become a near future application [4]. In other cases, drone-based systems are used to enhance functionalities such as surveillance and reconnaissance, monitoring, mapping and photogrammetry, automatic fault detection or inventory tasks. There are also many examples urban infrastructure inspection scenarios in which drones are starting to be applied [5], [6], such as roofs inspection [7], real estate monitoring [8], construction management [9], etc. Additionally, monitoring of environmental gases for hazard assessment or air pollution management may complement in the city though UAVs. For example, authors in [10] describe the design of a Gas Sensing System ready to be

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mounted on any UAV. For city management, road inspection may be clearly enhanced using drones help to detect early signs of erosion and pavement distress [11–14]. Similar approaches might be used for railway inspection [15]. From the previous literature review it si clear quite a few of such applications, and especially those with a higher economical value will be implemented in urban environments, where both the flight context and the traffic environment will be more complex (due to the presence of human-made obstacles, of other aerial vehicles, etc.).

The mission type obviously determines the type of flight to be completed [16], with clear differences for local (Visual Line of Sight VLOS) and remote (Beyond Visual Line of Sight, BVLOS) operations. All these applications need tools to accelerate and partially automate the creation of missions, the calculation of the optimal trajectories and the automatic execution of parts of the mission with the least human intervention, in order to obtain cost effectiveness. But also, quite often, at least critical parts of the flights need to be piloted by humans (e.g. due to the higher adaptability of human pilots to mission requirements).

Most of the aforementioned applications rely on the definition of ad-hoc procedures for missions design, which tend not to consider the flight safety constraints, but assume a safe environment. It is clear it is not at all the case in urban environments, where there will be a large number of obstacles, areas restricted to flight, etc. And additionally, if the air traffic starts to grow, there will be needs to coordinate operations to avoid drone collisions and surely it will be necessary to impose physical constraints to flights (in the form of corridors, airways, and explicit rules of air, etc.), at least in some areas [17]. In order to ensure flight safety, a collection of concepts and tools have been developed in the last few years, such as those related to the FAA-NASA UTM (Unmanned Traffic Management [18]) program, or to the European U-Space concept from SESAR program [19]. Also, there is quite a large amount of companies developing so-called UTM solutions (most of the relevant actors are included in GUTMA association [20]), and the flight regulators (i.e. ICAO, AESA, etc.) are working in the problem of opening the sky for these new actors. With respect to regulators, it is especially interesting the work of JARUS group [21], which is defining a methodology for risk assessment (called SORA [22]) with the final aim to be able to automate flight authorization, as part of the UTM process.

In this paper we will define a set of flight planning use cases, interfaces, requirements and tools based on a fundamental premise, which is the integration of the existing flight planning processes with UTM processes. The whole flight planning process will be analysed in conjunction with an UTM working prototype being developed at our group. This simulation/experimentation platform not only covers most UTM functions as described in the paper, but also UTM operation and experimentation context:

- Flight operation context simulation, modeling terrain, weather, navigation infrastructure, ...

- Simulated drones and ground control systems, capable of ”flying” following a predefined flight plan, and enabling testing UTM along-flight functions
- Real drones and ground control systems implemented through an Android app, using DJI SDK, which can follow a predefined flight plan, for more realistic experimentation
- Simulation and evaluation system HMIs

Summarizing, this flight planning tool needs to define flight plans for different applications to: 1) Cover different use cases and applications, both before the flight operation and along it; 2) Enable the prediction of the risk of a given operation, using a SORA inspired methodology; 3) Coordinate the occupancy of the airspace, minimizing the chance of mid-air collisions and allowing a fair sharing of airspace resources.

The paper continues with a section devoted to a high-level description of some current example flight planning tools (section 2), and then it focuses of UTM functional architecture (section 3). Section 4 describes the Flight Planning Use Cases, while Section 5 describes the prototype flight planning tool we have implemented. Then, section 6 describes some Flight context data models, sumarizing some of the inputs provided by the UTM system to the flight planning system to enable coordinated definition of new flight plans. Section 7 is devoted to the associated input (mission definition) and output data (flight plan specification) requirements. Then section 8 includes some practical experimental results. Finally, section 9 contains some conclusions and discusses some future research lines.

2 Description of current Flight Planning Systems

There are currently in the market many tools for the definition of missions for drones, such as the ones developed by drone manufacturers (i.e. Parrot or DJI tools [23, 24]). Drone manufacturers tools, integrated with the drone control systems, usually follow similar concepts:

- They allow the user to flight manually the drone or to establish a set of waypoints that conform a path to be followed by the drone;
- They rely on standard map technologies such as Google Maps and offer a 2D point of view;
- They allow to create a flight plan and to automatically upload it to a drone or Ground Control System for an automatic flight. For instance, in the case of Parrot, they use MAVLink [25].

These tools are designed to enable a fast and easy way for the users to interact with them, to the detriment of more complex scenarios and systematic mission definition. Other companies provide more advanced platforms, specially devoted to specific applications and vertical markets, and with associated tools for mission specification. Two examples of such platforms can be found in [26, 27]. Also, for other drones such as those based on Pixhawk or

Ardupilot autopilots, other similar tools as APM Planner 2 [28], with similar features and interfaces to the drones are available.

The academic ambit has also focused on the goal of generalizing and abstracting the definition of the missions, as can be seen in [29], where the authors developed a Domain Specific Language that enables setting mission specifications and predicting trajectories. This contribution is somehow similar to efforts in commercial aircraft trajectory predictions for Air Traffic Management [30], later extended to unmanned vehicles in [31], which describes a complete language hierarchy and associated trajectory prediction/computation engines. The multi-rotor oriented trajectory prediction basis is summarized in [32]. Alternatively, in [33], the flight plan is defined through a concatenation of legs joining waypoints using predefined trajectory primitives.

Other support tools focus in making it possible for non-expert users (e.g. firefighters, rescue workers, etc.) to specify missions are also being delivered [34]. Another example of this approach is described in [6], which is also practical use of this kind of abstracted trajectory prediction paradigms to a complex application. There a system for partially automated design of infrastructure inspection is described, which, from 3D primitives, derives flyable flight plans (expressed in terms of the language hierarchy described in [32]) and even translates them to a MAVLink specification.

Meanwhile, current commercial systems for UTM (i.e. Airmap [35] or Unifly [36]) allow for declaration of basically two types of flights:

1. Waypoint based flight plans;
2. Flight Areas/Volumes

We find this kind of approaches, focused in users, especially appealing, as they allow for non-experts to be able to declare flight plans for their applications, irrespective of the actual type of mission. What we find in general is that most of the Flight planning tools support tools lack any integration with the Unmanned Traffic Management system which define the flight operation context. To overcome this limitation and provide some key integration means we need some additional background on the main functions of UTM and their relation, which will be analyzed in next section.

3 UTM Functional Architecture description

The definition of the services which should be provided to users within UTM is currently under discussion, with different potential architectures. In all of them there will be a collection of services provided to the airspace users (drone operators and pilots) by either a central entity (i.e. an Air Navigation Service Provider, ANSP), or by a collection of UTM Service Providers (USPs), working collaboratively. A summary of the intended services to be provided is detailed in Table 1, taken (and summarized) from SESAR2020 U-Space documentation [37]. The table also shows the associated target time for services launch, in four phases called U1, U2, U3 and U4.

