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UAS Pilot Support for Departure, Approach and Airfield Operations

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Abstract—Unmanned Aerial Systems (UAS) have great potential to be used in a wide variety of civil applications such as environmental applications, emergency situations, surveillance tasks and more. The development of Flight Control Systems (FCS) coupled with the availability of other Commercial Off-The Shelf (COTS) components is enabling the introduction of UAS into the civil market. The sophistication of existing FCS is also making these systems accessible to end users with little aeronautics expertise. However, much work remains to be done to deliver systems that can be properly integrated in standard aeronautical procedures used by manned aviation.

In previous research advances have been proposed in the flight plan capabilities by offering semantically much richer constructs than those present in most current UAS autopilots[1]. The introduced flight plan is organized as a set of stages, each one corresponding to a different flight phase. Each stage contains a structured collection of legs inspired by current practices in Area Navigation (RNAV[2], [3]). However, the most critical parts of any flight, the depart and approach operations in a integrated airspace remain mostly unexplored.

This paper introduces an assessment of both operations for UAS operating in VFR and IFR modes. Problems and potential solutions are proposed, as well as an automating strategy that should greatly reduce pilot workload. Although the final objective is a full autonomous operation, the pilot is always kept in the control loop and therefore HMI aspects are also considered.

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1. INTRODUCTION

Nowadays, in civil aviation, a set of procedures and standardized practices are followed in order to operate safely, effi-

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ciently and regularly all kind of aircraft. As it is well known, civil air traffic can be divided in two main groups: those aircraft evolving under Visual Flight Rules (VFR) and those which are under Instrumental Flight Rules (IFR). In addition, other classifications exist in civil aviation like for example the aircraft category (A,B,C,D or E) in function of the aircraft speed at threshold [4] and even more basic divisions such as the ultra light models (ULM), the very light aircraft (VLA), the helicopters etc. These classifications play a very important role in how most of the aircraft procedures may be conducted, specially air navigation and separation procedures.

Most Unmanned Aerial Systems (UAS) are, at present, designed for military purposes and very few civil applications have been developed mainly because the lack of a regulation basis concerning their certification, airworthiness and operations. Therefore, UAS operations have always been solutions highly dependent on the mission to be accomplished and on the scenario of flight. The generalized development of UAS applications is still limited by the absence of systems that support the development of the actual mission. UAS developers face the development of specific systems to control their desired flight-profile, sensor activation/configuration along the flight, data storage and eventually its transmission to the ground control. All this elements may delay, increase the risk and cost in the implementation of a new UAS application. Should realistic missions be developed, additional support must be created to offer flexible and adaptable platforms for any application that is susceptible to use them.

This paper addresses one of the issues that will arise if extensive civil UAS application became a reality in a near future, imagining a scenario where manned aircraft will coexist with unmanned vehicles. In particular, the integration of UAS in the depart, arrival and approach phases is assessed, taking into account all possible situations ranging from high or low performance UAS into busy and controlled airspaces or remote and uncontrolled aerodromes.

In Section 2 of this paper it is discussed how departs, arrival and approach procedures are carried out, at present, by manned aircraft. In Section 3 our proposal for the UAS integration in departure, arrival and approach phases is presented. HMI aspects of the ground systems that should support a high level of automating for our proposed operations are discussed in Section 8. Finally the paper ends with the Conclusion and Further work of Section 9.

2. CURRENT DEPART, ARRIVAL AND APPROACH OPERATIONS

There exist two kinds of flight rules in civil aviation: VFR (Visual Flight Rules) and IFR (Instrumental Flight Rules). VFR navigation is based on visual references which the pilot picks from the outside, such as rivers, mountains, roads etc. This kind of navigation is strictly constrained to the existing meteorology with some minimum conditions measured in terms of visibility and minimum separation from clouds. As a consequence, the use of VFR is usually restricted to private or leisure aviation. On the other hand, an aircraft flying under IFR rules uses several navigation instruments which provide the pilot with information for following its trajectory or navigation route with no need for external visual references. The route to be followed can not be any trajectory, but one which has been previously studied by the competent authorities in air traffic, and conveniently published to let it be known by the users of the air space. Particularly, these trajectories are called procedures (for airport departure, arrival or approach manoeuvres) or airways (for the en-route phase). The design of procedures and airways guarantees the clearance to obstacles (mountains, buildings...) by means of a secure flight altitude, as well as the minimum separation between aircraft using different procedures or airways in the same zone and, finally, it helps managing and directing the air traffic flow in a better way. VFR or IFR operations are highly dependent on the kind of airspace or airport being used.

IFR operations

All aircraft evolving in IFR conditions must follow a specific procedure, which have been previously designed and approved by the competent authority. Therefore, an airport accepting IFR flights will have one or several depart/approach procedures already published. Instrumental flight procedures are usually divided in three different types: Standard Instrumental Departures (SID), Standard Terminal Arrival Routes (STAR) and Instrumental Approach Charts (IAC). Different procedures might be published in function of the aircraft category and radionavigation system being used.

Even if Air Traffic Control (ATC) services are not present in the airport (not controlled airport), there must exist some IFR procedures published if IFR operations have to be carried out. In some cases, omni directional departures and/or arrivals are published. These procedures do not specify a particular route to follow for the departing or approaching aircraft but indicate the minimum altitudes for one or several sectors around the airport in order to satisfy a minimum obstacle clearance altitude. These omni directional procedures may also apply for controlled airports but with a relative small volume of traffic and, therefore, giving the operation aircraft the maximum flexibility for choosing their departing or arrival routes [5].

In non controlled airports, it is the responsibility of the pilot in command to ensure the minimum separation with the other traffic. All pilots in the area may coordinate among them and respect the published procedures. In this context, the pilot in command reports his/her positions and intentions at each significant point of the IFR procedure.

IFR procedures in non controlled airports are not permitted in all countries and are subject to different regulations. For example, in France, the instrument approach procedure is only permitted if there exists at the airport a station designated to provide QNH or an automatic data information system. In this case, the approach is restricted to a circling to approach procedure (i.e. an instrumental procedure ending in a visual maneuvering phase) and straight-in approaches are prohibited. In addition, for night operations, an operator agent should be present at the aerodrome being able to trigger the safety plan of aerodrome if an emergency occurs[5].

VFR operations

For high density Terminal Manoeuvring Areas (TMA) VFR flights may have important restrictions like for example VFR sectors, corridors or routes as well as some limitations in minimum and/or maximum altitudes. Concerning VFR operations in dense airports, these may publish Visual Approach Charts (VAC) detailing, for example the preferred side for the airport traffic pattern circuit, eventual exit or entry points etc. For example, in Figure 1 the VAC from Eelde airport for runways 05/23 is presented. In general, these kind of charts identify one or more traffic patterns, entry or exit points and, eventually possible routes to follow.

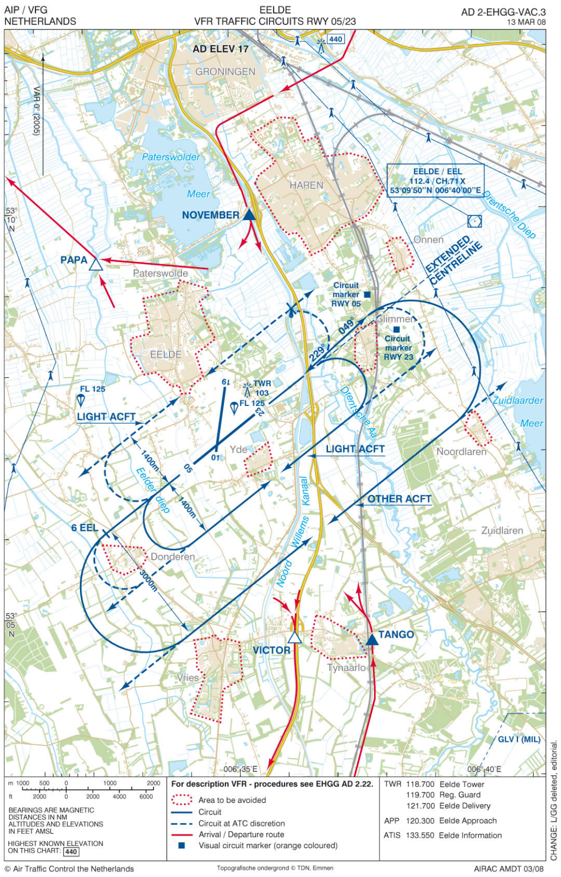


Figure 1. VAC chart from runways 05/23 from Eelde aiport (EHGG).

A completely different situation exists for VFR operations in non-controlled aerodromes. In these cases there may not exist any VFR specific procedure published and a default procedure is generally applied. It is the captain's duty to fly his/her aircraft within its maneuvering limits according to circumstances so as not to bother other aerodrome traffic or traffic in the vicinity.

The arrival phase is maybe the most challenging one. In this case, the pilot in command must evaluate the prevailing conditions of the aerodrome before joining the traffic pattern by overflying the intended landing runway in circles in order to see the physical status of the runway, possible other traffic operating nearby and the wind conditions if a wind-sock is operative (see Figure 2). This should be done at a height greater than the highest of the aerodrome circuits (usually 500 ft above) minimizing, in this way, possible conflicts with existing aircraft already in the traffic pattern [6].

After this evaluation, the aircraft starts an integration to the beginning of the downwind leg while attaining the published altitude for the traffic pattern. This joining maneuver is done maintaining the hold altitude until passing through the extended runway centerline so as to not bother possible departure traffic. It is at this point where the descent begins. As stated above, the target is to arrive at the begin of the downwind leg at the correct height, speed and heading.

Once the integration is finished, an standard traffic pattern is flown with downwind, base and final legs with the possibility to dynamically adjust them in function of the other traffic while assuring safe separations. As a general rule, aerodrome circuit dimensions are not strictly defined but the base leg and the end of the downwind leg take usually a minute of flight. On the other hand, if not specified otherwise, the downwind leg is flown at 1000ft AAL (Above Aerodrome Level) and a left hand turn is used. On the other hand, when going around (in a missed approach maneuver), the pilot in command should not make any maneuvers which could bother other circuit traffic.

It is possible to join directly the traffic pattern at the downwind leg, base leg or even final leg at aerodrome circuit height ensuring visual separation with aircraft already in the aerodrome traffic if the pilot in command estimates that this maneuver is safe and is not bothering other aircraft already in the circuit.

The captain does not have to examine the aerodrome on arrival if he is aware of the runway in use by listening to the messages transmitted on the auto information frequency by aircraft already in the aerodrome traffic and if he already knows the wind direction and velocity and what signals are displayed on the signaling area and taxiway. This standard procedure can be slightly changed for noise abatement reasons, obstacle clearance or air traffic management purposes. The changes might include avoid overflying certain noise sensitive areas, join the aerodrome circuit at further distances than in the default case and/or fly the aerodrome circuit at higher altitudes than the default case.

On a non controlled aerodrome an aircraft in the aerodrome traffic which is aware of an inbound IFR flight must, un-

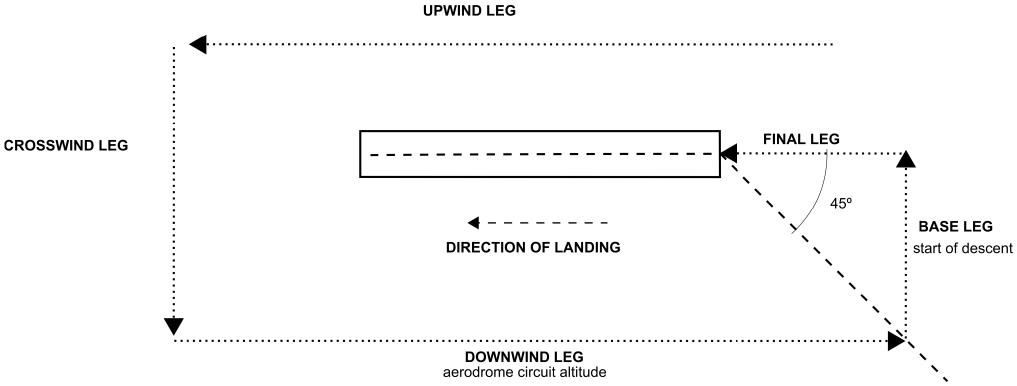


Figure 2. General VFR integration and approach to non-controlled aerodromes.

less previously agreed between captains, fly in such a way so as not to interfere with the approach and landing of the IFR flight. This disposition only applies if the IFR flight is making a final instrument approach for a direct landing on the runway in use or when the final approach is followed by a visual maneuvering with prescribed track.

