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Departure and Approach Procedures for Unmanned Aircraft Systems in a Visual-Flight-Rule Environment

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This paper assesses the departure and approach operations of unmanned aircraft systems in one of the most challenging scenarios: flying under visual flight rules. Inspired by some existing procedures for (manned) general aviation, some automatic and predefined procedures for unmanned aircraft systems are proposed. Hence, standardized paths to specific waypoints close to the airport are defined for departure operations, just before starting the navigation phase. Conversely, and for the approach maneuvers, a first integration into a holding pattern near the landing runway (ideally, above it) is foreseen, followed by a standard visual-flight-rule airfield traffic pattern. This paper discuses the advantages of these operations, which aim to minimize possible conflicts with other existing aircraft while reducing the pilot-in-command workload. Finally, some preliminary simulations are shown in which these procedures have been successfully tested with simulated surrounding traffic.

I. Introduction

THE safe, efficient, and regular operations of all kinds of aircraft mainly rely on a set of procedures and standardized practices. Aircraft operations can be divided in two main groups: those aircraft operating under visual flight rules (VFR) and those that are under instrumental flight rules (IFR). In addition, other classifications exist in civil aviation [such as, for example, the aircraft category (A, B, C, D, or E) in regard to the aircraft speed at threshold [1]], and even more basic divisions exist in regard to aircraft performance (such as ultralight aircraft, gliders, helicopters, etc.). These classifications play a very important role in how most of the aircraft procedures are conducted, especially for air navigation and separation purposes. For example, pilots evolving under VFR rely entirely on what they see outside the cockpit for aviating and navigating their aircraft. Moreover, in almost all classes of airspace, these visual references are also used for ensuring self-separation with other aircraft (the so-called *see and avoid*). Conversely, pilots flying under IFR use several onboard instruments to control and navigate their aircraft, and in almost all classes of airspace, the separation with other aircraft is ensured by an air traffic control (ATC) service.

This paper deals with airfield operations of unmanned aircraft systems (UAS), imagining a civil scenario in which manned aircraft will coexist with unmanned aircraft (UA). Nowadays, UAS are mainly designed for military missions, and very few civil applications have been developed so far. One of the principal reasons for the absence of civil UAS is the lack of a regulation basis concerning their certification, airworthiness, and operations [2]. Nowadays, the few existing civil UAS use special airfields away from populated areas and closed to other traffic (see, for instance, [3]). However, if extensive and commercial UAS applications might be a reality in the future, airfields for UA operations should be chosen according to the mission requirements, as much as possible. This means that in most of the cases, UA operations will have to coexist with other manned operations in the same airfield.

From an end-user point of view, the operation of a UA is similar to the operation of a manned aircraft in IFR conditions. In general, the UAS operator will not use external visual references to aviate and navigate the UA, since it is expected that UAS will be equipped with autopilots and flight-planning capabilities. However, even if a UAS may be fully capable of flying under IFR rules, an extra functionality is needed if the UAS operations are performed in an airport with no IFR procedures published. In fact, it is quite probable that initial UAS operations in civil airspace will be conducted in small airports instead of in busy ones. Hence, it is also quite probable that in such airports no IFR operations will be published. Moreover, in these airports the majority of traffic will be general aviation aircraft, which are generally less equipped than commercial airliners with respect to sensors and automated systems. Therefore, in order to minimize the risk of midair collisions, an extra safety layer must be added by introducing procedures that are predictable and well known by all the users [4].

In this work, among all separation and collision-avoidance mechanisms, we focus only on the procedural layer by assessing UAS departure and approach procedures in one of the most challenging environments: airfields with no IFR procedures published. Thus, some specific procedures are proposed in order to safely operate UAS while minimizing the interference with other traffic. The next section gives a brief overview on current airfield flight procedures and discusses the challenges that a potential integration of UAS would face. Then Sec. III presents a set of proposed procedures for UAS evolving in VFR environments. Finally, Sec. IV shows some preliminary flight simulations implemented in a specific UAS architecture that was also developed by the authors.

II. Airfield Flight Procedures

Figure 1 summarizes different mechanisms present in civil aviation that aim to minimize the probability of collision with other aircraft. The two inner layers include the sense mechanisms and avoidance maneuvers that may prevent the aircraft from an imminent collision in case the minimum separation has been lost for any

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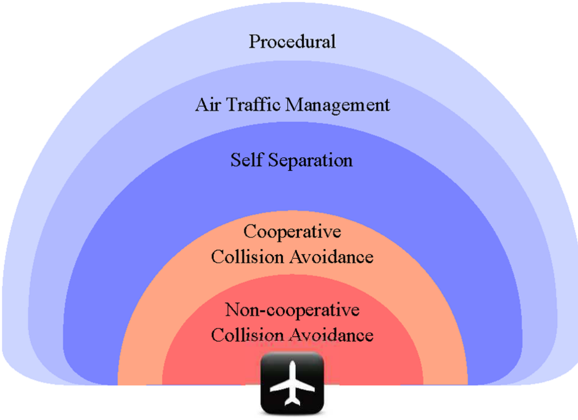

Fig. 1 Separation and collision-avoidance mechanisms.

reason. Conversely, the outer three layers are devoted to ensure these minimum separations. Each layer is summarized as follows:

1) *Noncooperative collision avoidance* is the lowest-level mechanism to prevent an imminent collision with any type of aircraft, obstacles, or terrain. In manned aviation, this relies entirely on the ability of the crew members to *see and avoid*. Yet, the equivalent *sense and avoid* (S&A) for unmanned systems is one of the main issues that must be addressed before integrating them into civil airspace. Several technologies and architectures are subjects of ongoing research worldwide that aims to provide this required S&A capability. These solutions can range from human observers (either on the ground or with chase planes following the UA), vision-based onboard systems or radar, or ad hoc ground surveillance radar, as proposed in [5].