Table 1: U-Space Services

Phase(year))	Services
U1 (2019)	Registration, identification, provision of static geofences (No drone zones) to users
U2 (2022)	Drone Tracking, air safety monitoring (no incursion in geofences, terrain avoidance, conflicts between aircraft, etc.), flight plan authorization (including strategical deconfliction of flight plans), flight plan conformance monitoring (compliance of flight with authorized flight plan), weather provision to operators, access to aeronautic and Air Traffic Control (ATC) data, emergency management, provision to pilots of nearby traffic information
U3 (2027)	Dynamic (on-board) geofencing, improved interface with Air Traffic Management (ATC/ATM), tactical (in-flight) conflict detection & resolution, and drone congestion management
U4 (2035)	Full integration with ATC/ATM and manned aviation and additional services

The main idea behind this collection of services is the need to deploy a system which:

1. Orchestrates the use of airspace shared resources, by requesting users to declare their needs in form of flight plans or flight authorization requests, to be assessed taking into account the flight context and other airspace users requests, and trying to maintain safety, both for airspace users and for other involved actors (i.e. overflown pedestrians or drivers, urban real state owners, critical infrastructure managers, etc.). The services related to this orchestration of resources operate in so called ”strategic” time horizon, on the basis of trajectory predictions.
2. Monitors the compliance of actual operations with authorizations and with potential changes in the flight context (i.e. sudden weather changes, appearance of new No Drone Zones in real time, etc.), and of potentially unpredicted conflicting/emergency situations (i.e. lack of separation between drones). Those systems related to this monitoring perform ”tactical” assessments, on the basis of real time telemetry (and/or other sensors information), building a real-time air situation picture.

From this UTM definition it is clear the flight planning cannot be performed independently of the UTM systems: the flight planning systems and the UTM systems must enable a partially-automated collaborative process to allow users to plan, authorize, and monitor flights. This process will enable UTM to strategically distribute the available airspace resources to potentially conflicting Flight Plans issued by different operators. In Fig. 1, the main UTM functions related to pre-flight (strategic) processes are depicted, along with their main relations. Note here we are being agnostic with respect to the actual system architecture (centralized by an ANSP, provided by a federation of USPs, or a mixture of both), so any of those functions may be implemented by a central entity or several coordinated implementations may coexist. It must be emphatized our UTM experimentation/simulation platform covers all the functionality described in this figure, following a centralized architecture (each function is implemented through a microservice collaborating with the rest of the architecture).

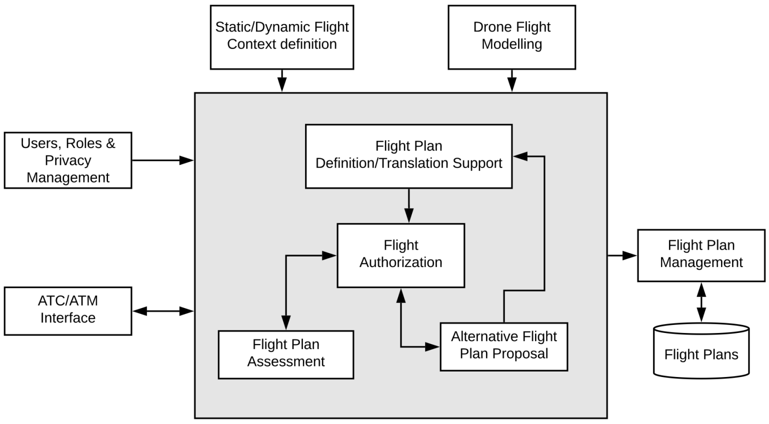


Fig. 1: Flight Planning and Authorization (Strategic distribution of airspace resources)

The two central processes here are those related to Flight Planning (Flight Plan Definition/Translation Support in the figure), and those related to partially automated Flight authorization (Flight Plan Assessment, Alternative Flight Plan Proposal and Flight Authorization in the figure). All those functions need to take into account contextual information (both static and dynamic), potential manned traffic in the area (needing therefore interfaces with ATC/ATM systems), and use accurate drone flight modeling. Of course, UTM system must respect the drone operators privacy concerns. Next, we will summarize each of the central pre-flight functions (the surrounding processes are named where the associated functionality is needed):

- Flight Plan Definition/Translation Support should provide means to easily define most typical flight plans, either though an attached map based (potentially 3D) HMI, or enabling the use of most specialized flight planning tools by the operators, followed by a translation process. This function, which is the input to the whole UTM process, and related to it the definition of a common flight plan format supporting the different UTM functions is the main focus of the paper. Specifically, the format must be understood by the authorization processes, and contain all the different information enabling efficient operation monitoring in real time.
- Flight Authorization process uses the flight plan specification, and by calling the Flight Plan Assessment process automatically decides if the flight

might be authorized or not. In certain cases, it may request for human assessment and authorization confirmation. If the flight plan is not authorized, it may also automatically provide amended flight plans to the Flight Plan Definition/Translation Support service (designed by the Alternative Flight Plan Proposal process), so that the drone operator may establish an informed negotiation process (but without having access to other operators flight plans). Also, this process might ban a previously authorized flight due to changes of the Dynamic Flight Context (i.e. new geofences, sudden change in predicted weather, etc.).

- Flight Plan Assessment Process must consider Static Flight Context (air rules, static geofences, terrain, obstacles), Dynamic Flight Context (Weather, dynamic geofences, communication and navigation systems availability and integrity, ground occupancy by people, urban traffic, etc.) and previously authorized flights to assess the safety of each flight. To do so, it needs an accurate space-time description of the flight, which at the same time needs to be operationally consistent with drone operator mission needs.
- Alternative Flight Plan Proposal process must be able to amend requested but not authorizable flight plans, providing alternatives which are authorizable while respecting (as much as possible) mission definition. From this definition, it is clear the drone operators would need to specify parts of their operations to be critical (no mission would be performed if this is not respected) and others which may be changed by this process, if needed (i.e. altitudes while performing an approach to the place where a delivery is to be performed, or times to start a not-time critical mission). The proposed flight plan data format must support the potential alternatives issued by this function, either constraining certain parts of the flight plan definition or amending non critical parts of it.

Summarizing the process, the operator creates/fills a flight plan making use of the ”Flight Plan Definition/Translation Support” service, and requests it to be authorized by the ”Flight Authorization” process, which makes use of the ”Flight Assessment” process to decide. If not authorized, the ”Flight Authorization” process requests the ”Alternative Flight Plan Proposal” process to provide alternative flight plans which are safe. These alternative flight plans are forwarded to the ”Flight Plan Definition/Translation Support” service so the operator may inspect and edit it and send it back to the ”Flight Authorization” process, closing the flight negotiation loop.

Once a flight plan gets authorized, it would enter the Flight Plan Management process, which is the link between the pre-flight (strategic) and the along-flight (tactical) services within the UTM. The processes associated to tactical services are depicted in Fig. 2. Again, our UTM experimentation/simulation platform covers all the functionality described next, but with limited implementation of conflict resolution functions.

The basis of the UTM Tactical process is the derivation of tracks for all drones (using a collection of data sources, such as drone telemetry, non-cooperative sensors deployed in the field, etc.). Then the UTM system must

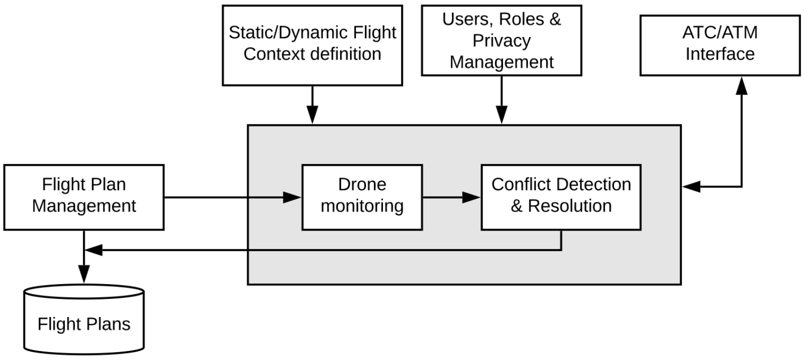


Fig. 2: Drone Monitoring and Safety Assurance (Tactical drone management)

continuously check they follow the previously authorized flight plans, do not invade any geofence or problematic area, do not become too close (to avoid mid-air incidents or accidents) and there are no associated contingency problems such as loss of command and control communications or loss of navigation. Next, we will summarize the central along-flight functions:

- Flight Plan Management is in charge of maintaining the current state of the flight: is it active (the drone is flying), was it terminated by the pilot, did the plan authorization got revoked by the UTM system?
- Drone Monitoring function does all the safety assurance functions related to each individual aircraft: Drone Tracking, incursion in geofences monitoring, terrain avoidance monitoring, flight plan conformance monitoring, and provision to pilots of nearby traffic information (including both manned and unmanned aircraft). To do this, it must consider the current Static and Dynamic Flight context.
- Meanwhile, Tactical Conflict Detection and Resolution Process checks potential near future loss of separation for drones, according to their tracks and to their intended flight plans. In the case of potential conflicts it also provides resolution advisories, specifically by amending the current flight plans and updating those amendments in Ground control Systems, alerting drone pilots, etc.