In controlled airports any aircraft must be given clearance before going on to taxiing on the ramp, going on to the runway, taking off, joining aerodrome traffic and landing. It is possible that the air traffic controller can clear the pilot in command to fly directly to any segment of the landing pattern.

Finally, for take-off and depart operations the aircraft should arrive 500 ft above the runway and then turn direct to navigation. In the case when the destination point is just in the opposite direction, the usual maneuver is to join the traffic pattern, continue climbing and leave the circuit pattern at the end of the downwind leg.

3. UAS OPERATIONS IN ARRIVAL AND APPROACH PHASES

As has been previously remarked, UAS use is expected to grow, so their integration in different airports with different traffic is expected. The nominal use of UAS systems will be like IFR systems, they will not use external references in order to perform the navigation. However, their use in aerodromes without defined IFR procedures needs to be possible, especially if their use will probably start in small non-controlled airports instead of in busy ones. Four different scenarios for UAS arrivals and approaches have been identified in this work:

- controlled airports with IFR procedures published
- non-controlled airports with IFR procedures published
- controlled airports without IFR procedures published
- non-controlled airports without IFR procedures published

Airports with IFR procedures

In controlled airports where IFR procedures exist, different STARs are used and published in function of the aircraft category. Therefore, the UAS will follow the procedures that fits with its performances. The main advantage of this solution is that its behavior will be the same as manned traffic and thus transparent to the ATC (Air Traffic Control). With the future introduction of DataLink between the ATCO (Air Traffic Control Officer) and the aircraft [7], the UAS can easily become fully autonomous. In the actual concept of operations, with voice communications, the pilot in command will interact with the ATCO, that will not have to distinguish between manned and unmanned traffic, and transmits the orders to the UAS. The first problem that outcomes is that UAS with significant smaller performances than the A category will fly long and non-optimal procedures. In this case, some specific procedures for aircraft with less performances will have to be assessed. Another issue that must be taken into account is the delay in communication between the UAS and the pilot in command. Depending on the technology used and on the position of the ground station with respect the vehicle the delay can be greater than the acceptable one. In this case, the ground station that controls the UAS has to be close enough to the airport to deal with ATC clearances and orders in a response time equal to a manned aircraft.

In the case of an UAS operating in a non-controlled airport that has published instrumental procedures, the UAS will be able to develop the trajectory published like in the previous scenario. However, the coordination with other aircraft becomes an issue. If ADS (Automatic Dependent Surveillance) becomes available, the UAS will be able to have an autonomous system to detect and deal with other traffic. Otherwise, the authors propose a solution similar to the applied to IFR aircraft operating in non-controlled aerodromes at night, where an operator agent should be at the aerodrome. In the UAS case, this operator will be able to deal with the traffic and avoid any conflict. Moreover, IFR traffic, like the UAS one, will have priority over VFR traffic and thus conflicts will be minimized. If necessary a procedure like the one described in the case of airports with non IFR procedures can be used.

Airport without IFR procedures

Obviously the most challenging situation for a UAS is the operation in an airport where only VFR flights are permitted. As it was commented in section 2, VFR operations are only based with visual cues that can be seen from the cockpit by the pilot in command. For unmanned flight, one possible solution for VFR operations would be to install a set of cameras in the aircraft and transmit all the video signals to the ground control station, where the UAS pilot in command would *remotely fly* in visual conditions. However, this approach is not considered in this paper because in the great majority of UAS implementations this solution would not be feasible. Thus, another solution is proposed based in specific and predictible procedures for the UAS either for depart or arrival/approach operations. These procedures are thought aiming at minimizing the interference with surrounding traffic. Moreover, they may facilitate coordination with eventual ATC or, in the non controled case, with the rest of pilots operating in the same area.

Depart operations—It is clear that a manual take-off is always possible. In this case, the pilot in command will fly the UAS to an height or point where the navigation phase will start. However, the authors propose an automatic take-off phase to do this process easier, more predictable and safer.

The goal of the auto take-off phase is to fly from the runway to an End of Departure Way-Point (EDWP). The EDWP, are way-points that are close to the airport, in order to do not require a difficult navigation process but far enough to do not bother the possible traffic on the airport. At he EDWP the UAS will start the navigation phase commanded by the Flight Plan Manager System (FPMS).

The entry and exists points that are usually described on the VAC charts can not be used as EDWPs because they are too far from the aerodrome and a navigation is needed to reach them. That is the reason why the authors suggest that previously at the use of an airfield, the system will compute five different EDWPs for each runway. These diagrams are defined in function of the traffic patterns and built in base to it. Some operational facts need to be take into account in order to define the limits of position of the EDWPs. The authors proposal is to generate two standard traffic patterns (one clockwise and one counterclockwise) for each runway. And then apply eventual restrictions to them. The flight dispatcher will modify the pre-computed points if necessary. For instance, it could be possible that some computed EDWPs are not valid and need to be cancelled due to obstacles, restricted areas or preferred senses of operations, or that they need to be slightly moved. This work should be done once for each runway of each airport. After that a diagram like the one showed in Figure 3 will be created providing the FPMS enough departure way-points to cover all possible destinations.

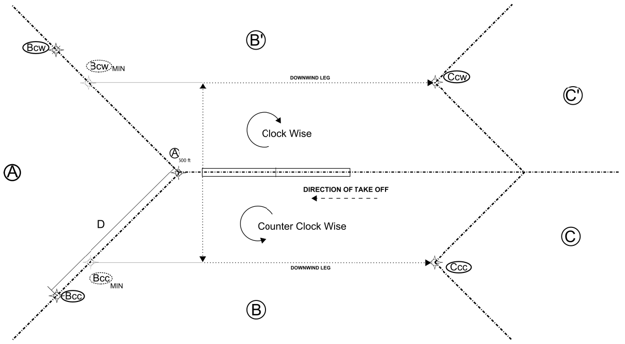


Figure 3. Reference points for departure.

In Figure 3 can be observed that five EDWPs exists (A, Bcw, Bcc, Ccw and Ccc) and that four areas are created (A, B, B', C and C'). In function of in which area is the first navigation waypoint one EDWP or another will be selected. For example, if the first navigation waypoint is located in the C' area, then the selected EDWP will be Ccw.

The way-point A is computed as the point where the UAS reaches 500 ft AGL. If this altitude is reached before the end of the runway then the WPA is translated to the runway threshold.

This EDWP should be selected if the flight plan starts in the area A, which is the area limited by $45°$ from the axe of the runway.

From the way-point A the UAS will be allowed to go directly to the way-points Bcw and to Bcc. This points should be placed at least at a distance of $1.5 * D_{minturn}$ from the WPA and the line defined by Bcw and WPA and by Bcc and WPA should have $45°$ with respect the axe of the runway. This distance is needed to ensure that the aircraft arrive to the point in a stable manner. If locating the points at $1.5 * D_{minturn}$ from the WPA they are within the traffic pattern then they must be located at least in the intersection between the downwind legs and the defined line of $45°$ (points Bcw_{min} and Bcc_{min} in the Figure 3).

Finally Ccw and Ccc are located at the intersection of the downwind and base legs of the traffic pattern. This points define the areas C and C' with lines that have $45°$ with respect the downwind legs. If these EDWPs are selected the UAS will fly the landing pattern following the appropriate downwind leg to them.

The limits of $45°$ have been selected in order to avoid excessive turns.

The UAS should gain altitude during the whole procedure of departure until arriving 1500 ft AAL, in addition they should maintain V_{app} until arrive to 250 ft over the traffic pattern level in order to bother as less as possible the other traffic.

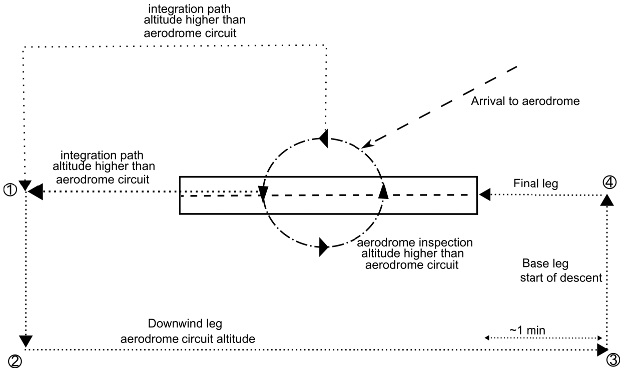


Figure 4. UAS approach and circuit pattern proposal.

It is possible that during the take-off phase something suggest than an abort and safe landing is needed. In this case, it should not be necessary to go to the navigation phase. If the abort phase is executed while the take-off is taking place, the UAS will join the traffic pattern and then change to the land mode.

The integration on the downwind leg can be extended in order to avoid the bother of other traffic and a emergency downwind at 500ft AGL should be possible to be commanded to the UAS if necessary.

Arrival and approach operations—If the UAS should operate in a controlled airport where non IFR procedures have been published, if the ATCO demands, it is possible to directly integrate the traffic pattern at any of its segments. However, the authors propose a procedure based on the VFR procedures in non-controlled airports, see Figure 4.

Taking into account all possible restrictions such as entry and exits points, altitudes, etc., the UAS will overfly the airfield at a height greater than the highest of the aerodrome circuits. By default, the hold will be done at a point over the aerodrome's vertical. At this point, the aircraft will be able to wait at a safety altitude before joining the aerodrome traffic pattern. Even if a go-around is done by any aircraft in the aerodrome, the UAS will be safe at the vertical of the field because all the aircraft will know its presence and because it is responsibility of the aircraft doing the go-around procedure to do not make any manoeuvre which could bother other traffic [6].

The pilot in command will be able to inspect the aerodrome and contact by radio with other possible traffic. With this information the pilot will have the capability to choose which is the sense of landing, the wind direction etc.

In order to have an omni directional arrival, it is proposed the use of a five waypoints holding pattern (four in a square and center one). Those points can be automatically computed by setting the coordinates of the center and the holding speed (see Figure 5). The idea is to have a circumference holding pattern where the pilot in command chooses the entry point, the sense of the hold (clockwise or counterclockwise) and the height.

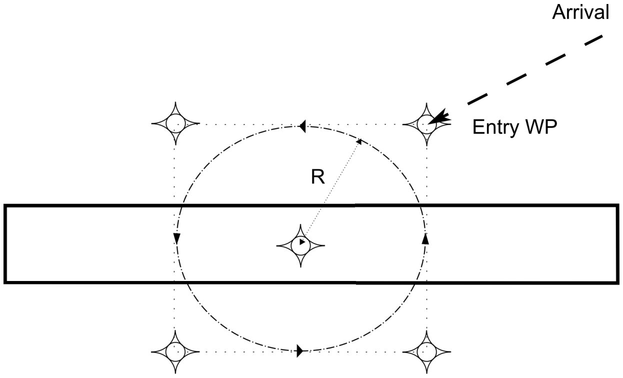


Figure 5. Holding pattern within a VFR procedure.

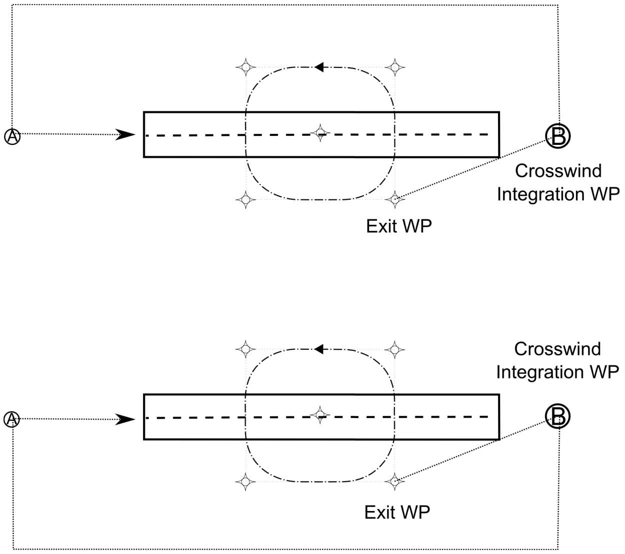


Figure 6. Selection of the of integration point.