2) *Cooperative gcollision-avoidance* mechanisms form the following collision-avoidance layer and contain all of these systems and procedures between cooperative aircraft that can avoid imminent collisions. The well-known traffic collision-avoidance system, mandatory in manned aviation for certain types of aircraft, belongs to this category.

3) *Self-separation* is the lowest layer that can guarantee a minimum safe separation. See/sense-and-avoid systems again play an important role, which can be enhanced with different kinds of airborne separation assistance systems that are based, for instance. with automatic dependent surveillance (ADS) applications.

4) *Air traffic management*, which includes air traffic services (ATS) and ATC, adds a very significant extra layer of protection but is very variable in regard to the type of airspace.**

5) *Operational procedures* are the outermost layer in ensuring separation with other aircraft (along with known obstacles and terrain). Here, we find not only navigation procedures, but also aircraft operating procedures.

The particular mechanisms available at each layer depend on several factors, such as the type of aircraft, airspace, meteorological conditions, flight rules, etc. For example, in noncontrolled airspace the air traffic management layer is almost not present; in instrument meteorological conditions, the availability to see and avoid will be drastically reduced for manned aircraft, or self-separation mechanisms will be undoubtedly better if all aircraft are ADS-equipped.

In this context, the minimum required equipment for each aircraft will also depend on many variables. In manned aviation, airspace class, aircraft type, and altitude of operation mainly determine the requirements for radio communications, transponders, or traffic collision-avoidance systems. Similar requirements are expected for UAS, but in addition to them, additional particular considerations are also foreseen: for instance, the automation level of the UAS (autonomous, automated, or remotely controlled), the type of communication relay with the control station, or the presence of the UAS operators in the airfield of operations. Moreover, flights over populated areas also raise increased safety issues, since minimum safety figures are usually derived from the number of fatalities an accident may cause [2,4]. Therefore, the UAS minimum equipment requirements and, in particular, the S&A capability, will depend on all of these considerations and are out of the scope of this paper, since we focus on the highest layer of the separation assurance mechanisms: flight procedures. Section III details our proposals for UAS operations, and the reminder of this section is devoted to providing some background on current airfield manned operations, while pointing out the challenges for UAS integration.

Four different scenarios are identified if we consider aircraft flight operations outbound or inbound to a given airport [6]: 1) controlled airports with IFR procedures published, 2) noncontrolled airports with IFR procedures published, 3) controlled airports without IFR procedures published, and 4) noncontrolled airports without IFR procedures published.

In controlled airports, ATC services ensure different levels of separation between aircraft in regard to the class of airspace, whereas in noncontrolled airports, it is always the responsibility of the pilot in command (PiC) to ensure the minimum separation with the other traffic. In this case, all pilots in the area may coordinate among themselves by reporting their positions and intentions at different significant points. If IFR operations are performed, these points may be navigation fixes, intersections, distances to the runway threshold, etc. In the case of VFR operations, pilots may report visual reference landmarks or relative positions inside the airfield traffic pattern.

Each state is responsible for publishing how aircraft should operate within its boundaries, facilitating all kinds of aeronautical information. These regulations and requirements are, in general, local adaptations of the framework directives published by the International Civil Aviation Organization [1,7]. For some examples of these aeronautical information services, the reader could refer, for instance, to [8–10].

A. Airfields with IFR Procedures

IFR flights always execute standardized navigation procedures that have been previously published by a competent authority. For example, an airport may publish standard instrumental departures (SID), standard terminal arrival routes (STAR), and instrumental approach charts in order to accommodate IFR operations.†† IFR procedures in noncontrolled airports are not permitted in all countries and are subject to different regulations. For instance, in France, IFR straight-in approaches are prohibited in noncontrolled airports and they are restricted to a circle-to-approach procedure (i.e., an instrumental procedure ending in a visual maneuvering phase) [11].

These environments are in line with the automation existing in UAS operations, and it is expected that the behavior of the UA will be the same as manned traffic, since all of them will execute very precise and predictable procedures. A potential issue in these scenarios would be for those UA with performances significantly below aircraft in category A [1]. In this case, some specific procedures for these slow UA will have to be assessed for the procedure designers. On the other hand, in the case of a UAS operating in a noncontrolled airport but with IFR procedures, the UAS will be able to execute the published trajectory such as in the previous scenario, but then the coordination with other aircraft becomes an issue. Nevertheless, the new paradigms in air traffic management (coming with SESAR and NextGen programs) will introduce technologies and operations that will overcome these difficulties: namely, the use of ADS, datalink communications, the availability of very accurate 4-D trajectories, the possibility of sharing information between aircraft, etc. [12,13].