Once we stated the main UTM functions, at a very high level, we will start describing more in detail flight planing used cases, flight plan data requirements and flight planning tools. It should be noted, though, some other UTM functions (such as emergency management), not so related with flight planning or flight plan management, will not be studied here.

4 Flight Planning Systems Use Cases

Although in current civilian drone operations most of the systems are focused on performing VLOS operations, as described in section 2, it is clear that many of the future applications of drone technologies to urban areas will demand implementation of safe BVLOS flights. Coincidentally, the near-future deployment of 5G networks has the potential to allow for safe remote ubiquitous command and control and information retrieval from drones in urban environments. Therefore, this is the kind of environment (extremely low latency, high reliability and high bandwidth communications) we may assume for the description of the following use cases. Also, the presence of intelligence on-board (enabling drone autonomy) or in the ground (i.e. deployed in cloud/edge computing servers) will become less relevant due to the presence of 5G. In any case we will assume the coordinated efforts from on-board and ground systems (including potentially human pilots at least for contingency management) allows to pilot two basic types of operations:

1. Automated flight, following 3D waypoints. This kind of operation is aimed in the translation of the drone from its take off-area to the actual area of business related operations and from there to the intended landing area, or for goods delivery. In this kind of operations, the flight may be accurately planned following an open-loop control approach, based on trajectory prediction tools supported by drone dynamic models, and the operation is therefore not dependent on the information being retrieved by the drone (apart from the obvious navigation information allowing plan implementation).
2. Manual/autonomous flight. In this other kind of operations, the flight operation depends on the data provided by drone sensors in real time, which makes the autopilot/human pilot take real-time decisions on the trajectory to be implemented. In other words, depending on the information being retrieved from the drone, the actual flight operation may change (i.e. in emergency or police operations, in large area infrastructure inspection operations ...). This is therefore a closed loop control approach, and the flight planning cannot be so accurate but just impose constraints on the flight envelope (i.e. define areas or volumes of operations, flight duration, etc.). This kind of operations may also be used to model final landing in a not fully controlled environment. Also, this could be used to plan drone swarm operations without defining individual flight plans.

Based on these ideas, we will next define the flight planning use cases and from them we will derive a more detailed description if the requirements of an integrated flight planning process for urban operations.

4.1 Pre-Flight Use Cases

Next, we will describe several use cases for flight planning and authorization process, describing the interactions between the different functions and the potential outcomes:

1. "Public trajectory to UTM" waypoint based flight planning: In this use case, the operator needs to design a flight plan from a take-off location to a landing location, and has no privacy/security-related problems with the publication of the fine-grained details of this flight plan to the UTM service providers (please note this details will not be public, in any case, to other drone operators). The operator, in this case, will make use of the Flight Plan Definition/Translation Support process, which provides him (through a map-based HMI) up to date information about the flight context, including, for instance, data referring to:
   - airspace airways structure, so the operator fills only a few waypoints and automatically the system fills additional waypoints following those airways.
   - geofences (no drone zones).
   - airspace areas with flight limitation/manual authorization requests, etc.
   - weather prediction, specially related to wind, storms or other hazardous events precluding/difficulting drone operation
   - GNSS availability/Communication coverage predictions, potentially precluding flight to be performed.

   In this case the flight plan is designed iteratively, making use of either Flight Plan Definition/Translation Support HMI (just by selecting waypoints over a map) or an alternative ad-hoc flight planner connected to it, whose flight plans are translated to the UTM internal format. In the former case the Flight Plan Definition/Translation Support completes the flight plan, based on drone dynamics and flight context information (airways, terrain models, weather prediction, etc.). In the second case (external flight planner HMI), the Flight Plan Definition/Translation Support system will translate all the available data from the external flight planner format, and complete it if necessary, also making use of drone dynamic models and context models. In any case, the operator must define a maximum and minimum initial time for take-off. The support system also checks the flight may be completed by the drone, given its endurance.
2. Manual/autonomous area operation flight planning: In this case, the mission is assumed to need a manual/autonomous flight operation, where we are not able to establish waypoints before flight. Instead, the flight plan is defined through a 3D volume to be reserved for a given time interval. This defined volume then becomes a geocage for the operation, not to be exited. In this case the flight plan is designed at once, and there is no point in trying to use drone dynamics to calculate time intervals. The operator must specify a flight duration interval and a maximum and minimum initial time for take-off. Also, the operator needs access to up to date information about

the airspace airways structures, geofences, weather situation, etc. to design its flight plan in a safe way. In this case the user directly uses the Flight Plan Definition/Translation Support HMI and defines the volume and time constraints, directly specifying the flight plan in an UTM-compatible way.

3. Hybrid operations flight planning: There is also the possibility that the operator wanted to plan, for instance, the consecutive delivery of several goods to different not fully controlled landing areas, or the inspection of several infrastructures in a single flight. In this case, the flight plan may be composed of a concatenation of waypoint lists and manual/autonomous flight areas. This case has the two previous ones as particular cases. The use of either the Flight Plan Definition/Translation Support HMI to define the whole flight plan is feasible. Also, the use of alternative ad-hoc flight planners connected to it, whose flight plans are translated to the UTM internal format, for those sections of the flight plan defined through a collection of flight plans, is posible (although possibly the process is much more complex for the operator).
4. "Blind trajectory to UTM" waypoint based/hybrid flight planning: In this later use case, the operator needs to design a flight plan from a take-off location to a landing location, or a hybrid flight plan, but he/she has privacy/security-related concerns with the publication of the fine-grained details of this flight plan to the UTM service providers. In this case the process need to be performed in two phases:
   - Definition of a fine grained waypoint based/hybrid flight plan, as previously described. This flight plan will be used internally by the operator (for instance, as an input to its Ground Control System).
   - Definition of an associated "Bounding-Box" volume (or collection of volumes), and associated time intervals, which fully covers the previous flight plan. This would be the flight plan to be sent to the UTM service provider. This volume becomes again a geocage for the flight.

   It should be noted this later use case, although having obvious advantages to the operator, has also an important disadvantage. This potentially much rougher specification of the mission results in a request for additional airspace resources, which makes harder for this kind of flight plans to get authorized (they could be more easily in conflict with other operator requests previously authorized), and also constraint the available resources for later request.

In any of the previous use cases, after designing the flight plan, the operator provides it to the UTM Flight Authorization process which either authorizes it or denies it. If denied, it is possible the authorization system provides alternative flight plans which could be used by the operator to either send it back to UTM and get almost automatic approval (as it has been pre-assessed by the UTM assessment system), or as a basis for flight plan refinement on its side and the start of a new authorization process. To make the negotiation process faster, the operator might mark several parts of the flight as business-critical. In fact, there are cases where it is business-critical to perform the flight not only following a defined path or in a given area, but also conforming tight time constraints (i.e. when the drone is used to perform surveillance of a given event in a certain position and time).

The definition of time constraints for each part of the flight is a hard requirement for different parts of the UTM system. Specifically, Flight Plan Assessment needs the time in order to be able to predict potential interactions (i.e. separation losses) between several drones, to assess the impact of weather, etc. Also it is necessary that the planning tools help the user to constrain flight heights to avoid obstacles, and as previously stated, to avoid forbidden areas and respect potential airways structures.

Finally, there are other two pre-flight use cases, related to the potential revoking of a previously allowed flight plan by the UTM (due to changes in the Dynamic context), and to the removal of authorized flight plans by their creators. In the first case, the flight planning support HMI seems the most adequate channel to inform both operators and drone pilots of this kind of event (using some kind of notification process). In the second, the same HMI may be used to select an authorized flight plan and requests its removal.

Depending on the kind of operation, it is clear the capacity to rapidly fill in an authorizable flight plan, and all the associated data, will be of paramount importance from the business perspective. This would be the case of emergency services, fast delivery of critical goods (or freshly cooked food), etc.