Once in the holding, the pilot in command should select the circuit pattern or the ATC will command the integration in one defined sense. The pilot in command has to choose the Exit WP from the holding, the Integration WP and the Initial downwind WP (see Figure 6). Thanks to the 4D trajectories, the UAS will be able to performs the calculation of how much time is needed to make the upwind and crosswind length in order to do the integration in the landing circuit. This information is useful for the pilot in command to be able to deal with ATC clearances and restrictions. The pilot in command will know if the commands the UAS to do the integration how much time it will take (see Figure 7).

Once cleared by the ATCO to join the traffic, the UAS will do the procedure like any other VFR flight. It will fly the upwind and crosswind length and integrate the downwind leg at the height of the circuit. This integration maneuver is very important to assure that the UAS arrives to the downwind leg at the correct height, heading and speed. It is important to avoid integrations while descending. [8]

This integration maneuver ends at the beginning of the down-

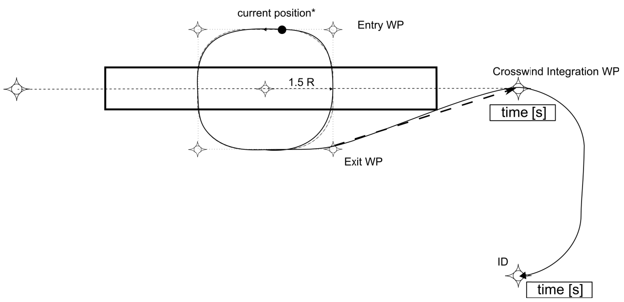


Figure 7. Integration times feedback to the PiC.

wind leg at the aerodrome circuit altitude. Therefore, it is preferred to link the holding pattern and the aerodrome circuit at the end of the upwind leg in order to assure a stable arrival of the UAS to the downwind leg. To avoid bothering departure traffic, the aircraft must not start descending until it arrives to the Integration WP (which is placed over the extended axes of the runway), see Figure 7.

When the UAS has join the traffic pattern at the beginning of the downwind leg the auto land phase should start.

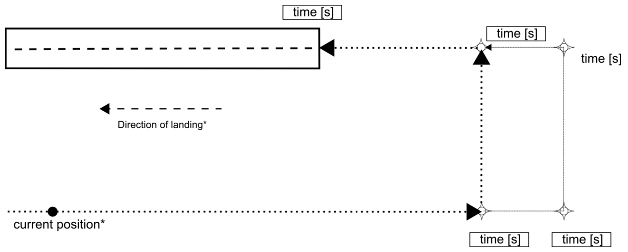
If there is a published VAC that specifies an preferred traffic pattern this should be used. Otherwise, the pilot in command will use the standard pattern in a left or right turn.

The downwind leg is parallel to the runway and one minute flight at V_{app} away from it. It finish where a line forming a $45°$ angle with respect the axe of the runway from the touching point intersects with the downwind leg.

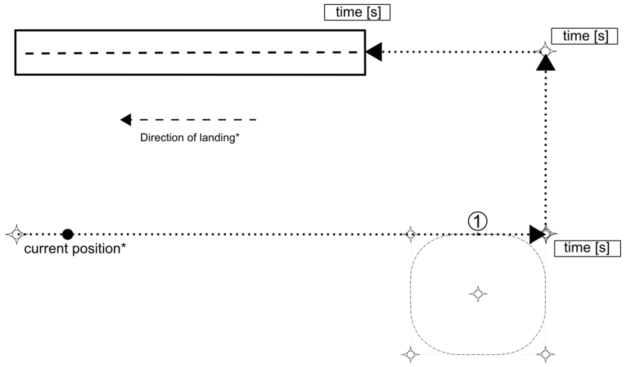
On demand, it will be able to make adjustments on the length of the downwind leg by the adjustment of the landing-decision length, in order to ensure the separation from other traffic. It is suggested to extend the landing-decision length in thirty seconds blocks, however, the pilot in command can abort the extension at any time and command the UAS to continuous with the base leg. It will be also possible to make a holding if necessary (see Figure 8).

After the downwind leg is finished, the UAS will fly the base leg has any other aircraft. Usually the base leg is perpendicular to the downwind leg and a descend starts.

Finally, the landing maneuver is formed by a single leg which angle of descent should automatically be computed by setting the last way-point of the base leg and the touchdown fix. The auto pilot should compute the difference between the Desired Touch-Down Fix (DTDF) and the real one (RTDF). If the deviation obtained is greater than a predefined threshold, the missing approach procedure should start by passing to the abort phase. It is clear that the same abort procedure should be used with respect any lateral deviation, speeds variations out of a valid range, or rates of descent out of valid margins.



(a)Extension of downwind leg



(b)Holding on downwind leg

Figure 8. Adjustments of downwind leg to adapt to traffic.

In case of an abort of the landing, the UAS should fly until re-joining the traffic pattern or until arriving to an EDWP of the runway. The pilot in command should have the capability of command an abort at any time during the approach or landing.

Following the criterion used in the downwind leg, in case of re-joining the traffic pattern, the pilot in command can command an extension of the missed approach leg if necessary to deal with other traffic in the circuit. On the other hand, if the pilot in command desires to go back to navigation, the UAS should fly to an EDWP of the runway (by default the A EDW should be used).

Finally, if the UAS should land on an airfield without air traffic control and without IFR procedures the last concept is also suggested to be used. First, an evaluation of the situation is done by doing a holding over the aerodrome in a stack philosophy. Once the pilot in command consider that it is possible to joint the traffic, it will demand the UAS to do so. The pilot in command can use predictions computed by the UAS of how much time the aircraft will take to do the integration, in order to take the decision of when is the best moment to starts the manoeuvre. Like in the previous case, the UAS is able to adjust the length of the downwind length or make a hold to ensure its separation form other traffic.

In all the cases, it could be possible to publish different circuits for UAS that have performances much more limited than general aviation aircraft, in IAC or in VAC charts, like nowadays is done for ULM or gliders. For the UAS it should not be a problem to do an left or a right hand circuit. This will not be incompatible with the main integration process described before but can help to segregate slow traffic when necessary.

4. USAL ARCHITECTURE OVERVIEW

The implementation of complex UAS operations cannot be achieved through existing autopilot technology. Most of the existing UAS autopilots only provide support for waypoint navigation and for some crude form of take-off and landing support. In order to alleviate this situation it has been introduced the The UAS System Abstraction Layer (USAL) as an architecture working around available autopilots, but extending their capabilities to cope with advanced flight-planning, contingency and elaborated HMI interfacing.

The USAL is the set of available services running on top of the UAS system architecture to give support to most types of remote sensing UAS missions [9]. USAL can be compared to an operating system. Computers have hardware devices used for input/output operations. Every device has its own particularities and the OS offers an abstraction layer to access such devices in a uniform way. Basically, it publishes an Application Program Interface (API) which provides end-users with efficient and secure access to all hardware elements. The USAL considers sensors and in general all payload as hardware devices of a computer. The USAL is a software abstraction layer that gives facilities to end-users programs to access the UAS payload. The USAL also provides many other useful features designed to simplify the complexity of developing the UAS application.

USAL Services types

Even though the USAL is composed of a large set of available services, not all of them have to be present in every UAS or in any mission. Only those services required for a given configuration/mission should be present and/or activated in the UAS. Available services have been classified in four categories according to the requirements that have been identified.

The principal element is the UAS autopilot. USAL considers the autopilot as a co-processor; it provides the system with a specific set of primitives that control the flight in the short term. The autopilot operation is supervised by a Flight Plan Manager that abstracts users from autopilot peculiarities and offers flight plan specifications beyond classical way point navigation, thus improving operational capabilities. Additional services help improving the security and reliability of the operation. The services in charge of the flying capabilities of the UAS are named *Flight Services*.

The next relevant system is the computing system that should orchestrate the overall mission. This system may be joined by specific to mission additional systems like image processing hardware accelerators, etc. Storage and communication management should also be included by default. This set of standard plus user-defined services that control the mission intelligence are named *Mission Services*.

Payload includes all those other systems carried on board the UAS. The list of UAS hardware elements is completed with devices with less intelligence but with input/output capabilities. We divide them in data acquisition systems (or input devices) and actuators (or output devices). Input devices can be flight sensors (GPS, IMU, Anemometers) and earth/atmosphere observation sensors (visual, infra-red and radiometric cameras, chemical and temperature sensors, radars, etc.) Output devices are few or even do not exist in UAS civil missions because of the weight limitations: flares, parachutes or loom shuttles are examples of UAS actuators. Services controlling these devices are named *Payload Services*.

Successful integration of UAS in non-segregated aerospace will require a number of features to be included in the UAS architecture. Interaction with cooperative aircrafts through transponders, TCAS or ADS systems; and detection of non-cooperative aircrafts through visual sensors, should be implemented and the UAS must inform the pilot in command or automatically react following the operational flight rules for UAS that are currently being developed [10]. However, for certain cases, e.g. flying in segregated airspace, such services may not be necessary. Services that manage the interaction of the UAS with the surrounding airspace users, controllers or conditions are named *Awareness Services*.

The proposed USAL architecture abstracts all these hardware components as services. Figure 9 offers a layered view of the responsibility carried out by each set of services with respect the overall capability increase objective. To summarize, the USAL services are divided in the same four types we divided the hardware elements: Flight Services, Mission Services, Awareness Services and Payload Services.

- Flight Services are those in charge of basic UAS flight operation. This includes the autopilot management, the basic flight monitoring for end-users and the flight contingency management.
- Mission Services are those in charge of developing the actual UAS mission, controlling the payload and the area of surveillance, processing or saving the earth observation information and showing it to the end users.
- Awareness Services are in charge of the safe operation of the UAS with respect terrain avoidance and integration with shared airspace.
- Payload Services are lower level services, not necessarily available to the end-users. They are like device-driver, this is, the facility services that abstract the details to access to the input, output and communication devices.

Flight Services

Many autopilot manufacturers are available in the commercial market for tactical UAS with a wide variety of selected sensors, sizes, control algorithms and operational capabilities. However, selecting the right autopilot to be integrated in a given UAS is a complex task because none of them is mutually compatible. Moving from one autopilot to another may imply redesigning from scratch all the remaining avionics in

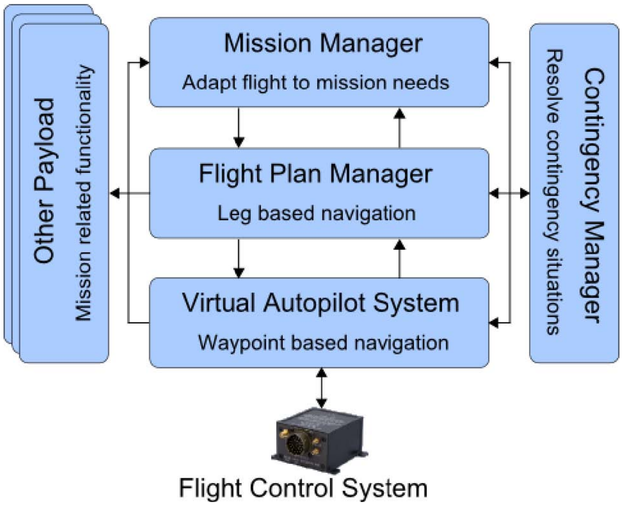


Figure 9. Layered view of the USAL architecture.

the UAS. Current commercial UAS autopilots also have two clearly identified drawbacks that limit their effective integration with the mission and payload control inside the UAS:

- The complexity of exploiting on-board the autopilot telemetry by other applications is complex and autopilot dependent. Autopilots telemetry is typically designed just to keep the UAS state and position under control and not to be used by third party applications.
- The flight plan definition available in most autopilots is just a collection of waypoints statically defined or hand-manipulated by the UAS operator. However, no possible interaction exists between the flight-plan and the actual mission and payload operated by the UAS.