B. Airfields with VFR Procedures

For high-density terminal airspaces, VFR flights may be subject to important restrictions (such as, for example, flight sectors or

**Civil aviation airspace is classified in seven different classes (A, B, C, D, E, F, and G). In regard to the class, different levels of air traffic services are given to aircraft, ranging from full separation assurance (classes A and B) to noncontrolled airspace (classes F and G).

††In small airports or in those with low traffic volumes, omnidirectional IFR procedures may be published instead of specific SID and/or STAR procedures.

corridors), along with limitations in minimum and/or maximum altitudes. Airports with a significant volume of traffic may publish visual approach charts, eventually detailing the preferred side for the airport traffic pattern, some exit or entry points, or specific routes for inbound/outbound traffic, among others. In controlled airports, aircraft must receive clearances before executing certain maneuvers such as taxi, takeoff, joining the traffic pattern, landing, etc. In the same way, it is always possible that the ATC may clear the aircraft to fly directly to navigation (in a departure) or to a particular segment of the traffic pattern (in an arrival), overriding the standardized maneuvers to some extent.

A completely different situation exists for VFR operations in noncontrolled airfields. In these cases, default and generic procedures are usually applied and it is the PiC's responsibility to fly his/her aircraft within its maneuvering limits and according to the surrounding terrain and traffic. For takeoff and departure operations aircraft usually climb to 500 ft above aerodrome level and then turn direct to their intended navigation. In the case when the destination point is just in the opposite direction from the takeoff heading, the usual maneuver is to first join the traffic pattern while continuing to climb and to leave it at the end of the downwind leg.

Nevertheless, the arrival and approach phases are the most challenging ones in the VFR noncontrolled scenarios. First, the PiC evaluates the prevailing airfield conditions before joining the traffic pattern (wind direction, status of the runway, surrounding traffic, etc.). This is done by overflying the landing runway in circles at a height greater than the highest of the airfield traffic patterns (usually 500 ft or more above the traffic pattern). Thus, conflicts with existing aircraft already in the traffic pattern or departing the airfield are minimized. After this evaluation, the aircraft integrates to the downwind leg of the traffic pattern while descending to the appropriate altitude. Then the standard downwind, base, and final legs follow, with the possibility of dynamically adjusting them in regard to the other traffic ahead. It is also possible to directly join the traffic pattern at the downwind, base, or even final legs if the PiC estimates that this maneuver is safe. This is usually done when the PiC already has information on the prevailing conditions in the airfield and other traffic is not present. Moreover, IFR flights usually have landing priority over VFR flights already in the traffic pattern [8]. Figure 2 shows a diagram of the whole procedure explained above.

In all kinds of VFR operations, proper voice communications with the ATC or among pilots are paramount to ensure safe operations. Moreover, airfield traffic patterns are more of a *concept* than precise routes in space, since their dimensions, in general, are not precisely defined. As a general rule, it is considered that the downwind leg is parallel to the runway and the base and final legs should take approximately 1 min of flight (at the approach speed of the aircraft). This means that the turn to the base leg is performed when an imaginary line forming a 45° angle with the runway intersects with the downwind leg. Finally, the turn to the final leg is performed when

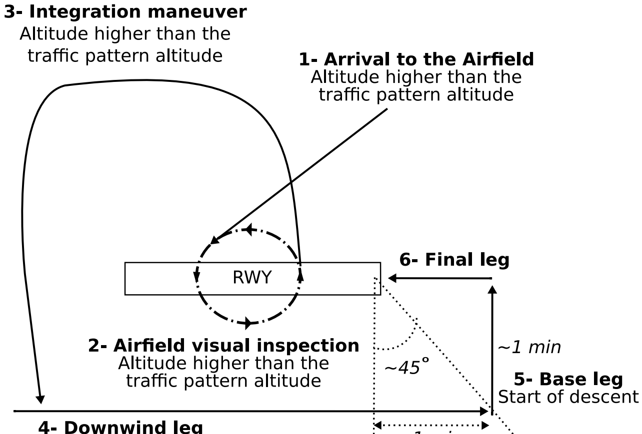

Fig. 2 Standardized procedure for the arrival and approach operations in noncontrolled VFR airfields.

intersecting the extended runway centerline. Even if *fuzzy*, these operations have been always used all around the world and proved to be safe and efficient, mainly because of the flexibility and fast adaptability to changes that manned aircraft operations can offer. However, this scenario is the most challenging for the integration of UAS operations, because of the lack of predictability, precision, and repeatability of the existing procedures, and it is assessed in the next section.

III. UAS Operations in VFR Environment

As noted previously, VFR operations are based on visual cues that the pilot takes from outside the cockpit, representing a big challenge when performed by UAS. Several research efforts are devoted to develop S&A systems that aim at fulfilling the future safety requirements for such UAS operations (see, for instance. [14–20]). On the other hand, new self-separation applications are also foreseen, for example, by using ADS equipment, datalink communications, and information sharing networks, among others [21]. Recalling Fig. 1, in addition to specific S&A and separation systems, the use of standardized and predictable procedures for the UA would be a complementary safety layer, which would eventually decrease the complexity of these systems and their certification process.