4.2 Along-Flight Use Cases

During flight Drone Monitoring service will make use of the authorized flight plan and of real-time tracking of drone kinetic state (position, velocity) supported by drone measurements (i.e. telemetry, cooperative and non-cooperative sensors networks deployed in the city, etc.) to detect potentially hazardous events such as:

- Lack of conformance of actual flight with authorization both in spatial dimension (getting out of approved ”geocages” or too far away laterally or vertically from the lines connecting waypoints) or in time dimension (not respecting the authorized time constraints).
- Future tactical conflicts (losses of separation) between drones in the near future, to be assessed making use their intent (expected maneouvers to implement the authorized flight plan) to enhance the dynamic predictions of current flights.
- Future interactions with dynamic geofences, with hazardous changing weather, etc.

Some of those events, when detected, will result in the need to perform a contingency procedure and abort the flight operation in a safe manner. But in some cases, there could be a procedure to allow for flight plan edition to resolve the situation, following a fast flight-planning-to-UTM negotiation process. This process, similar to that of the authorization, could result in the edition of business-critical parts of the flight. Again, in order to guarantee operations safety, it is not only necessary that the geometry of the flight is defined (new waypoints, amended volumes), but also flight planning system and UTM need to have a shared view of the time constraints of the flight (even tighter during actual flight operation).

Our Flight Planning system, in its current implementation, does not cover along-flight flight plan edition/amendment. Improvements in real-time performance are needed to allow it to be included in a real-time safety critical control loop related to mission amendment. In any case, neither flight plan definition, validation/authorization or operator interaction would be very different from those in pre-flight, with the logical simplifications needed to provide safe solutions in a short time.

5 Prototype Tool

In this section we will describe, at a very high level, a flight planning tool prototype partially implementing the aforementioned use cases. Its architecture is depicted in Figure 3, being conformed by a collection of layers. The lower one is related to basic trajectory prediction to derive Time & Height constraints making use of drone dynamic models. Over it, there is a layer related to avoidance of terrain and physical objects described in a ground model. Then, two functions take care of making flight plans compatible with the aeronautical constraints in the airspace: No drone zones and other aerospace constraints. Finally, all those functions are managed, according to the use cases described in section 4, through an HMI and a flight plan translation system.

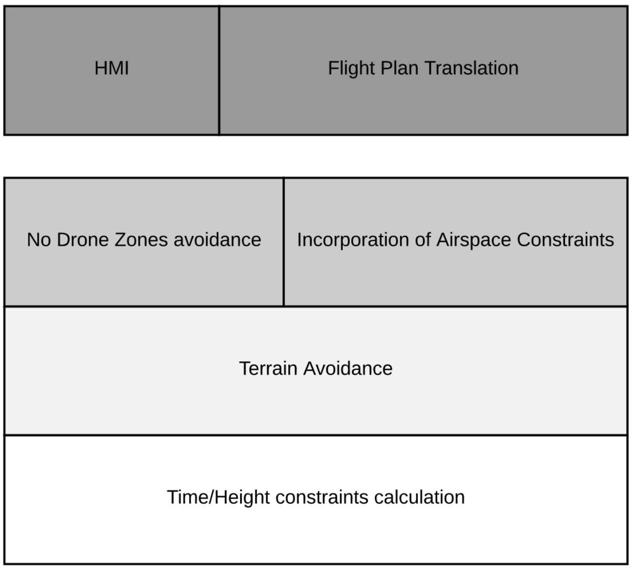


Fig. 3: Flight Plan Definition/Translation Support Architecture

In the next subsections details on the functional parts of the prototype system will be provided, starting from the lower parts of the architecture.

5.1 Time/Height constraints calculation

From the previous description, it is clear the mission specification of the flight (to be detailed in section 7.1), is basically composed of the take-off and landing points, with additional waypoints and volumes ("geocages"). Using the HMI, it is also posible, in general, the user specifies some time and height constraints for some waypoints, as well as the expected duration of the flights in the volumes. All those constraints will in general take the form of time/height intervals. Then, in order to implement the strategic resources allocation and the flight plan monitoring, it is clear it is necessary to calculate time/height constraints for the rest of the flight, so a set of time/height gauges for each position/area are always available. All those constraints need to be compatible with potential drone dynamics. Although other potential input data could be included, in our prototype, the operator-eligible constraints are:

1. for the takeoff point, the takeoff minimum time and maximum time at which the drone starts flying must be specified, to take into account the uncertainty in drone preparation, etc.

2. for waypoints, a minimum height and a maximum height may be selected at user will. In the case of fixed-wing or VTOL drones, the selection of those parameters needs to be checked to ensure compatibility with drone dynamics. Time windows/gauges cannot be constrained by the user directly, but indirectly by constraining drone dynamics (i.e. groundspeed), as times need to be compatible with flight geometry (i.e. distance to waypoints), weather, etc.
3. for volumes both height and flight duration within the geocage must be limited (with maximum and minimum values).
4. for the landing point, no constraint can be selected. Time windows will just be calculated by the system, propagated from previous constraints according to potential drone dynamics.

From previous points (and specially from points 2. and 4.), it is clear there is a need to propagate time windows from previous constraints according to potential drone dynamics. This is done through an effective use of a drone trajectory prediction infrastructure, described in [38]. Two trajectories, with different groundspeeds (high-speed and low speed), are predicted, making also use of the potential height constraints, to calculare the time window for each waypoint. The fastest trajectory starts from the earliest takeoff time and the drone moves at the fastest possible speed. If there is a volume present, the duration constraint added is the minimum to get the fastest trajectory. This trajectory provides the minimum time at which the drone passes through each of the waypoints, polygons and the earliest time at which the drone will land completing the flight plan. The slowest possible trajectory is calculated the later takeoff time, the slowest possible speed, and maximum flight durations within geocages, to calculate maximum times. In the case in which the speed has been restricted by the operator for any portion of the flight, the trajectories calculated for those segments will use this user-defined groundspeed instead of the maximum-minimum speeds.

In addition to obtaining the time constraints from the calculation of the two trajectories, the height constraints are also established for each of the waypoints at which the user has not previously restricted it. Here the aim is to keep the flight as low as possible (respecting a minimum height over terrain at waypoints position) to avoid wasting time and energy. A height window, compatible with typical piloting/flight technical error is established. The calculated heights are both in height above ground level (AGL) and height above sea level (WGS84 heights) formats, needed for different parts of the UTM services.

Simplified functionality is performed when processing flight plans from adhoc flight planners, where some additional time/height data on trajectories may have been calculated by the outer tool.

5.2 Terrain Avoidance

Although the previous approach enables avoiding terrain at waypoints positions or at volumes, it does not allow to avoid obstacles or terrain discontinuities between waypoints. For these reasons, it is necessary the presence of an algorithm for terrain avoidance. Making use of the horizontal path being followed by the drone, according to trajectory predictions, a terrain profile may be derived from a Digital Surface Model (DSM), to be described in detail later, in section 6.1. In Figure 4 the input to such process is included, in the form of the associated height profile vs flown distance, in a case where the intented trajectories height gauge intersect with the terrain.

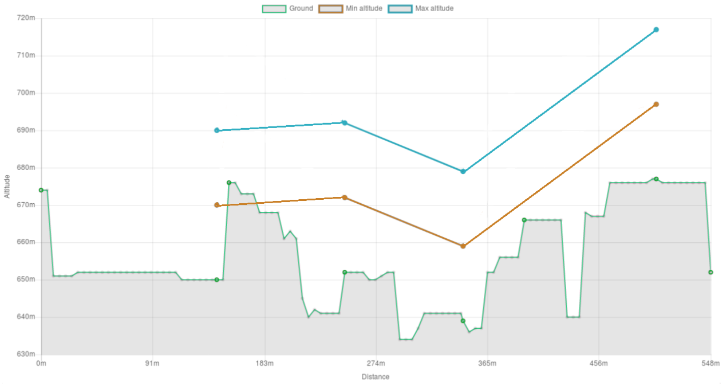


Fig. 4: Height profile before terrain avoidance

The solution to this process is to calculate intermediate 3D waypoints to be incorporated to avoid such collisions and thus ensure safety during flight. The horizontal position of those waypoints need to be aligned with the expected trajectory, so they will be in the lines between consecutive waypoints, while in the vertical dimension they will move the initial gauge to ensure it remains free of obstacles. In figure 5 the resulting height profile may be seen.