Flight services are a set of USAL applications designed to properly link the selected UAS autopilot with the rest of the UAS avionics [11], namely the *Virtual Autopilot Service*, the *Flight Manager Service*, the *Contingency Service*, the *Flight Monitor Service*, etc. (see Figure 10):

- The *Virtual Autopilot Service* (VAS) is a system that on one side interacts with the selected autopilot and is adapted to its peculiarities. The VAS abstracts the implementation details from actual autopilot users. From the mission/payload subsystems point of view, the VAS is a service provider that offers a number of standardized information flows independent of the actual autopilot being used.
- The *Flight Plan Manager* (FPM) is a service designed to implement much richer flight-plan capabilities on top of the available autopilot capabilities. The FPM offers a virtually unlimited number of waypoints, waypoint grouping, structured flight-plan phases with built-in emergency alternatives, mission oriented legs with a high semantic level like repetitions, parameterized scans, etc. These legs can be modified by other services in the USAL by changing the configuration parameters without having to redesign the actual flight-plan; thus allowing the easy cooperation between the autopilot and the UAS mission.
- The *Contingency Management* services are a set of services designed to monitor critical parameters of the operation (like battery live, fuel, flight time, system status, etc.). In case contingencies are detected, actions will be taken in order to preserve the security and integrity of the UAS: from flight termination, mission abort or system re-cycle.
- The *Electrical and Engine Management* services are a set of services designed to gather data on the operation of the UAS electrical system and the propulsion system. Such information is relayed to the Contingency Manager to take the appropriate decisions.
- The *Flight Termination System* is a system outside the USAL architecture, and it is in charge to deploy a parachute system in case the Contingency Manager requires it; also the parachute may be deployed in case a major USAL failure.

5. FLIGHT PLAN CAPABILITIES WITHIN USAL

Current UAS autopilot systems rely on lists of waypoints as the mechanism for flight plan specification and execution. This is a very restrictive approach: it is difficult to specify complex trajectories, changes to the flight plan may imply having to deal with a considerable amount of waypoints, there is no support for conditional or iterative behavior and it does not facilitate reuse of flight plan fragments. In short, current autopilots specialize in low level flight control and navigation is limited to very basic go to waypoint commands. For these reasons a new flight plan specification mechanism has been proposed[12] that provides higher level constructs, with richer semantics, and which enables adaption to mission progress. The flight plan is represented by means of an XML document that contains the navigation instructions for the UAS. This document contains the main flight plan plus a number of alternatives for emergency situations. Each one of them is composed of stages, legs and waypoints hierarchically organized as seen in Figure 11.

Stages are the largest building blocks within a flight plan. They organize legs into different phases that will be performed in sequence. Legs specify the path that the plane must follow in order to reach a destination waypoint. Several primitives for leg specification are available. A waypoint is a geographical position defined in terms of latitude/longitude coordinates. A waypoint may also be accompanied by target altitude and speed indications. Optionally, a partial flight plan to be carried out if an emergency occurs can be associated to a flight plan. This emergency plan will be superseded by emergency plans specified at stage or leg level. A partial flight plan follows the same structure as the main flight plan but contains only those stages necessary to fly from the current position to the landing runway of choice.

Optionally, a partial flight plan to be carried out if an emergency occurs can be associated to a flight plan. This emergency plan will be superseded by emergency plans specified at stage or leg level. A partial flight plan follows the same

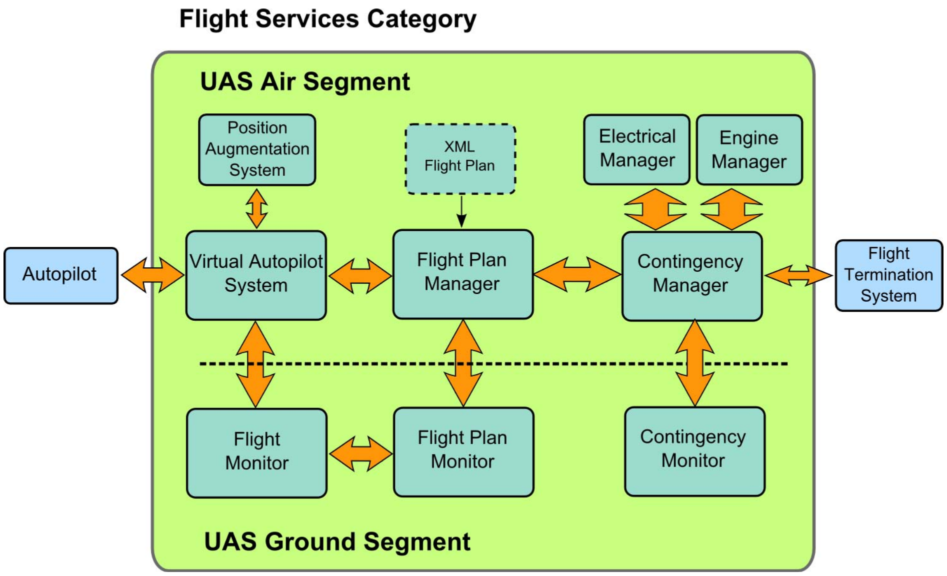


Figure 10. Overview of the Flight Services category

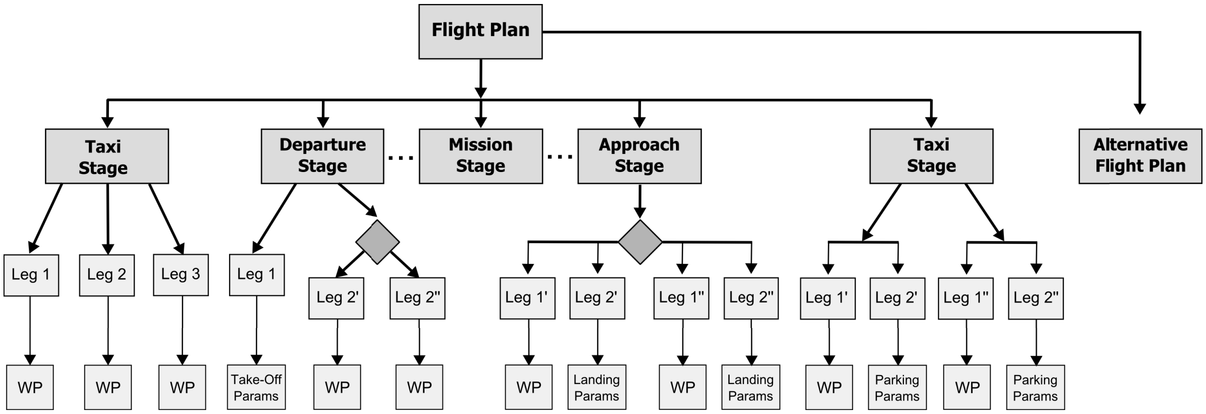


Figure 11. A flight plan is composed of stages, legs and waypoints

structure as the main flight plan but contains only those stages necessary to fly from the current position to the landing runway of choice [13], [14].

Stages

Stages constitute high-level building blocks for flight plan specification and are used to group together legs that seek a common purpose. They correspond to flight phases that will be sequentially executed:

- Taxi: Move to or return from runway.
- TakeOff: Description of take off operations.
- Departure: Legs flown after take off to reach the starting point of the next stage.
- EnRoute: Cruise to a destination area.
- Mission: Series of legs that will be flown during main mission operations.
- Arrival: Legs connecting the end of the route with the approach procedures.
- Approach: Prepare for landing.
- Land: Landing operation.

Every stage, except for the first and last stages, has a single predecessor and a single successor. A stage may have more than one final leg. For instance, a take off stage may end at different points depending on the selected take off direction. Also, a stage may have more than one initial leg as could be the case for departure procedures that start at different positions depending on the chosen take-off direction. There will be a one-to-one correspondence between the final legs of a given stage and the initial legs of the next one. Thus providing a seamless transition between stages. There are constructs that enable the flight plan designer to provide this one-to-one correspondence.

Legs and conditions

A leg specifies the flight path to get to a given waypoint. In general, legs contain a destination waypoint and a reference to their next. Most times legs will be flown in a single direction, but within iterative legs (see Section 5) reverse traversal is also supported. In this case a reference to the previous leg will be present too. Only intersection legs, which mark decision points, are allowed to specify more than one next and previous legs.

There are four different kinds of legs:

- Basic legs: Specify leg primitives such as 'Direct to a Fix', 'Track to a Fix', etc.
- Iterative legs: Allow for specifying repetitive sequences.
- Intersection legs: Provide a junction point for legs which end at the same waypoint, or a forking point where a decision on what leg to fly next can be made.
- Parametric legs: Specify legs whose trajectory can be computed given the parameters of a generating algorithm, e.g. a scanning pattern.

Intersection legs differ from the rest in that they may be reached from more than one predecessor and may lead to more than one successor. All legs have an optional parameter indicating what emergency flight plan is to be carried out when an emergency occurs.

Basic Legs—This section describes the basic legs available to the flight plan designer. They are referred to as basic legs to differentiate them from control structures like iterative or intersection legs and parametric legs. All of them are based on already existing ones in RNAV. Its original name is preserved.

- Initial Fix: Determines an initial point. It is used in conjunction with another leg type (e.g. TF) to define a desired track.
- Track to a Fix: Corresponds to a straight trajectory from waypoint to waypoint. The initial position is the destination waypoint of the previous leg.
- Direct to a Fix: Is a path described by an aircraft's track from an initial area direct to the next waypoint, i.e. fly directly to the destination waypoint whatever the current position is.
- Radius to a Fix: Is defined as a constant radius circular path around a defined turn center that terminates at a waypoint. It is characterized by its turn center and turn direction.
- Holding Pattern: Specifies a holding pattern path. There are three kinds of holding patterns which differ in how they are terminated. Hold to an Altitude terminates when a given altitude is reached. A Hold to a Fix is used to define a holding pattern path, which terminates at the first crossing of the hold waypoint after the entry procedure has been performed. The final possible type is the Hold to a Condition. In this case the holding pattern will be terminated after a given number of iterations or when a given condition is no longer satisfied (regardless of the number of iterations).

Iterative Legs—A complex trajectory may involve iteration, thus the inclusion of iterative legs. An iterative leg has a single entry (i.e. its body can be entered from a single leg), a single exit and includes a list with the legs that form its body. Every time the final leg is executed an iteration counter will be incremented. When a given count is reached or an specified condition no longer holds the leg will be abandoned proceeding to the next one.

Figure 12 shows the two different possibilities for iterative leg specification. Figure 12a displays the case when holds to a fix are used to reverse the aircraft course and cycle back and forth. After entering the iterative leg, the legs forming its body are executed. Then a hold to a fix is found which reverses the aircraft direction. Now the body legs can be executed again, but in reverse direction, until another hold to a fix is found. In the holding patterns, the solid line represents the path followed by the aircraft in order to perform the turning maneuver. This back and forth behavior is only allowed when it is possible to obtain the inverse of all legs involved. Figure 12b shows a simpler case when the legs of the body are executed one after another in a single direction.

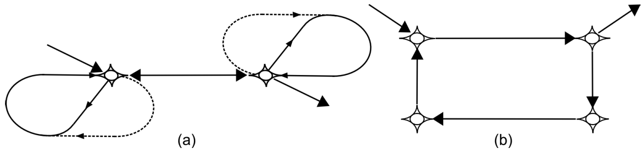


Figure 12. Iterative leg types.

Intersection Legs— Intersection legs are used in situations where there is more than one possible path to follow and a decision needs to be made (see Figure 13). This leg type contains a list with the different alternatives and a condition for picking one of them. Intersection legs are also used to explicitly indicate where two or more different paths meet.

Together with parametric and iterative legs, intersection legs provide a powerful means for adapting the flight as best suited to the ongoing mission circumstances.

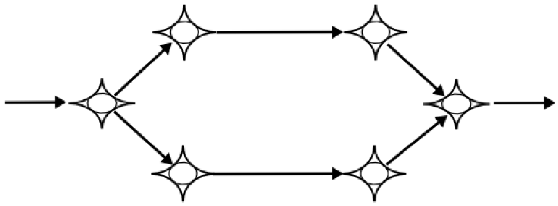


Figure 13. Intersection legs.

Parametric Legs—With parametric legs complex trajectories can be automatically generated from a reduced number of input parameters. If the actual values of these parameters change, the resulting trajectory will be dynamically recomputed. In this way, the aircraft trajectory can be modified depending on the evolution of mission variables. Eventually a complete enough library of different parametric legs will be available so that a wide range of missions can be performed. With the use of parametric legs two goals are achieved. First, complex trajectories can be generated with no need to specify a possibly quite long list of legs. Second, the UAV path can dynamically adapt to the mission requirements.