These procedures are described in this section and are conceived for a wide range of UAS, regardless of their actual S&A and separation systems. In fact, they aim to minimize the interference with surrounding traffic and also the PiC workload, which will be connected with the UA by using some kind of datalink communications. As mentioned earlier, the midair collision risk is reduced if procedures are clearly defined, and their use is even more important around airports, because a greater risk of midair collision exists [18]. In addition, the procedures may facilitate the coordination with eventual ATC or, in the noncontrolled case, with the rest of pilots operating in the same area.

A. Planning Operational Stages

All kinds of aircraft operations are preceded by some sort of preflight planning or preparation stage: from simple and short briefings of light aircraft when performing local flights to the complex planning and dispatching processes present in big airlines. UAS operations will be no exception and will indeed also follow some kind of preflight planning flow [22]. With respect to airfield operations, we have identified three clear operational stages that are somehow strategic, tactical, and real-time levels in the operation of the UAS:

1) In the *airfield analysis stage*, well before actual operations, the airfield of operations for a particular UAS will be studied. In this stage some *default* procedures and waypoints will be generated automatically according to the location of the airfield, the runway length and orientation, and the average UA performances. Then these default settings will be refined by considering the specific particularities of the airfield, the surrounding scenario, and the characteristics of the UAS. Thence, aspects such as terrain, populated areas or restricted zones, existing procedures for other aircraft types, the presence of ATS, the type of the UAS S&A equipment, its level of automation, its reaction in case of contingencies (see Sec. III.D), among others, will be considered to finally place the location of certain waypoints defining departure or approach procedures or to even add or remove some of them.

2) The *dispatch stage* is performed some hours before the actual operation of the UA. Hence, more information will be available on weather conditions, ATS, actual sensors on the UA and final UAS architecture, estimated traffic conditions around the airfield, UA performances and limitations, etc. Therefore, the initial procedures and waypoints defined in the previous stage will be fine-tuned according to all of these considerations and uploaded to the UAS flight services.

3) In the *flight stage*, it is also expected that during actual operations, waypoints and procedures can be always updated by the PiC by uploading new parameters in real time. This would allow

him/her to react to unexpected changes such as weather or traffic conditions.

In this paper, we show a set of generic procedures and associated waypoints that will be automatically generated at the airfield analysis stage. They are conceived with the aim of providing a set of well-defined and predictable trajectories that minimize conflicts with other aircraft. Yet, they are flexible enough to be modified during the dispatch process or even in real time, should particular conditions mandate.

B. Departure Operations

It is clear that a manual takeoff is always possible, especially if the PiC is present in the departing airfield and has visual contact with the aircraft. In this case, the UAS would fly up to a point and/or height at which the navigation phase can be initiated and the autopilot system can be engaged. Yet, the authors propose an automatic takeoff phase to make this process easier, more predictable, and therefore safer. Thus, the takeoff phase will automatically fly the aircraft from the departing runway to an end-of-departure waypoint (EDWP). These waypoints are located close enough to the airport to avoid complex navigation paths for the UA, but far enough to reduce conflicts with surrounding traffic as much as possible. Once at the EDWP, the UAS will engage to navigation mode.

In general, the exit points that are depicted in some visual approach charts could not be used as EDWPs, since they are usually placed too far from the runway. In the case of flying in a airport where these kinds of points are published, the UAS will fly from the EDWP to the published exit point in the same way that the rest of the flight plan would be executed.

1. End-of-Departure Waypoints

Given an airport and a departing runway, five default EDWPs will be systematically computed. The locations of these points rely on the characteristics of the traffic pattern for that particular runway. In the general case, two standard traffic patterns (clockwise and counter-clockwise) will be considered and the five EDWPs will be allocated as shown in Fig. 3. Point EDWP-A is defined 500 ft above aerodrome level and along the extended runway centerline. Point EDWP-B is defined along a line starting at EDWP-A and forming 45° to the left of the extended runway centerline. Symmetrically, point EDWP-A is at the right of EDWP-A. On the other hand, point EDWP-C is defined at the end of the left downwind leg for the considered runway, and point EDWP-C′ is defined symmetrically at the end of the right downwind leg. The end of the downwind is that point where a line from the landing threshold forms 45° with the extended runway centerline.

Once the five EDWPs are defined, five different areas can be associated with them, as shown in Fig. 3. The first navigation waypoint will fall in one of these areas, and this will determine which of the EDWPs will be used for the departure. For example, if the first navigation waypoint turns to be inside area-B′, then the UA will perform an initial climb up to EDWP-A, followed by a right turn directly to EDWP-B′, where the takeoff procedure will be terminated. From that point, a direct navigation to the first waypoint will be performed. The different limiting lines of 45° with the extended runway centerline have been chosen with the aim of reducing the amount of the turn heading change that follows the EDWP (i.e., just when the aircraft flies directly to the first navigation point).