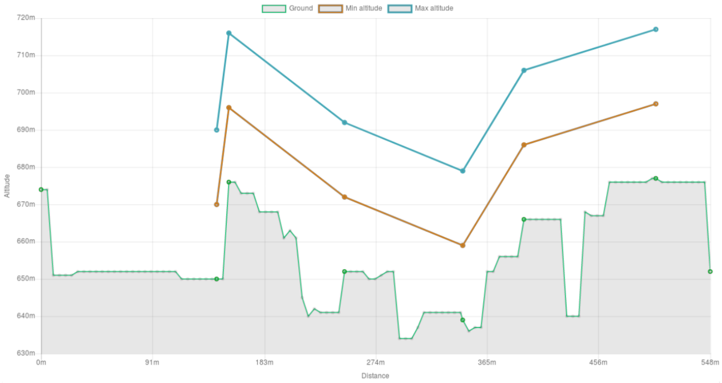


Fig. 5: Height profile after terrain avoidance

Also, due to regulations, there is an implicit ceil to drone operations (typically in the order of 100-150 m, in so called Very Low Level airspace). So, the same kind of refinement for terrain avoidance must be performed to avoid the flight to overcome this maximum height limit.

Any change to flight plan related to terrain/flight ceil avoidance results in changes of flight timing, therefore requiring new calculations at the lower Time/Height constraints calculation, following the same principles described in section 5.1.

5.3 No Drone Zones avoidance

An additional restriction to flight comes from the presence of No Drone Zones (NDZ). Although avoiding them might be simple if the flight plan is designed using a NDZ-aware interface (as the HMI in our prototype tool), as the user may avoid them, ad-hoc flight-planning tools might not provide this information to the drone operator. Therefore, it is necessary to check if the trajectory, according to the flight plan, intersects or passes too close to NDZ (taking into account the presence of navigation and flight technical errors). In the case of potential NDZ violation, out flight plan design tool automatically modifies it following a set of predefined strategies, which have been created to slightly modify the original flight plan. These flight plan alternatives are then provided to the operator so he may chose one of them (future iterations of the prototype will assess the quality of the solution according to some user-defined heuristics and may automatically select the alternative to be provided to UTM for authorization). The four NDZ-avoidance strategies in our prototype are:

- NDZ Height-based avoidance: If the NDZ has a maximum and minimum height the drone could fly above or below it. This is implemented through the inclusion of new waypoints with adequate height restrictions, or by the

restriction of heights in volumes. This strategy will try to allow the drone fly as low as possible respecting a safety margin with the NDZ.
- NDZ Time-based avoidance: If the NDZ has a maximum and minimum activation time the drone could fly through this area before or after it. To do this, the minimum and maximum times of takeoff, the drone groundspeed and the durations of the operation in the volumes present in the flight plan can be modified, using additional safety margins.
- NDZ Route-based avoidance: this strategy modifies the horizontal route to be followed by the drone avoiding the no drone zone, by either moving laterally its waypoints or adding additional waypoints. This solution is used when NDZ incursions occur between waypoints.
- NDZ Volume-based avoidance: Conversely, if there is an intersection between a flight plan polygon (volume) and a NDZ, an alternative strategy may be is to reduce the flight plan volume by "substracting" the NDZ from it (removing the intersection of both volumes). In this way, the drone is allowed to fly in a volume smaller than the one created initially by the operator.

The prototype algorithms at this layer need to take into account the definition of parts of the flight as business-critical by the operator. So, some parts of the flight route, heights or time constraints cannot be changed. This results in cases where no alternative flight plan can be found. Additionally, our prototype implementation of these strategies do not always reach a valid result, only working for a reduced amount of NDZ intersections for a given flight plan. In any case, our flight planner tools precludes sending to the UTM authorization process any flight plan not compatible with the set of currently known NDZs.

5.4 Incorporation of Airspace constraints

Our prototype has a very simplistic airspace model (described in detail in section 6.3), and related to it, it performs the following processes:

- Flight rules imposition: in some airspace volumes, maximum/minimum heights, groundspeeds and maximum drone weights may be defined, and also drone/operator access list might be implemented. Also, flight cannot be allowed at some hours. Those limitations are imposed in the flight plan. Some of them are imposed by changing the flight plan following strategies analogous to those of NDZ avoidance processes (for heights/speed limitations, and for airspace closing time-intervals). Some others are solved by rising an alert in the flight planning HMI (i.e. for non-permitted drone weight, lack of previous authorization), so that the operator changes it to respect the associated limitations.
- Airspace routes imposition: in some airspace sections, in order to have an ordered flight flow, an airspace structure may be defined. If this is the case, and the flight needs to traverse one of this areas, a shortest-path solution is calculated (using a Dijkstra algorithm).

In any case, any of those amended flight plans result of this function need to be re-assessed and maybe redefined by the lower levels of the prototype tool (NDZ-avoidance and terrain-avoidance). Finally, all the prototype algorithms (at the three previously described layers) need to take into account the definition of parts of the flight as business-critical by the operator, not performing changes on related magnitudes and rising alerts if no potential solution can be found to the problem of finding an adequate flight plan compatible with both operator and context constraints.

6 Flight Context Data Models

All previous algorithms in our prototype are based on the definition of a series of data models, to be described in this section. Specifically, they are a Ground/Terrain model (section 6.1), the No Drone Zones Model (section 6.2), and the airspace model (section 6.3).

6.1 Ground/Terrain Model

In order to perform Terrain avoidance processes, the height profile of the terrain needs to be known with high accuracy. To this end, a service has been created that is responsible for accessing the underlying ground model services and providing information for the rest of the system on the height of the terrain.

The ground model service comprises a Digital Terrain Model (DTM, including ground elevation) and the Digital Surface Model (DSM, comprising the elevation of the physical barriers/obstacles) [39]. The DTM can be described as a 3D representation of a terrain surface consisting of (longitude, latitude)-indexed height (above Mean Sea Level elevation) coordinates stored in digital form. Meanwhile, the DSM represents the heights of the surfaces of trees, buildings, and other features potentially elevated above the ground, based on LiDAR or photogrametry reconstructions.

In our prototype, the system is centered in Spain, so we filled the DSM model with public LiDAR data taken from the Spanish IGN [40], passed through several data processing layers to remove outliers, fill in the gaps in low LiDAR cloud density areas, and make the map resolution roughly constant (in our prototype, given the flight safety constraints, and computational performance requirements a 5 meters resolution of the map was used). They are then converted into an internal GeoTiff format, and stored in a fast-access database of images, indexed using an Universal Transversal Mercator grid, with 1km x 1km GeoTiff images (both part of the grid and an specific Geotiff image may be seen in figures 6 and 7).