Conditions and alternatives

There are several points in the flight plan where conditions can be found: namely in holding patterns, iterative legs and intersection legs. For intersection legs, they are necessary in order to determine what path to follow next. For the rest of legs they will let the FPM know when to leave the current leg and proceed to the next one.

Conditions are not directly specified in the flight plan. Instead, each leg that depends on a condition contains an identifier, which is used to refer to the condition, and sometimes also a default value. Conditions are processed separately and when a condition is given a result, i.e. an integer value telling which is the selected path, the FPM dynamically recomputes affected waypoints.

Analysis of the potential contingency situations and planning the correct reaction is a critical task to be carried out by any airplane to guarantee its safe operation. Pilot's reactions to any kind of incidences that may occur in-flight, like engine malfunctions, loss of electrical power, hydraulic failure, unexpected weather, etc; are critical and will determine the fate of the flight in case such contingency occurs.

Both the main flight plan and its emergency alternatives are hierarchically structured in the same XML. Alternative plans can be specified at the root level, for a given stage or for a given leg. If an emergency occurs when executing a given leg, and this leg has an alternative plan associated to it, the alternative plan will be executed. If the leg has no such alternative plan, the FPM will check its parent stage. If no alternative plan is found there either, then it will take the alternative plan associated to the flight plan root node.

Flight Plan Manager Waypoint Generation

The Flight Plan Manager (FPM) is the service responsible for the execution of flight plans. In our system a flight plan consists in an XML document that contains the navigation instructions for the aircraft. Each stage contains a structured collection of legs. The leg is used to describe the path to follow for reaching a given destination waypoint. The leg concept is extended to accommodate higher level constructs for specifying iterations and forks. Additional mission oriented legs are included to automatically generate complex patterns from a small number of input parameters, e.g. for performing scans over an area or point of interest. Emergency alternatives can also be specified both at the stage and leg level.

The FPM translates legs into a sequence of waypoints to be processed by the VAS. Once the flight plan has been loaded into the FPM, an internal representation is generated and the service is ready to start waypoint generation. The flight plan is represented by a tree whose root node corresponds to the whole flight plan (see Figure 14). Stages are located at the next level of the tree, legs follow. At this point some degree of recursion can be found due to iterative legs, whose children legs form the body of the iterative structure. Finally most legs contain a destination waypoint. When the start command is received a traversal of the tree begins. The execution engine goes through each one of the flight plan stages, processing the legs they contain and generating waypoints as appropriate. Legs that represent curved paths are approximated by sequences of waypoints.

A critical feature of the FPM is its ability to process updates to the flight plan and recompute waypoints as needed. Thus providing a high level of adaption to the mission circumstances. There are two kinds of flight plan updates: first, setting the result value for a condition used in the flight plan. In this manner we can select what path to follow at a given decision point. The other kind of update consists in the modification of the parameters of one or more legs. As depicted in Figure 14), flight plan updates are incorporated by modifying portions of the tree that describes the leg structure.

6. PIC ROLE IN THE USAL ARCHITECTURE

Within the USAL architecture all the Human-Machine-Interfaces (HMI) have been divided in three coordinated interfaces. Two of them will manage the flight aspects of the operation, while the third manages the mission/payload aspects. In this work we will focus only on the flight interfaces.

Having two separate interfaces to manage the UAS flight may seem as an overkill. However, as we will try to justify, the capacities of the flight plan management introduced by the USAL prevent an immediate mix between the classical Pilot in Command (PiC) station and the necessary interfaces required to properly exploit the flight plan capacities.

Autopilot versus Flight Plan Capabilities

As it can be seen in Figure 9, the USAL architecture is layered with three levels of competence, each one working on top of the capabilities of the previous.

The USAL architecture assumes that the actual flight is carried out by a commercial autopilot that it is interfaced to the overall system through the VAS. The VAS offers to the overall USAL services the already built-in autopilot capabilities, but also implements, if necessary, other managing capabilities in order to always work with a common and generic interface. Higher level flight plan capabilities are implemented by the FPM. Both the VAS and the FPM operate on board the UAS, while the HMI interfaces work at the ground control station. Figure 15 clearly describes the separation in flight responsibilities between the two main flight HMI interfaces: the Flight Monitor (FMo) and the Flight Plan Monitor (FPMo).

Generally speaking, current UAS autopilots offer manual and/or assisted piloting capabilities plus basic waypoint navigation capabilities. The first decision in the design of the

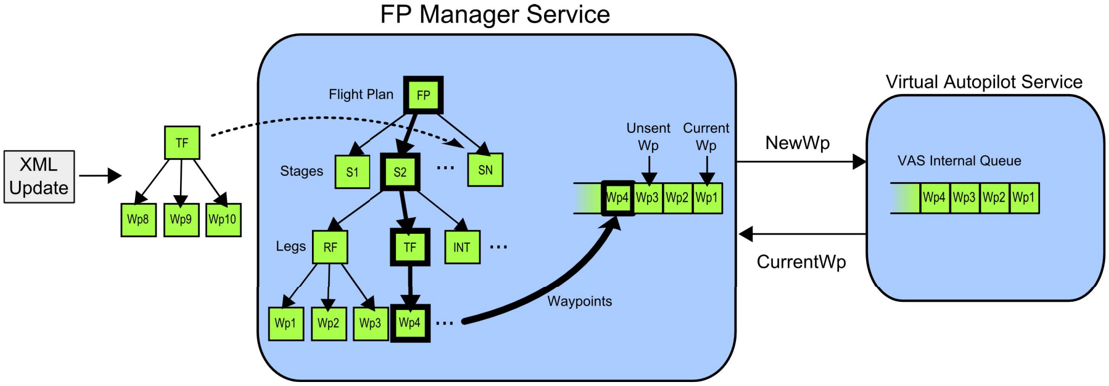


Figure 14. FPM waypoint generation. Internally the flight plan is represented as a tree, which is traversed in order to compute trajectory waypoints. These waypoints are stored in a queue and forwarded to the VAS.

USAL HMI interfaces is to maintain such manual piloting capabilities and a minimum waypoint navigation capabilities, although standardized through the VAS, in the FMo service. The FMo service retains the following capabilities, in some sense, related to those operations that a pilot may eventually develop manually:

- Manual piloting support.
- Flight monitoring, aerodynamics, engine, fuel, electrical system.
- Basic flight contingencies.
- Basic navigation support including waypoint, directed and hold modes.
- Taxi, take-off and landing support.
- Pilot's view video stream.

When a UAS using the USAL architecture develops a complex mission, the flight plan itself will contain all the required information required to identify landing and takeoff parameters, etc. At each stage of the flight, the FPM will notify the VAS and the FMo which should be the actual usage of those parameters. This scheme opens the door to implement complex operational schemes in which the FPMo supports the selection process of the most convenient parameters, to be later on sent to the VAS/FMo for their implementation.

7. FLIGHT MONITOR HMI INTERFACE

There is too much flight and mission information to be shown at once, so the solution is to divide the application in two different screens. The Flight Monitor (FMo) is composed by the Pilot Screen (PS) and the Multi Function Screen (MFS). The most relevant flight information is shown in the PS and all the available information is selectively monitored in the MFS.

The reason for dividing the FM visualization in two areas is to display all the information in a clearly and easy way. It is not possible to show all the necessary information in one single screen; this screen will be overcrowded with information and become incomprehensible.

In the PS there is the necessary information for the pilot to control the UAS, additionally the user can consult the MFS in order to obtain more detailed information and complement the summaries in the PS. The MFS is not dispensable because some operations must be done in this screen.

During the design and implementation phases of both screens it has to be taking into account that they have different purposes and uses. The PS is only a visualization screen, without interaction with the user; there could not be any button or textbox. All the parts in the PS must have the same design and appearance, without any part that could distract the user. The MFS is completely different, in this screen the user interacts with it by touch, so the controls or buttons must have a size according to it. Against the PS, that it has a static distribution, the MFS would has many different views, each one for a different purpose.

Next it is going to be explained more detailed the architecture of both screens.

Pilot Screen Distribution

The PS has a static distribution, without buttons or interaction with the user. The parameters are automatically configured and some of them can be changed from the MFS.

During this developing phase we have consulted the opinion of different expert private aircraft pilots. Given their experience in piloting airplanes, they have indicated which are the necessary and most important information to be displayed at any time. They indicated that is completely essential to have a Primary Flight Display (PFD) that shows the telemetry, a video in real-time and also a summary of the main flight plan information.

Thus, the main function of this screen is to show information summaries of all the systems in the UAS. The pilot needs the most important information to pilot the UAS. The distribution includes the three components listed below by the experimented pilots and some additional components that complement the PS. Figure 16 displays the design and distribution of

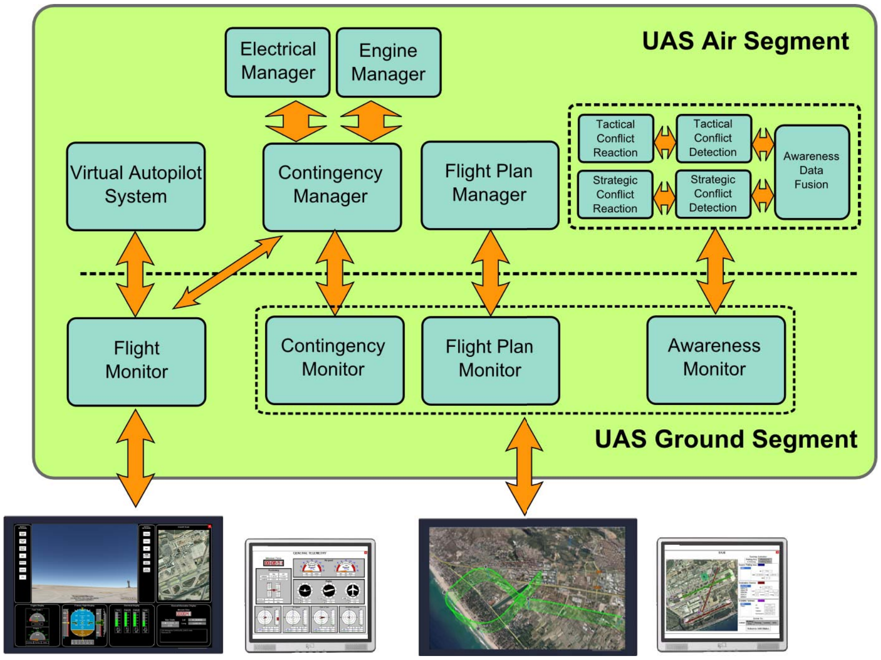


Figure 15. USAL Flight Oriented HMI Interfaces.

the different components in the PS. Each one of these components are going to be described below.

The center of the screen is used to monitor the real video streaming from any of the cameras on board. Thanks to that, the pilot can see the same view as he was in the UAS cockpit.

In each side of the video area, there is a column with different alarms of the system. The alarms could be turned off, or turned on in different colors depending of the importance or they could be flicking.

The right column in the screen is dedicated to monitor the geo-positioning of the UAS. The whole box is a map and over it the UAS is positioned. The different cartographies showed in the map can be chosen from one of the configuration screens in the MFS. Also in the map, it can be displayed the different waypoint and route of the flight plan, in order to see which flight plan is following the UAS.

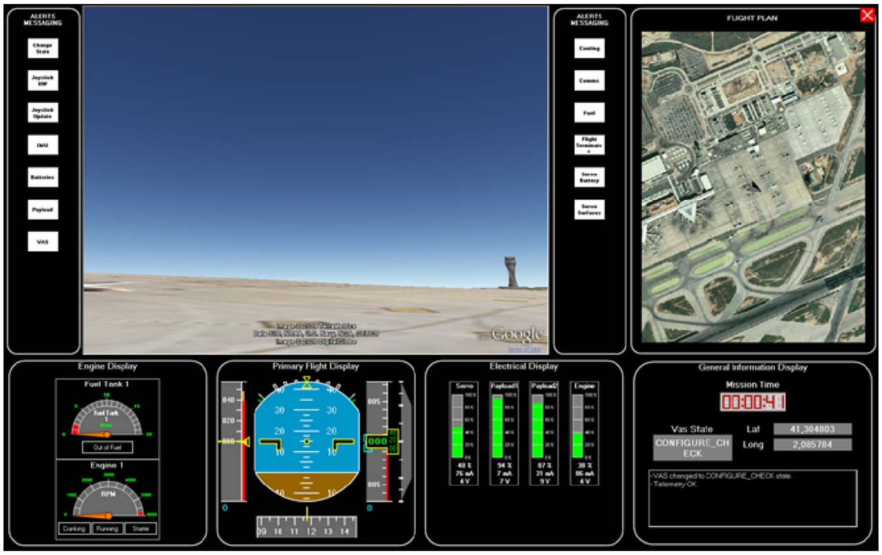
The bottom of the screen is used to locate information summaries, four different ones are used: the Engine Display, the Primary Flight Display (PFD), the Electrical Display and the General Information Display. These boxes shown similar information as the Electrical Centralized Aircraft Monitor (ECAM) in the Airbus systems.