2. Flexibility and Constraints in the Definition of EDWPs

So far, the EDWP presented above are those computed by default, for a given runway. Once they are computed, the user of this system will have the ability to manually erase, modify, or apply specific restrictions (such as altitude restrictions) to these precomputed points, in regard to the scenario and specific UAS equipment. Moreover, in order to improve safety in the proposed operations, some constraints in the placement of these EDWP (default or user-selected) have to be considered. They are summarized as follows:

1) The earliest EDWP-A placement shall be the departure end of runway (DER).

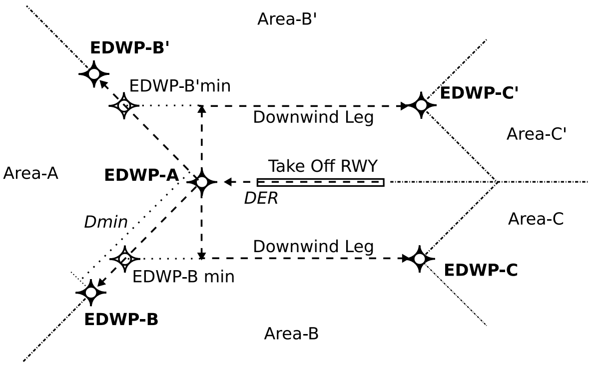

Fig. 3 EDWPs and associated departure areas.

2) The earliest EDWP-B and EDWP-B′ placements shall be at the intersection with the extended downwind line. Figure 3 shows these binding placements as $\text{EDWP-B}_{\min}$ and $\text{EDWP-B}'_{\min}$.

3) Waypoints EDWP-B and EDWP-B′ shall be placed at a distance equal to or higher than $D_{\min} = D_{\text{B}} + vT_{\text{B}}$ from EDWP-A, where D_{B} is the distance required to complete the turn, v is the aircraft speed, and T_{B} is a safety buffer time. The turn distance D_{B} can be computed geometrically and in regard to the aircraft speed and bank angles; T_{B} allows for roll stabilization, and it is an aircraft-dependent parameter (usually between 1 to 10 s) [23].

Constraint 1 prevents the aircraft from turning before the end of runway, reducing possible conflicts with aircraft in the airfield traffic pattern once the navigation is engaged after overflying EDWP-A. In the same way, constraint 2 ensures that EDWP-B and $\text{EDWP} - \text{B}'$ fall outside the standard traffic pattern zone, and therefore the aircraft will not cross any portion of the downwind leg when starting navigation. Finally, constraint 3 guarantees that the aircraft reaches the EDWP properly stabilized, with the wings leveled.

3. Summary of the Actions Taken at Each Operational Stage

Figure 4 summarizes for each of the three operational stages defined in Sec. III.A, the different actions and decisions taken relative to the departure procedures. In the airfield analysis stage, the default EDWPs will first be computed automatically. Some adjustments will follow according to the scenario and UAS particularities, and some of them will even be deleted. The dispatching process will fine-tune these waypoints and, according to the mission to be performed, one EDWP will be selected. During the execution phase, the PiC will have to confirm the selected EDWP after assessing the current situation and proceed to take off. Finally, once the UA is flying, the pilot will have always the ability to abort the procedure and commute to approach mode; if a contingency occurs, the UAS will react accordingly, as explained in Sec. III.D.

C. Approach Operations

Following the same philosophy as with the departures, we propose some standardized procedures that may be performed by the UAS in the approach phases to a given airport. These procedures are based on current operations executed by manned aircraft operating in VFR and in noncontrolled airfields (see Fig. 2). We think that these procedures will improve the predictability of UA trajectories, so they might be also used in case of flying to an airport even with ATC services, but with no IFR procedures published.

1. Arrival to a Predefined Holding Pattern

The proposed approach procedure will start in a holding pattern located near (or over) the landing runway. The flight-planning system will guide the UA to this holding point by using normal navigation waypoints while taking into account all possible restrictions that may prevail in the airport (entry points, minimum/maximum altitudes, etc.). The minimum arrival altitude will be at least 500 ft above the highest of the airfield traffic patterns in order to avoid conflicts with aircraft already there. By default, the holding maneuver will be