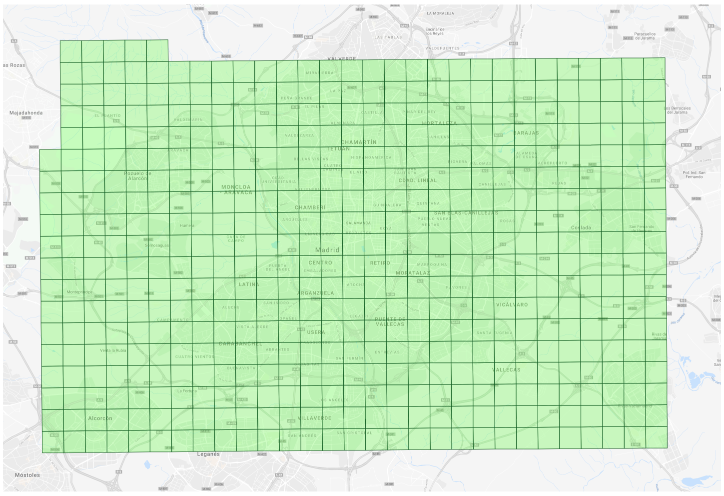


Fig. 6: Universal Transversal Mercator grid of Madrid

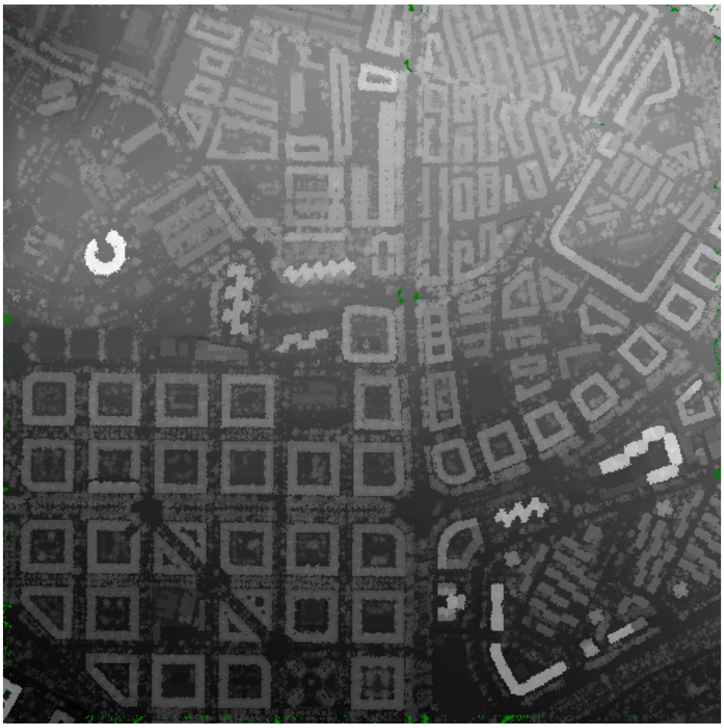


Fig. 7: Geotiff image from an urban zone of Madrid

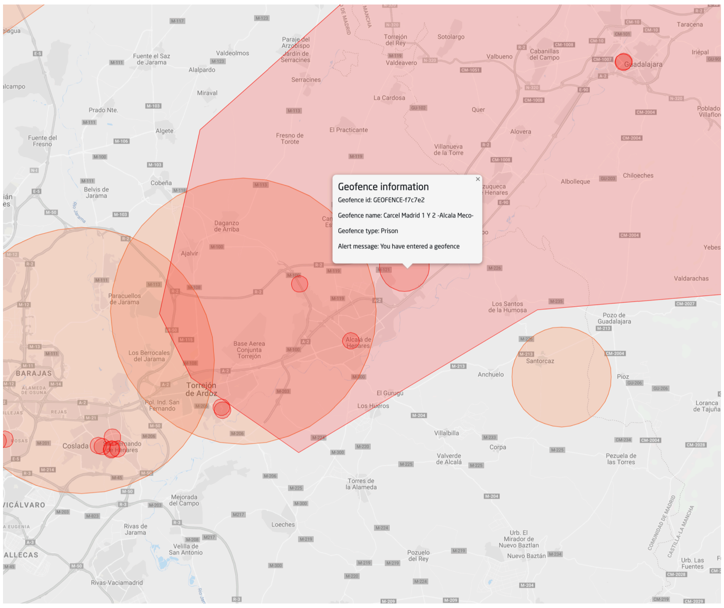
The service related to the model needs to provide several fast access procedures to the rest of the UTM service:

- To provide the height for a specific point or collection of points, such as take-off or landing points, or any waypoint, expressed as (longitude, latitude).
- To provide the height profile along a line connecting two consecutive point, or a linear interpolation of a series of points, all of them expressed as (longitude, latitude). This profile is key for the terrain avoidance functionality, as described in section 5.2.

6.2 No Drone Zones model

”No drone zones” are areas where flying a drone may be unsafe or illegal (e.g. airports, stadiums, parks, monuments, etc.). In UTM systems, these zones are generally modeled using geofences: *a virtual geographic boundary that enables software to trigger a response when a device enters or leaves a particular area* [41]. The typical behavior generated by a geofence invasion is alerting the pilot and the UTM authorities, although modern Ground Control Systems and drone autopilots may preclude drone access to those geofences.

In order to enable realistic use of this concept in UTM services it is needed to extend the geofence model including some additional features. The basic structure of our geofences in our prototype is a geoJSON Polygon geometry [42], to which a minimum and a maximum height constraint need to be added. In this manner, it is possible to create vertical stacks of geofences with different features. Fig. 8 shows a collection of Geofences in Spain, as obtained from Spanish AIP, which are relevant for Very Low Level flights.



Geofence id: GEOFENCE-f7c7e2

Geofence name: Carcel Madrid 1 Y 2 -Alcala Meco-

Geofence type: Prison

Alert message: You have entered a geofence

Fig. 8: Example of geofences in the VLL airspace

Minimum and maximum time constraints need also be added to reflect the possibility to program future activation and deactivation of the geofence. With this feature it is very easy to create a temporary geofence, for example preclude flights over the roof of a building during an event or a portion of a road after a car accident.

Additional parameters of the geofences may be a list of drones, operators and pilots that have permission to fly in the geofence, each with a time-window constraint (e.g. to a drone of the maintenance staff of a park after closing time). In addition to these permission fields, in case of emergency, a boolean flag can be used to manually activate or deactivate a geofence.

During the creation of a flight plan, the geofences need to be visible to the operator and they can be hidden to create flight plans that require to fly in the geofence (and that must have the right permissions to be approved). The permissions are checked by the UTM during the authorization process of a flight plan.

6.3 Airspace model

As described in section 5.4, our prototype has a very simplistic airspace model comprising:

- Airspace volumes definitions, specifying flight rules and constraints associated to an specific part of the airspace:

  - maximum/minimum heights(above ground level).
  - maximum/minimum groundspeeds.
  - maximum drone take-off weights.
  - an access list for specific registered drones.
  - another access list for specific registered drones.
- Airspace routes: In out very simplified airspace model, a network of 3D routes ("airways") is defined, linking a collection of intermediate nodes, for some airspace volumes. Each of these routes contain:
  - The ordered collection of 3D nodes it connects, defined by their latitude, longitude and geometric height above ground level.
  - Maximum/minimum groundspeeds.

Route vertical stacks are not modeled in our prototype, they would be seen as independent routes.

7 Flight Plan Data Requirements

From the previous use cases, next we will derive a collection of data requirements for the specification of missions (input of the Flight Plan Definition/Translation Support process), and for the provision of flight plans for the rest of the UTM system (out of the Flight Flight Plan Definition/Translation Support process)

7.1 Input mission specification data requirements

Next, we will detail the flight plan specification data fields, with some rationale, from the previous discussion. This would be the data defined interativelly using the HMI, or this data will be needed in some other format for translation:

- Identification data (for flight plan, operator, pilot, drone ...). Necessary to check compliance to regulation, certification, and to define the adequate drone dynamics. Also, the associated drone identification is used to check drone weight limitations, define maximum and minimum velocities, etc.
- Priority
- Drone flight endurance.
- Take off area and altitude: It is recognized in many cases it is impossible to define a take-off point at planification time.
- Take-off time interval: quite often the time needed preparation and deployment of the drone are not completely controllable, so it is necessary to open a time window.
- A collection of flight phases, which are either collections of successive waypoints (in 2D or 3D), with a potential groundspeed constraint, and a flag saying if this flight phase is business-critical (with respect to its spatial design or also considering times to be calculated by the system), and areas

(volumes), defined through polygons, with associated minimum and maximum duration of the flight within them. Again, there should be a flag indicating if this flight phase is business-critical.
- A landing area and altitude: again, it is acknowledged in many cases it is impossible to define a landing point at planification time.