- The Engine Information summary would just show the fuel levels in the different tanks and the Revolution Per Minute (RPM) of the different engines. The rest of the information generated from the engine is shown in a dedicated screen in the MFS.
- The PFD displays the telemetry of the UAS, the indicators in this display are the typical used in all the aircraft systems. There are the artificial horizon, the altitude indicator, the compass indicator, the mach/air speed indicator and the vertical speed indicator.
- The Electrical Information summary monitors the state of the different batteries in the UAS and the state of the alternator. The rest of the electrical information, as the consumption of the payload, is shown in a dedicated screen in the MFS.
- The forth box of the row is the General Information. This box shows the time mission, the geo-positioning of the UAS, the current VAS state and there is a console that writes different text messages. enditemize

Multifunction Screen Distribution

The function of the MFS is to display all the available information in the system. Each kind of information has a specific view in. The MFS has many different views, each one for a different purpose or use. The different views of the MFS are distributed in four groups depending of the purpose: Navigation, Autopilot, Status and Configuration. Figure 17 shows a diagram of this classification. This classification will allow the user to access easily to all the available views. The Navigation group has views dedicated for the navigation states during the mission. The Autopilot group has views for configuring and interacting with the VAS. The Status group has four views, each one for a different kind of information: General displays the telemetry, Engine, Electrical and the Contingency view with the alarms of the system. The Configuration group allows the user to configure the FM.

As it can be see in Figure 15, all information used within the operational options identified in Figure 17 is directly taken from VAS or from some of the contingency services shared



-VAS changed to CONFIGURE_CHECK state.
-Telemetry OK.

Figure 16. Main Flight Monitor Display.

between the FMo and the FPMo. Some additional information, like the parameters used during taxi, landing, etc, will be directly sent from the FPMa to all other involved services, including the FMo, at the appropriate time of usage.

In order to change between the different views, in the bottom of the screen there is a menu. The menu is divided in two parts. The first one would show the main menu, that it is the first level of the diagram in the Figure 17. This main menu has a button for each group and they are static, they are always visible. The secondary part of the menu is the submenu, it shows the second level of the diagram in the Figure 17. When a group is selected in the main menu, the appearance of the submenu changes and shows the available views in this group.

In the main menu there would be two extra fast-access buttons. The aim of the first button is the fast-access to the most interesting view for the current flight phase, for example during the land phase this button would show the Land view. The aim of the second button is to advice the user if any of the different views has an alarm or needs the pilot interaction and the fast-access to this view.

Specific MFS Interfaces

Figure 18 depicts some of the specific interfaces implemented in the MFS. Among others the VAS Interface, General Telemetry Interface, Electrical Information Interface, and Taxi View Interface are briefly described in this section.

VAS Interface—The VAS Operational States view shows over a schema all the states of the VAS. The current state is showed in green. The user can change the VAS state by clicking one of the available transitions in yellow. When the system is initialized, the VAS state is Stop.

Some of the states require a user interaction to activate some of the transitions. For example to activate the transition between the Parking Check state and the Taxi states the Parking Check list must be validated. For these interactions, there is a dedicated area in the top-right side, there are fast-access buttons to the dedicated states views.

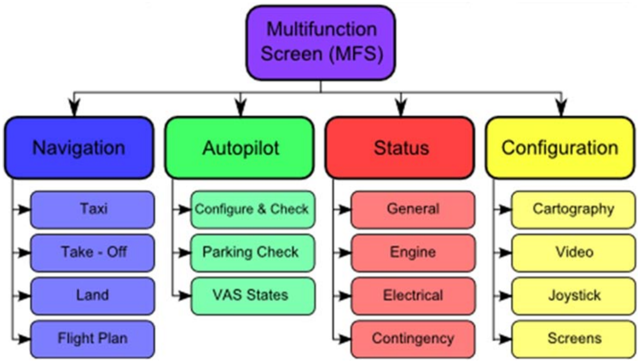


Figure 17. Menu options considered in the MFS display.

Also in this view has been located the navigation parameters. The user can change the navigation parameters by the keyboard and sending the new parameters. These parameters are used during the Directed state in the Navigation states.

General Telemetry Interface—The General Telemetry view in the Status group shows the same information that displays the Primary Flight Display in the PS plus some additional information. However, the distribution of the information is different as in the PFD; the PFD shows a lot of information in a very small place. There each data has in own indicator, depending the data type has its different format indicator. Each indicator displays the information in a visual way and in text format. Also they display it in different units.

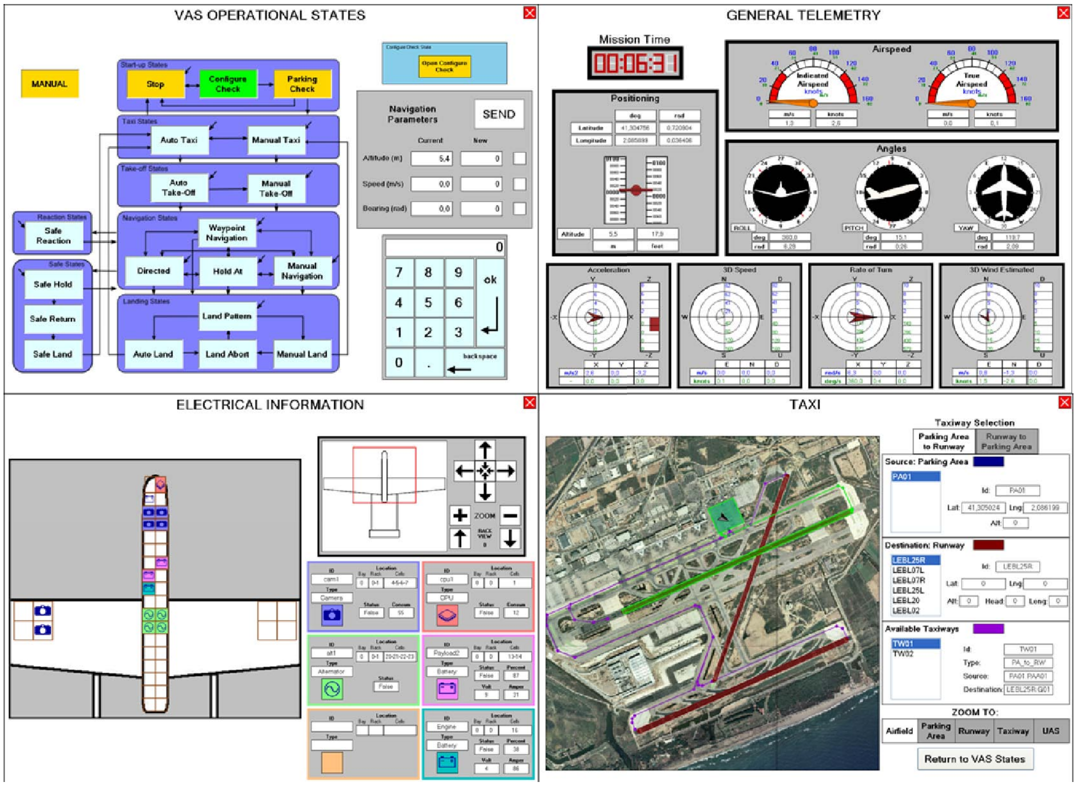


Figure 18. Some of the auxiliary Flight Monitor displays.

The mission time is displayed in the top left with a seconds precision. Below that there is the positioning indicator. It shows the latitude and longitude values in text format and also the altitude value. The altitude has also a visual indicator.

The airspeed area in the top right side has two gauge indicators. One for the indicated airspeed and another for the true airspeed. The gauge is able to display the information in two units and the warning areas. Below there is the angles information area. The angles displayed are the roll, pitch and yaw angles. Each one has an indicator with its different UAS outline.

The down side of the view is dedicated to the three dimension indicators. The acceleration, 3D speed, rate of turn and 3D wind estimated are values with three components. This kind of indicator is able to show this kind of information; it has a two dimension circumference and a bar for the third dimension. This indicator also displays the values in two units.

Electrical Information Interface—The main area of the Electrical Information view is a schema of the UAS. This schema can be changed from the navigation buttons in the top right side. In the right down side, there are six components indicators. Each indicator displays the own values of a specific component. The first time the electrical view is loaded, no electrical components are selected to show its information. The user can select the electrical components to display up to a maximum of six.

The process of selecting a component to display takes two movements. The first movement is selecting the box where he wants to display the component; the box border will be highlighted. Then the user has to select the component from the aircraft schema. After that, the component will appear painted with the box color and its information showed in the box.

Taxi View Interface—When the parking check is correct, the UAS may proceed from the parking area to the header runway. This transition is done in the VAS Taxi states: Manual Taxi and Auto Taxi. The Taxi View Interface is a map monitor for the different taxiways of the airfield. It is also used after the landing states, to return from the runway to the parking area to finish the flight mission.

The pilot in command can select, on the right side of the view, if the taxiway is from a parking area to a header runway or from a header runway to a parking area. Depending the option, the source and destination panels display the available parking areas or the runways.

When the source and destination are selected, the third panel offers to the pilot in command the available taxiways. All the available parking areas, runways and taxiways are shown in the map, and the selected ones are shown in green color.

The user can also select the map zoom. There are five options: airfield, parking area, runway, taxiway and UAS. When the option is changed, the map adapts the zoom value and the center position to the specific object.

8. FLIGHT PLAN MONITORING DESIGN

The Flight Plan Monitor (FPMo) is the main interface system that should help the PiC to exploit all the automation and dynamic reconfiguration that the USAL architecture and the Flight Plan Manager can offer. The following sections describes the capabilities requested to this interface and the way we intend to implement them.

FPMo Requirements

Figure 15 describes which services on board the UAS are connected to the Flight Plan Monitor (FPMo). The capabilities required to the FPMo are related to inherent dynamic behaviors offered by the FPM and the surrounding services that help managing in flight contingencies, take-off and landing operations, etc.

Similarly to the the FMo interface, the FPMo interface is divided into two separated screens that work in coordination: a primary (PS) and a secondary screen (SS). The PS is an static screen mainly designed to display the flight plan an additional annotations in graphical way. The SS is a dynamic screen designed to interact with the PiC through a number of specific interfaces according to the different operational modes. Each one of these screens has a number of functional requirements that are briefly summarized in Figure 19.

The PS should be able to manage four different representation views, all of them specific implementation of a common flight-plan representation scheme. The representation views include (see Figure 19):

- Main flight plan tracking mode.
- Specific departure tracking mode.
- Specific approach tracking mode.
- Flight plan validation mode.

The SS manages a much wider set of representation views, each one of them tied to a specific PS representation. each one of the SS screens is designed to manage PiC interaction through a touch screen for simplicity of operation. The available views include (see Figure 19):

- FMo and FPMo interaction.
- Flight plan tracking.
- Flight plan modification.
- Flight plan validation.
- Departure operations.
- Approach operations.
- Alternative selection.
- FPMo configuration.

FPMo Primary HMI Interface

Flight plan tracking mode—In this mode, the PS will show a representation of the flight plan currently being operated by the selected UAS. The flight-plan will display representations of the main waypoints and legs being flown, actual position of the vehicle and expected flight time for each main waypoint. In case that other fragments of the flight plan are relevant in the selected area of display (e.g. alternative routes or non-selected intersections), they will be also displayed in a shaded view to indicate that they are present but not currently selected.