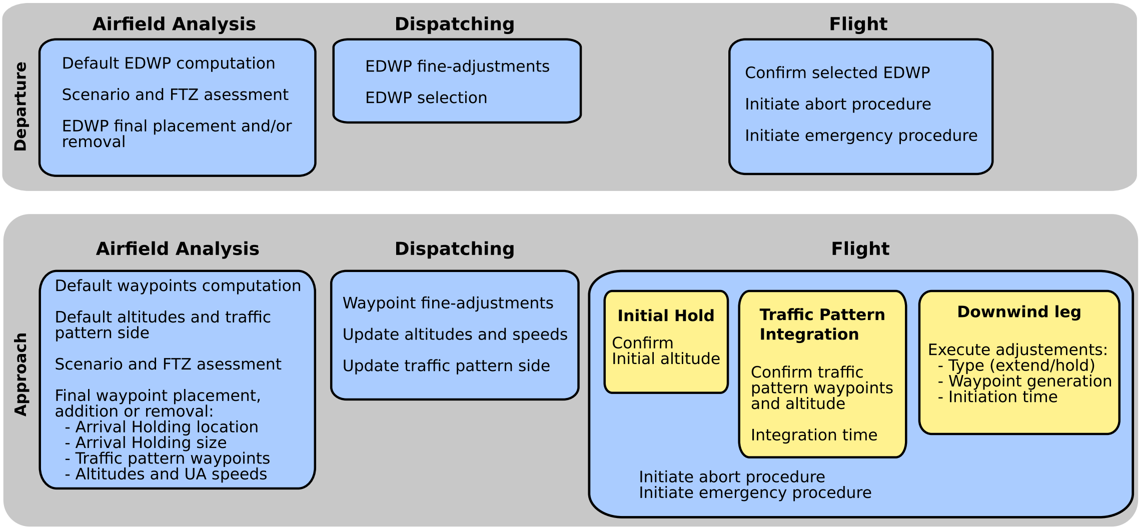

Fig. 4 Summary of actions and decisions taken at each operational stage.

performed just over the runway, as it is considered to be the location with less potential interferences with arriving or already approaching traffic. The UA will remain in this holding pattern up to the moment it is considered appropriate to integrate the downwind leg of the traffic pattern.

To ensure omnidirectional arrivals, five waypoints will define the holding pattern and, depending on the arrival direction, the UA will integrate the holding pattern by flying directly to one of the four external waypoints. These waypoints will be automatically computed by defining the coordinates of the center waypoint, along with the holding aircraft speed. Aircraft minimum turn distances (similar to those in Sec. III.B.2) will be considered in order to compute a minimum separation among these waypoints (see Fig. 5).

A source of potential conflicts may be with those aircraft aborting the landing in final. In general, it is the responsibility of the aircraft performing the go-around to avoid conflicts [8]. Yet, all the aircraft in the vicinity of the airfield will know that the UA is holding at the vertical of the runway, thus facilitating its visual identification.

2. *Integration to the Airfield Traffic Pattern*

Once in the holding pattern, the PiC will decide the best moment to integrate to a left (counterclockwise) or right (clockwise) traffic pattern. These decisions could be based on ATC clearances (in a controlled airfield) or on pilot-to-pilot communications (in the non-controlled case). In regard to the landing runway and the direction of the traffic pattern turns, one of the four external waypoints of the holding pattern will be designated as a holding exit waypoint. Only at this waypoint can the aircraft quit the holding pattern and fly directly to a predefined integration waypoint (IWP), which is located on the extended runway centerline. An initial downwind waypoint (IDWP) is also defined to guide the aircraft to the start of the downwind leg. Figure 6 shows the locations of these three predefined waypoints.

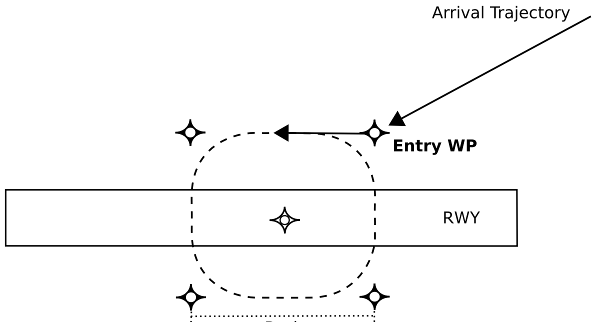

Fig. 5 Arrival holding.

Both IWP and IDWP ensure a smooth transition from the holding pattern to the traffic pattern in such a way that the aircraft integrates the downwind leg at the correct altitude (usually 500 ft below the holding). Moreover, and aiming to avoid conflicts with departing traffic, the aircraft will start the descent once the IWP is overflown.

Future UAS are likely to be equipped with a 4-D trajectory-prediction tool [13]. Therefore, the UAS pilot will have a good knowledge of the required times to fly from one waypoint to another. This will allow him/her to better deal with ATC clearances or coordination tasks with other pilots. Figure 7 shows an example of the type of diagrams that may be displayed to the PiC by the ground station system. Moreover, having a traffic information system (giving the positions of the surrounding aircraft and displaying them in the same screen) would definitely help the UAS pilot to perform this integration.

3. *Approach Phase: Flying the Airfield Traffic Pattern*

The airfield traffic pattern will be flown like any other manned or unmanned flight evolving under VFR: by sequentially following a downwind leg, at a specified constant altitude; a base leg, where descent will be initiated; and a final leg, aligned with the runway centerline. Moreover, if the used airport publishes some

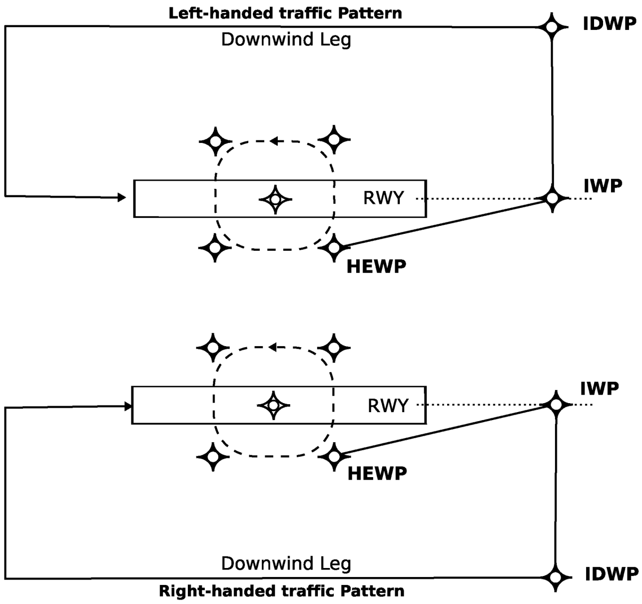

Fig. 6 Integration to the airfield traffic pattern.