7.2 Output flight plan specification data requirements

As described along the paper, from the previous data, the flight planning support process completes a flight plan containing, in addition to previous data, the following fields, demanded by some parts of the UTM system either at pre-flight or along-flight (with rationales):

- A collection of flight phases. The output flight plan may not only have the input waypoints, but some additional ones due to the need to be compatible with the airspace structures (such as airways or corridors), or to avoid no-drone-zones, airspace areas, or terrain obstacles present in direct paths. In addition to previous (input) fields, the flight plan needs to contain time and altitude constraints for all waypoints, calculated considering drone dynamics, to enable proper safety assessment and alternative flight proposals, and also to allow flight plan conformance monitoring in the vertical and time dimensions. Also, some of the flight phases may be defined by volumes, and those may have been changed due to the no drone zones avoidance or airspace constraints incorporation procedures. Initial and end times for input and output in the flight volumes are also calculated and included in the flight plan specification.
- A landing time interval calculated using drone dynamics.

8 Experimental results

In this section we are first describing the practical implementation of our prototype, and later providing a full example of application of the previously described techniques and some performance results to identify the computational bottlenecks.

Our flight planning tool is built making use of a microservice architecture, connecting contextual data retrieved from outer and internal Web Services, and based on the extensive use of REST APIs for service-oriented communications and MQTT for notification publication of asynchronous events. The front-end is built in HTML5/CSS/JavaScript, and the central parts of the backend logic are built either in JavaScript (Node.js) or making use of C++ for computationally complex parts of the system (specifically, for trajectory prediction). For trajectory prediction we are making use of the same kind of techniques outlined in [32] , which are an extension of the methods described in [30]. The system connects to the following services to obtain up-to-date data to describe both static and dynamic flight context:

- Mapping information is retrieved from Google Maps, which is also used as the basis for the map-based interface.
- Digital terrain (elevation and surface) models are retrieved from the Spanish National Geographic Institute [40].
- Weather data is retrieved from public servers such as Open Weather [43]
- 3G/4G communications services or navigation services performance are not assessed or used in our prototype.
- Static Geofencing is automatically created on the basis of a digital version of Spanish AIP, and other public databases (i.e. hospitals, nuclear facilities, national parks, etc.).
- Dynamic Geofencing is retrieved from the full-scale UTM prototype we are also developing, with interfaces for state services (police, firefighters, etc.).

It makes use of the aforementioned information to either perform trajectory predictions (mapping, digital terrain, and wind data are used at this stage), or to provide visual information to the flight plan designer HMI, so he creates flights compatible with the current flight context (for the time of the operation).

8.1 Flight Plan Design Example

Next we will show an example interactive flight plan design exercise, based on our flight plan design. Flight plan 2D specification can be seen in figure 9. It is composed of a take-off area (marked as 0 in the map), and a landing area (marked as 9). Then it has three phases:

- A linear operation, comprising waypoints from 1 to 5.
- a volume, depicted in light blue in the figure.
- Another linear operation, with waypoints from 6 to 8.

The drone parameters for trajectory prediction are summarized in Table 2

Parameter	Value
Drone	DJI Phantom 4
Take off min time	10/05/2019 12:07
Take off max time	10/05/2019 13:12
Min height above ground level (m) in volume	30
Max height above ground level (m) in volume	50
Min flight time (s) in area	100
Max flight time (s) in area	200

Table 2: Example parameters

The drone mission definition passes through two different areas. The first is a no drone zone (depicted in light red), whose details may be seen in 10. It should be noted the No Drone Zone is active during the initial intended flight duration, but it will become not effective 2 months later. The second area is the one marked with a green contour. This is an airspace area where a dense route network has been defined. In this case, the network is assumed to follow the same structure as the underlying streets. In other words, in this area, drones are constrained to fly over streets. No part of the flight is specified as business-critical.

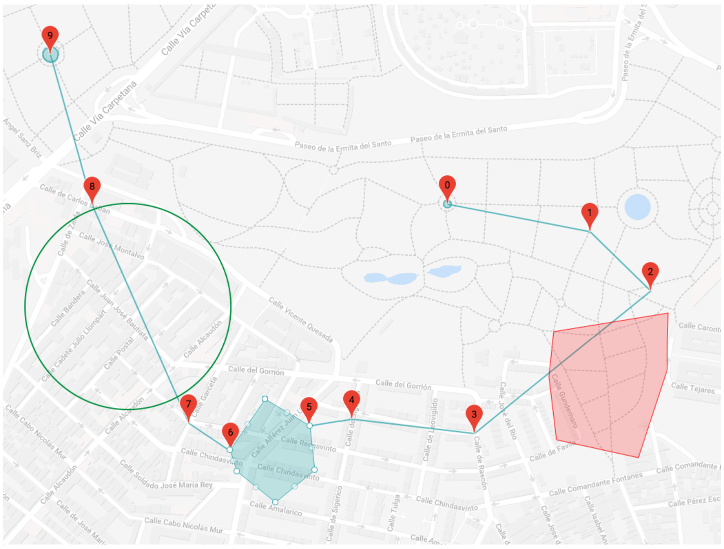
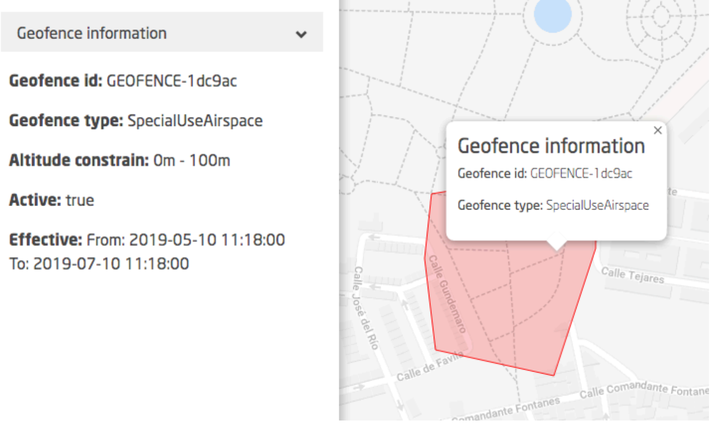


Fig. 9: Original input flight plan

This exercise is included as an example of representative flight planning covering major use flight planning cases: 1) "Public trajectory to UTM" waypoint based flight planning is similar to the trajectory between 0 and 5, and also between 6 and 9; 2) "Manual/autonomous area operation flight planning" is performed within the cyan volume; 3) The complete flight plan may be seen as a "Hybrid operations flight planning"; and 4) "Blind trajectory to UTM" is equivalent to "Manual/autonomous area operation flight planning" from the UTM point of view. So, this exercise covers all the use cases described in section 4.1. Also, the exercise demands actions at all layers of the flight planning service, as described in section 5.



Geofence information

Geofence id: GEOFENCE-1dc9ac

Geofence type: SpecialUseAirspace

Altitude constrain: 0m - 100m

Active: true

Effective: From: 2019-05-10 11:18:00
To: 2019-07-10 11:18:00

Geofence information

Geofence id: GEOFENCE-1dc9ac

Geofence type: SpecialUseAirspace

Fig. 10: No drone zone information

This flight may not be flown by directly linking the provided waypoints for a number of reasons:

1. The NDZ need to be avoided.
2. The terrain need to be respected, which is specially problematic in some parts of the flight.
3. Route structure would not be respected in the airspace green-contoured area.

Our prototype provides three different alternative solutions. All of them impose the route structure referred in point 3) of the previous list, while providing different coordinated solutions for problems 1) and 2).

The first solution introduces new waypoints at elevated altitude to pass over the no drone zone, and introducing other additional waypoints to avoid terrain. The resulting flight plan can be seen over the map in figure 11, while the associated height profile can be seen at figure 12.