Figure 20 depicts a highly schematic view of the flight plan tracking mode. The screen describes the actual UAS track as well as the active legs in the flight plan. On the right side, different indicators describe which is the UAS vehicle being actually under control (multiple vehicles can be depicted simultaneously, but only one can be controlled at the same time), the background layers depicted (cartography, locations, and other relevant layers), and some highly relevant flying information.

Departure tracking mode—Even though take-off operations are not direct responsibility of the FPMo interface, but reserved to the FMo interface, some additional support will be offered by the FPMo during this critical phase of the UAS operation.

Within the departure tracking mode, a general view of the airfield will be displayed, including its defined taxi areas (see Figure 25). The vehicle will be tracked during the overall taxi and take-off operation (controlled through the FMo interface), but the FPMo will become responsible for the rest of the departure operation as soon as the UAS reaches a safe altitude/speed on the outermost leg of the take-off procedure [15]. After this point, the FPM executes the high level fragment of the departure stage and its monitoring should be tracked through the FPMo interface. The areas being visualized will be progressively enlarged and moved to cover the relevant legs at each step of the operation.

The proposed flight plan structure is designed to be able to cope with all potential taxi/take-off alternatives than the pilot expects to require (they need to be prepared a priori during the flight dispatching phase). Decision fixes will be highlighted, with the actual tracks selected being highlighted. From the FPMo interface decisions can be dynamically modified and updated to the FMo interface for implementation.

Approach tracking mode—Similarly to departures, landing operations are not direct responsibility of the FPMo interface, but reserved to the FMo interface (see Figure 26). As for take-off, some additional support will be offered by the FPMo during this phase of the UAS operation.

Within the approach tracking mode, a general view of the legs to be flown, including a schematic view of the airfield will be

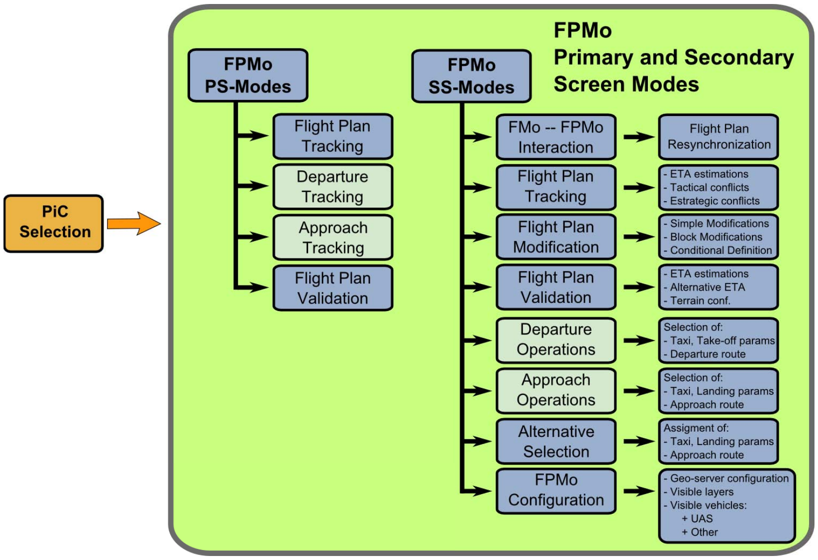


Figure 19. Design requirements for the FPMo HMI interface.

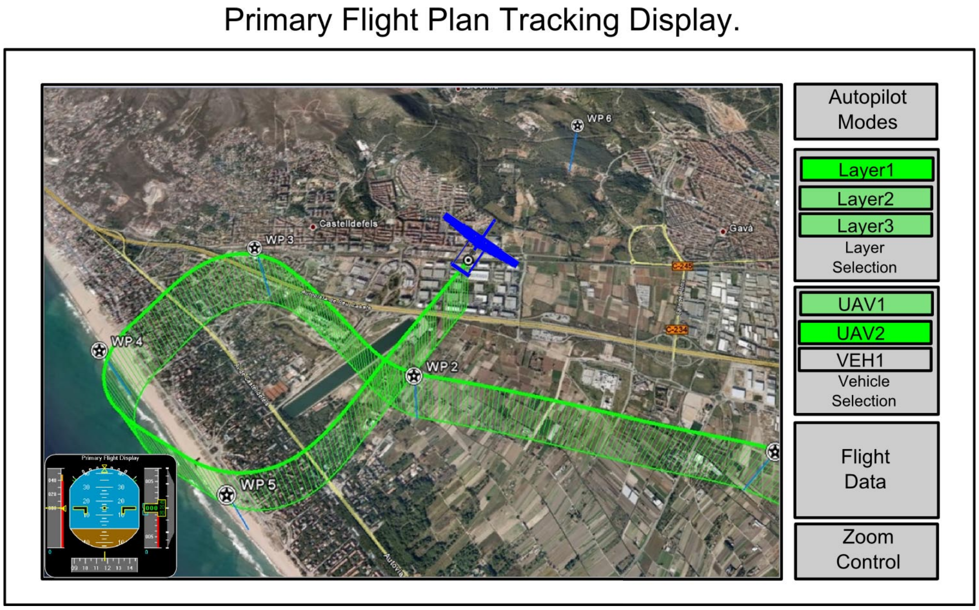


Figure 20. Structure of the Main Flight Plan Tracking Display.

displayed. The UAS will be tracked and controlled through the FPMo interface during the high level parts of the approach operation. Once the UAS reaches the external circuits of the selected runway, the control will be transferred to the FMo interface [15]. During this final phase of the landing operation, the FPMo interface will show general view of the airfield, including its defined taxi areas. The vehicle will be tracked during the overall landing and taxi operation up to the parking and shutdown point.

Flight plan validation mode—The flight plan validation mode is almost equivalent to the flight plan tracking mode, with the exception that additional information related to validation parameters will be overlapped onto the same view. Under this mode the flight plan is validated in terms of vehicle endurance, potential conflicts with the terrain, potential losses of communication due to the orography, airspace conflicts, etc.

FPMo Secondary HMI Interface

The secondary HMI Interface SS manages a wide set of representation views, each one specific to a number of divergent requirements. For this reason the screen design is left quite open (see Figure 21), just maintaining a number of button interfaces for submode selection on the right side of the screen to better exploit the dimensions of currently available panoramic-style screens.

FMo and FPMo interaction—Visualization in the SS of the status of the FMo and FPMo coordination. From this SS mode it can be managed the transfer of monitoring responsibility from the basic VAS mode to the more sophisticated FPM mode. This SS mode is compatible with any visualization mode in the PS.

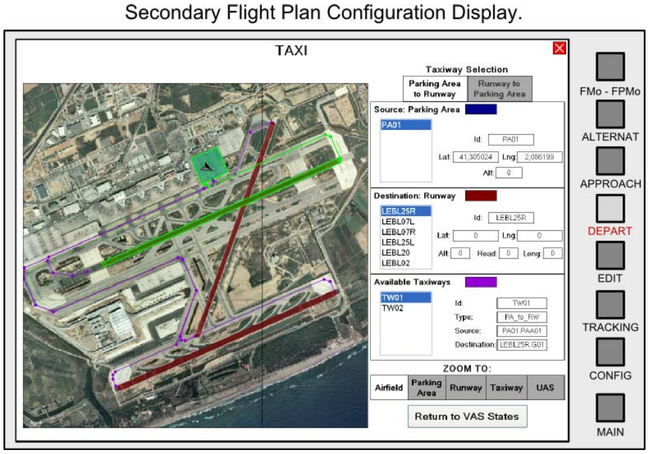
Flight plan tracking—Visualization of the active legs of the flight plan, potentially being selected for further edition if necessary. This mode is linked to the Flight plan tracking mode in the PS. From the SS it can be activated the visualization of estimated arrival time information, potential conflicts with the terrain and communication coverage. Also, if information is available, the visualization of potential conflicts with other vehicles can be activated from this SS mode.

Flight plan modification—From the flight plan tracking view it can be selected the flight plan modification view in the SS. This mode contains four different sub-modes that allow different levels of flight-plan edition: modify properties of a single leg and upload them; modify a condition in the flight plan, so that a different set of legs may be actively operated; modify properties of a set of legs and upload them as a single change; invoke an external flight-plan editor to develop more complex flight plan modifications (see Figure 22). Within the SS, a tree view of the flight plan will be employed so that different branches of the flight plan can be easily explored. Note that different colors/intensity will be used to indicate those portions of the flight plan that will be actively flown due to the current state of the conditionals.

Flight plan validation—From the flight plan validation secondary screen, a number of test can be executed to validate the the actual flight plan. This view is linked with the primary screen Flight plan validation mode. From this mode the typical checks on terrain conflicts and communication coverage conflicts can be performed, but additional elements for validation are also covered. Flight time availability and pre-planned contingency reactions can be inspected from this mode.

Flight time availability becomes a relative parameter given the inherent dynamic behavior of the flight plans operated within the USAL architecture. Flight time will depend on which branches of an intersection are selected and on the number of iterations will be flown of an iterative flight plan fragment. These elements can be inspected in this mode, before the flight (at dispatching time) or during the flight taking into account deviations due to wind, etc.

Departure and approach operations—In controlled airports where IFR procedures exist, different STARs are used and published in function of the aircraft category. Therefore, the UAS will follow the procedures that fits with its performances. The main advantage of this solution is that its behavior will be the same as manned traffic and thus transparent to the ATC (Air Traffic Control). With the future introduction of DataLink between the ATCO (Air Traffic Control Officer) and the aircraft, the UAS can easily become fully autonomous.



PA01
Id: PA01
Lat: 41,305024 Lng: 2,086199
Alt: 0

LEBL25R
LEBL07L
LEBL07R
LEBL25L
LEBL20
LEBL02
Id: LEBL25R
Lat: 0 Lng: 0
Alt: 0 Head: 0 Leng: 0

TW01
TW02
Id: TW01
Type: PA_to_RW
Source: PA01.PAA01
Destination: LEBL25R.G01

Figure 21. Structure of the Secondary Flight Plan Configuration Display.

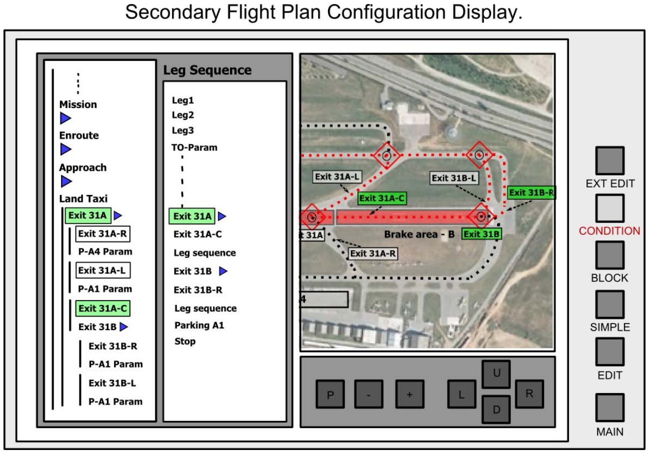


Figure 22. Flight plan modification view in the SS, containing four different sub-modes that allow different levels of flight-plan edition.

In the actual concept of operations, with voice communications, the pilot in command will interact with the ATCO, that will not have to distinguish between manned and unmanned traffic, and transmits the orders to the UAS. The first problem that outcomes is that UAS with significant smaller performances than the A category will fly long and non-optimal procedures. In this case, some specific procedures for aircraft with less performances will have to be assessed. Another issue that must be taken into account is the delay in communication between the UAS and the pilot in command.