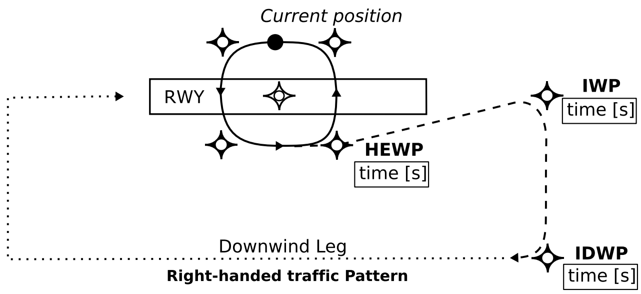

Fig. 7 Four-dimensional support information for the PiC for the integration maneuver.

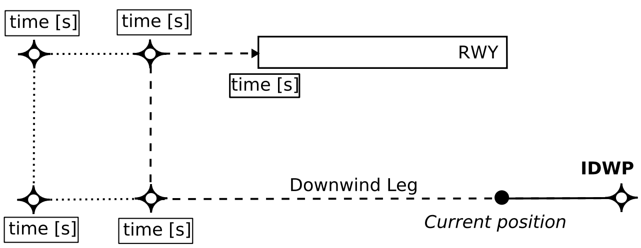

Fig. 8 Dynamic adjustments of downwind leg: leg extension.

particularities regarding the traffic pattern (nonstandard altitudes, prescribed legs, etc.), these will be taken into account by the UAS. Conversely, if nothing is published, a standard traffic pattern will be used (see Fig. 2).

In addition to the traffic pattern parameters, the UAS will incorporate two functionalities aimed at increasing the distance to the preceding aircraft for separation purposes. Thus, we propose to extend the length of the downwind leg as shown in Fig. 8 if the PiC considers it necessary. Again, the 4-D trajectory-prediction tool will assist him/her to choose the amount of time that this leg should be extended. For longer delays, it will be also possible to perform a holding maneuver at the end of the downwind leg, as depicted in Fig. 9. These two maneuvers will allow the PiC to adjust the separation with the preceding aircraft for the base and final legs, but also to give way to other aircraft (perhaps with higher right-of-way priority) that may directly join the final leg or to perform the opposite traffic pattern. Furthermore, it is also foreseen to start the holding procedure at any moment during the downwind and not only at the end of the leg. This will allow the UAS to react in case of an unexpected potential loss of separation with the preceding aircraft or with other aircraft with higher right-of-way priority that are integrating directly ahead in the downwind or base legs.

4. Landing Maneuver

The landing maneuver is formed by a single leg where the angle of descent should automatically be computed in regard to the last waypoint of the base leg and the touchdown fix. If the PiC, motivated for more or less automated tools and indicators provided by the UAS,

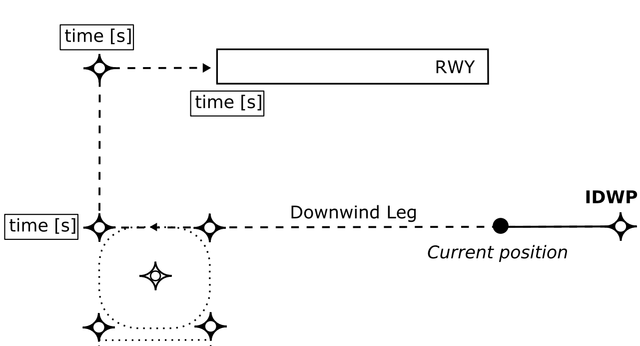

Fig. 9 Dynamic adjustments of downwind leg: holding.

considers that landing is not safe enough a missed-approach procedure will be commanded. In this abort phase, the aircraft will maintain runway heading and climb up to the traffic pattern altitude. Thus, potential conflicts with other aircraft holding above the runway would be minimized. Once at this altitude, and after overflying the DER (whatever comes later), three different options appear:

1) Rejoin the traffic pattern and thus continue at constant altitude toward the IWP and proceed to a normal traffic pattern integration.

2) Deviate to an alternate airfield and therefore fly to the desired EDWP.

3) Integrate the arrival holding.

Following the same principle used for the downwind leg, the end of the missed-approach maneuver can also be extended (by continuing to fly straight on the runway heading), delaying the execution of the following phase. This will allow the PiC to establish appropriate separation with surrounding traffic and/or to provide with enough flight distance to gain the required altitude to integrate the arrival holding (500 ft above the highest aircraft).