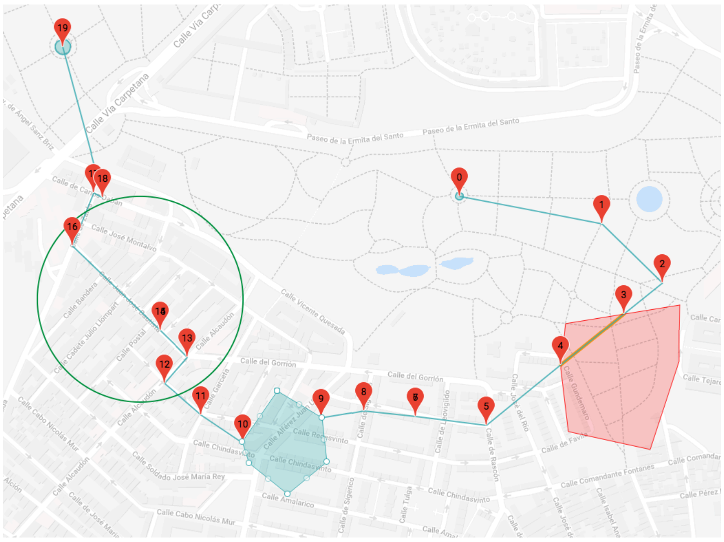


Fig. 11: Altitude solution flight plan

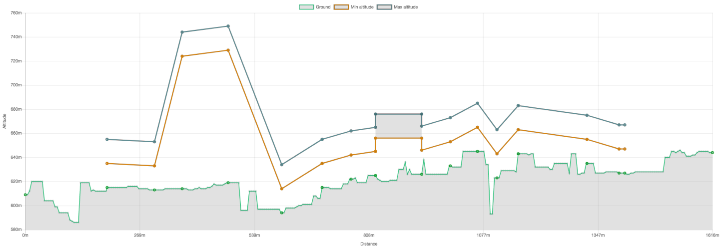


Fig. 12: Height profile of altitude solution flight plan

The second solution changes the time of taking-off, delaying it until the geofence becomes inactive, and also introduces some waypoints to avoid terrain. The resulting 2D flight plan over the map can be seen in figure 13, while the time constraints vs flown distance can be seen at 14. It should be noted this solution results in a 2 month flight delay for this synthetic example!

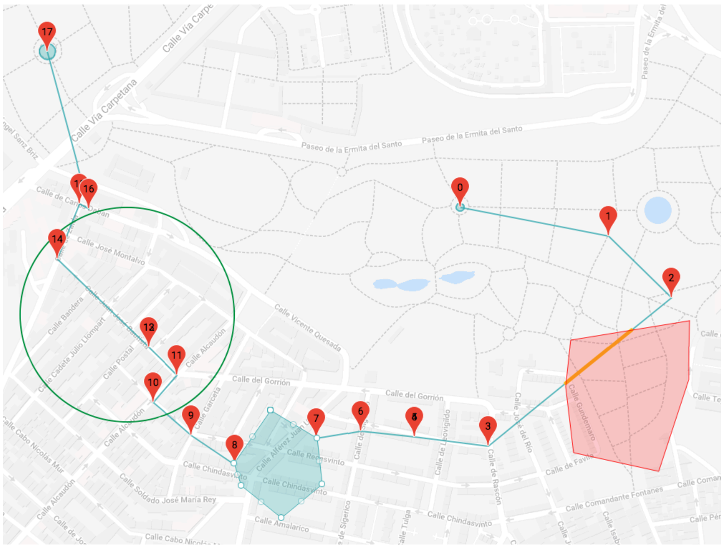


Fig. 13: Time solution flight plan

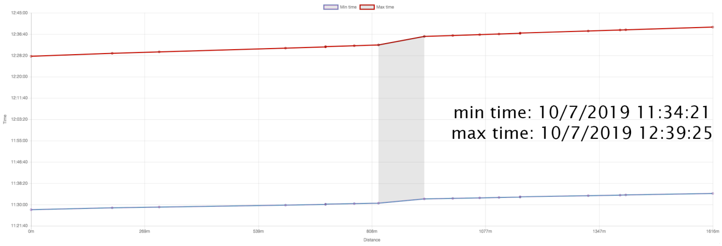


Fig. 14: Changed time constraints for time-based solution flight plan

The last solution is based on laterally avoiding the NDZ area, as it can be seen in 15.

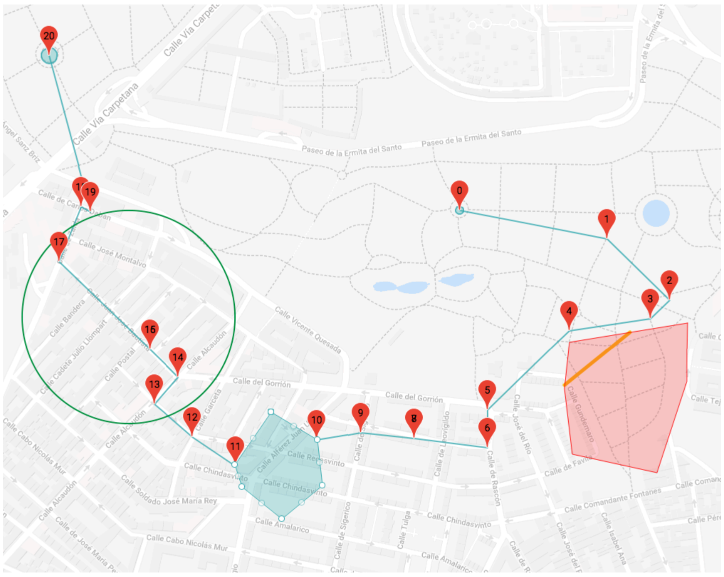


Fig. 15: Changed path flight plan

As it can be seen, the prototype is able to provide adequate solutions to all three problems, following the approaches described in the paper.

8.2 Performance evaluation

In this section we will calculate the performance of our prototype. We measured the time spent in each of the layers/services for flight plan calculation, using a dual CPU Intel ®Xeon ®E5-2620 @2.00 GHz server with SSD storage (twelve cores in total). To perform these evaluations, three flight plans of different lengths (235 m, 2067 m and 6.3Km), passing through a no drone zone, have been used. Again, the flight plans were designed in Madrid city urban area, needing all flight planning systems layer computations. The time results obtained can be seen in Table 3.

Service	Short	Average	Long
Ground	3.038 s	17.63 s	27.46 s
Time/Height constraints calculation and Terrain avoidance	0.655 s	1.13 s	1.69 s
No Drone Zones avoidance and Incorporation of Airspace constraints	0.65 s	0.68 s	0.7 s
Total	4.343 s	19.44 s	29.85 s

Table 3: Time Performance

From this time performance it can be inferred that the bottleneck of the system is the call to the underlying ground/terrain model service. Even taking this into account, the amount of time needed allows to use it in real time for not too complex/too long flight plans. It should be noted we are basically using mono-threaded implementations, and a parallel implementation of the ground service could result in important reductions of these times.

9 Conclusions and future work

This paper describes a collection of typical urban drone mission types and establishes the interfaces between flight planning systems and UTM systems. Its basic contribution is the analysis of the need to integrate the planning phases in the whole traffic management solutions, to enable fast design of safe flight plans, taking into account from the very beginning a flight context (i.e. airspace and terrain flight constraints). Also a functional layered architecture for flight planning has been described, and demonstrated through a working prototype. Associated use cases and data requirements have been derived. The described processes are being implemented in a full-scale UTM prototype to enable experimentation of most advanced UTM concepts, such as tactical and strategical deconfliction of traffic, capacity management, etc. Also, the major computational bottleneck, which is the access to high accuracy terrain model, has been identified , limiting its use to shorter trajectories until multitheraded access to model data is enabled (trajectories longer than a few tens of km result in several minutes of computation). Future enhancements will need to cope with this problem, and also improvements on the heuristics and solution algorithms need to be performed, to enable a more interactive flight planning process , usable not only before flight but also along flight. Also, a key aspect to be incorporated to the platform will be that of enabling the prediction of the risk of a given operation, using a Specific Operations Risk Assessment (SORA) [22] inspired methodology (both at flight planning and at UTM levels, to decide on flight plan authoprization). As our platform contains fine grained trajectory predictions, as well as flight context information, doing so seems quite in line with its capabilities, but fine-tuning risk models remains a challenge. Finally, context data (terrain, weather, etc.) integrity is a major concern, not only for our solution but for any flight planning/UTM system.

Acknowledgements This work was supported by UPM Project ”Tecnologías Avanzadas para la Monitorización y Gestión Remota del Tráfico Aéreo de Vehículos Pilotados y no Pilotados” (RP1509550C02), and by the Spanish Ministry of Economy and Competitiveness, Grant TEC2017-88048-C2-1-R

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