Both departure and approach primary and secondary screens are designed specifically to supervise these complex phases of the UAS operation. The screens not only describe the various legs of the operation, but also offer support to manage the

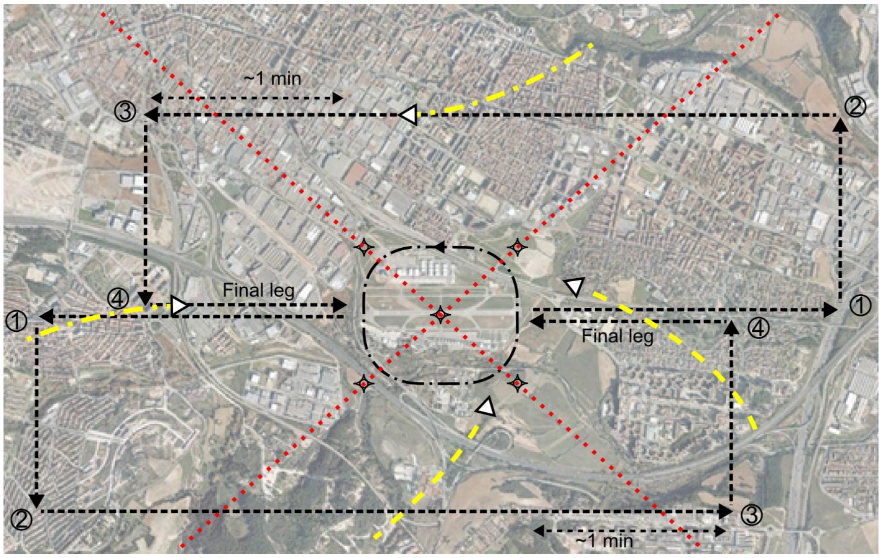


Figure 23. Approach operations when using VFR procedures.

various holding areas without having to move to the edition screens, or to abandon the predefined flight plan due to ATC heading instructions to latter return to it, if necessary.

In the case of an UAS operating in a non-controlled airport that has published instrumental procedures, the UAS will be able to develop the trajectory published like in the previous scenario. However, the coordination with other aircraft becomes an issue. If ADS (Automatic Dependent Surveillance) becomes available, the UAS will be able to have an autonomous system to detect and deal with other traffic. Otherwise, a solution similar to the applied to IFR aircraft operating in non-controlled aerodromes at night, where an operator agent should be at the aerodrome. In the UAS case, this operator will be able to deal with the traffic and avoid any conflict. The Flight Monitor interface will manage the landing procedure in this case, or in the final phase of an IFR operation [15].

In case a VFR operations is selected, the FPMo interface will allow the PiC to integrate in the designed VFR patters as described in Section 3. Figure 23 describes the general interface that will be necessary for such operation. Basically the UAS needs to integrate inside the initial holding pattern overflying the airfield. Once the holding pattern has been selected, the most appropriate insertion waypoint is automatically selected. From the holding area the adequate VFR pattern is selected and transferred to the FMo for its implementation.

Figure 24 a simple IFR operation used as example. Upon arrival to the selected airfield, the UAS PiC may choose using the available landing strip, according to the ATC, through any of its ends. Both options are already embedded in the flight plan, with a direct landing through finals with $\mathsf{Rwy}-13$ selection; or with a downwind, crosswind and finals sequence (with an optional holding point before the crosswind phase) through $\mathsf{Rwy}-31$ selection. In any case, precise landing parameters corresponding to the selected landing direction are uploaded to the VAS before control is transferred from the FPMo to the FMo for the final, touchdown and taxi operations.

Alternative selection—The USAL architecture supports an embedded mechanism for contingency reaction [14]. In particular, reaction to hazardous contingencies are directly managed by the FPM. This category manages all contingencies which reduce the aircraft airworthiness. This lack of airworthiness may put in danger the mission success or sometimes develop into catastrophic contingency. Also this category is composed by those contingencies which make impossible the mission objectives, as for example any failure in the payload needed for the mission. This component has different reactions in front of these contingencies:

- *Go Home*: In this response the UAS will be sent directly to its final destination and the mission will be aborted. The UAS damage is important enough and makes impossible the normal mission development. The path to go back home is managed by the Flight Plan Manager.
- *Go Home by Alternative Flight Plan*: In the dispatching phase, it is defined the flight plan to come back home. If the emergency situation in critical enough, it may be needed an alternative path to go back home. For example, the weather conditions have changed and the UAS airworthiness is in danger. Our flight plan description is composed by alternative paths; these paths are managed by the Flight Plan Manager.
- *Go Better Alternative Runway*: A UAS flight plan presents different landing possibilities. Due to its little size a lot of airfields may be suitable enough to ensure safety landings. This response is focused in finding the best alternative runway. The parameter in order to classify a runway as good can be the air traffic, number of runways, state of the airfield, etc.
- *Go Closest Alternative Runway*: When the contingency is very restrictive, it is needed landing as soon as possible in or-

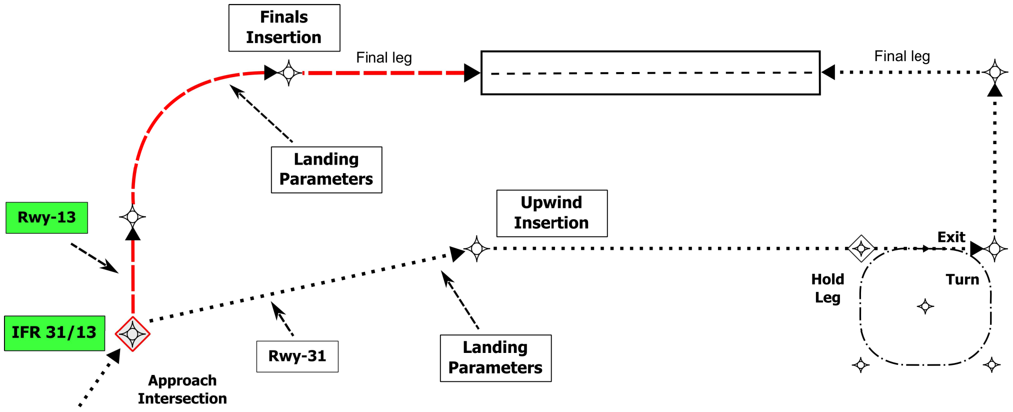


Figure 24. Approach operations when using IFR procedures.

der to preserve the UAS platform. This response is addresses to this type of contingencies. The Flight Plan Manager will guide the UAS to this new runway.

- *Go to Flight Termination Field*: We can find specific situation where the UAS cannot arrive to the closest runway. In these situations the UAS must find somewhere to terminate the flight. This place must guarantee that the potential impact to the ground of the UAS will not fatally damage any person or infrastructure.

Within this FPMo mode all these alternative flight plan fragments can be analyzed and reassigned if necessary so that flight times remain within the reachable limits by the UAS platform.

All flights require a single main flight plan, but additional emergency flight plans may be present to support the previously introduced contingency reaction scheme. The main difference between the main flight plan and emergency plans is that while the main plan includes the whole set of the aircraft's operations from take-off to landing, emergency plans only cover the finishing stages of a flight. The reason for not including all possible stages in an emergency plan is that they only get executed when something goes wrong during the mission, *i.e.* when the aircraft is already flying.

Another important characteristic that differentiates them from the main plan is that a higher degree of determinism is required. The inclusion of iterative and intersection legs in the main flight plan makes the total execution time difficult to predict. To address this issue iterative legs are not allowed inside emergency plans. Intersection legs are allowed as long as a default path is set. If any holding patterns appear in an emergency plan their number of iterations must be set to zero. These restrictions provide a bounded default path but still allow some degree of flexibility for a on-ground operator to make final adjustments. In the specification of the emergency flight plan time estimations for the default and the more time consuming paths will be provided.

The structure of an emergency plan is the same as for the main flight plan. It contains a name, a description and a list of stages that are going to be flown in sequential order. Another difference with regard to the main flight plan is that an emergency plan does not contain a list of emergency alternatives.

9. CONCLUSIONS AND FURTHER WORK

In this paper, a full analysis of the different scenarios where UAS will need to perform departures, arrivals and approaches has been done. As it has been presented, four different cases arises.

As previously said, the UAS will fly like an IFR flight, therefore, the procedures that exists for IFR aircraft can be used for UAS without major changes. In the controlled case with IFR procedures, the UAS will be transparent to the ATC who will deal with it like with any other aircraft. Only in the case where the aircraft has very limited capabilities new procedures might be needed; or even restrictions to their use might apply, like nowadays appends with UML or gliders in major airports.

The pilot in command and not the ATCO will have the responsibility to command the UAS. This means that the ATCO needs to clear and order to the pilot who will command the UAS. Therefore, a communication between the pilot in command and the ATCO should exist. Depending of the used technology the solution will be different but a delay analysis will be necessary in all cases to ensure that the response time of the vehicle is similar to the one reached by manned aircrafts.

Due to the fact that UAS are similar to IFR flight, in a controlled airspace, it should not produce any problem to deal with them. As a consequence, the most challenging operation will be in airfields without IFR procedures, non-controlled and with VFR traffic operating in them. Moreover, it is expected that in the upcoming years, the UAS starts to operate in this kind of fields instead on in busy airfields where IFR

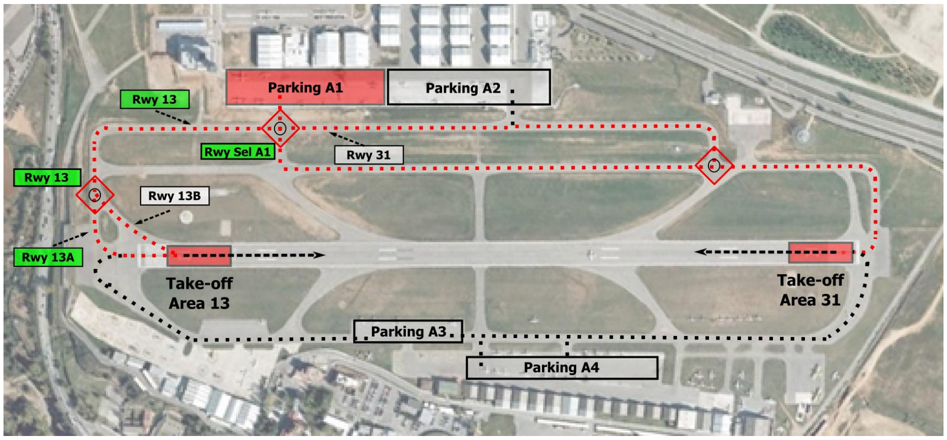


Figure 25. Taxi operations from parking area to take-off operation.

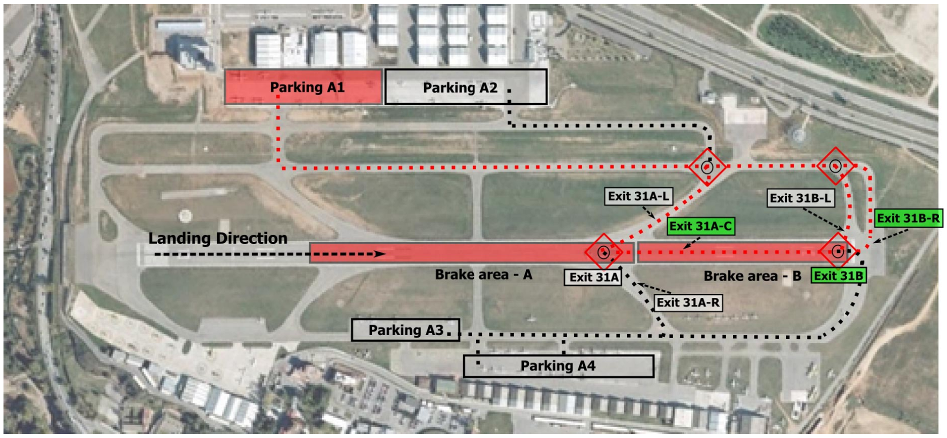


Figure 26. Landing and taxi operations up to parking area.

traffic operates.

In this case, for arrivals, the authors have propose the use of a pattern similar to the used on VFR on general aviation. This will allow the UAS to fly the most transparent as possible to other traffic in a predictable and safe manner. The authors suggest to use this generic proceeding when there not exists IFR procedures at an airfield even if it is controlled. This will give more confidence to the ATCO, who will know what are the UAS intentions and procedures.

Finally if there are not IFR procedures to take-off, it is proposed to use the diagram shown in Figure 3. Using one of the EDWPs the departure will be much more controlled and automatic. This will reduce the pilot in command workload and will increase the safety and the predictability. The UAS will take-off in a similar manner as general aviation. Moreover, the computation and validation of the EDWPs will be done during the dispatching phase minimizing the workload once in the field if a change on runway or on the first navigation way-point is done.

Further work should investigate how this procedures are integrated in an specific architecture of an UAS. Simulations of the procedures should be done. And finally it should be done a deep study of the interfaces the pilot in command needs to operate the UAS in an easy and safe manner for departure and approach.

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BIOGRAPHY

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