5. Summary of the Actions Taken at Each Operational Stage

Figure 4 summarizes the different actions and decisions taken relative to the approach procedures for each of the three operational stages defined in Sec. III.A. In the airfield analysis stage, the default waypoints and procedures will first be computed automatically. Some adjustments will follow according to the specific scenario and UAS assessment. For example, nonstandard rectangular traffic patterns could be foreseen in order to avoid overflying some areas (by adding extra waypoints), different minimum altitudes would apply, the initial arrival holding could be placed elsewhere and not over the runway, etc. The dispatching process will fine-tune these parameters and, since a significant amount of time may elapse from this stage to the actual time of arrival, some final decisions will be required at the execution stage.

Therefore, some time before the UA arrives at the airfield, the altitude of the arrival will be confirmed, while considering other aircraft already holding. As long as these aircraft leave their holdings, the UA will change its holding altitude until being the first aircraft to integrate the traffic pattern. At any moment in this holding process the UAS might abort the approach procedure and transition directly to navigation. If this is not the case, before leaving the holding, the side, shape, and altitudes of the traffic pattern will be confirmed, along with the time to leave the hold. Then the downwind leg will follow and the possible adjustments described before may take place, thus deciding their type (extension or hold) and the location of the associated new waypoints. Finally, the base and final legs will follow, and the only operational decision will be to either continue with the procedure or to abort it. If a contingency occurs in any moment of the approach, the UAS will react accordingly, as explained in Sec. III.D.

D. Contingency Management in Airfield Operations

A thorough analysis of contingency situations an reactions are out of the scope of this paper, since they are completely dependent on the UAS type, architecture, onboard systems, redundancies, etc. However, due to the relevance of this issue, some general discussion is given next, focusing on the type of contingencies that may occur during airfield operations and their possible reactions. In general, contingencies can be classified in three categories in regard to their severity: catastrophic, hazardous, and minor contingencies. Minor contingencies are related to payload malfunction and are therefore omitted in this discussion.

1. Catastrophic Contingencies

The most important and restrictive category is the catastrophic contingency, which applies for all of those situations in which the UA flight is still controllable but an immediate landing is required. In the majority of situations, this would lead to a forced landing, due to the impossibility of safely reaching an airport. For example, situations such as losing the powerplant, running out of fuel/batteries, experiencing a severe fire, etc., would fall in this category. In such a situation, immediate flight termination becomes the priority and must be performed safely regarding potential collisions with people and goods on the ground. Some UAS are equipped with parachute systems or can perform spiral maneuvers to reduce the energy of potential ground impacts. Both actions are designed to eventually terminate the flight while reducing the hazard when crashing into the ground. Some other aircraft may not be equipped with such a flight-termination system and would simply glide to a crash safe zone.

Because this paper focuses on procedures and not specific UAS technologies or implementations, we propose the definition of a set of flight-termination zones (FTZ) nearby the airfields. These FTZ will be analyzed beforehand and their location will be defined during the airfield analysis and dispatching stages. After the FTZ assessment has been completed, the whole nominal trajectories will be divided in different segments and a FTZ will be assigned to each of them. Thus, should a catastrophic failure occur, the UAS will immediately head to the associated FTZ to implement the termination maneuver there. It should be noted that these segments do not necessarily correspond to nominal legs (such as downwind or base legs), since they depend on the FTZ location and UA performances. Moreover, in regard to the risk that a ground impact represents, which mainly depends on the UA size and population density [2,4], the number and dimension of the available FTZ will be different for each case. Consequently, this will affect the final placement of the different waypoints (such as the EDWP, for example), and it could eventually happen that some UAS will not be able to operate in a particular scenario, because after a catastrophic contingency it cannot be guaranteed that a FTZ can be reached at any moment.

2. *Hazardous Contingencies*

All of the situations that reduce aircraft airworthiness, but still allow controlled flight, are considered hazardous contingencies. In these cases, the main priority is to land as soon as possible and closely monitor the status and trajectory of the aircraft in order to prevent a catastrophic contingency in a later stage. It is clear that a proper and quick contingency detection and reaction can save the UAS platform by performing an emergency landing at the airfield. Therefore, if the aircraft is already executing an approach procedure, the UA will continue toward a landing, because delaying the operations may simply aggravate the situation. In case of a departure, the transition to the navigation phase will not be performed and the UA will join the airfield traffic pattern, or the arrival hold, and then transition to the approach mode. However, if the risk of performing an emergency landing is deemed too high, the hazardous contingency can be reclassified as a catastrophic contingency and command a flight termination in the appropriate FTZ, as defined above. This decision will depend again on the UAS equipment, the type of contingency, the specific airfield scenario, and the presence of other traffic nearby the airfield. These reactions could have been preprogrammed in the UAS logic or uploaded from the ground control station in real time.

A very particular hazardous contingency is the case of failure of the datalink communications channel relaying the UA with the ground control station. In such a situation, the UA becomes completely autonomous, and again depending on the particularities of the UAS (and especially on the capabilities of the airborne S&A system), the reactions in front such a contingency may be different. A lost-link situation is somehow similar to a radio communication failure in manned aviation. In that case, if the airfield is not controlled, safety is ensured by see-and-avoid and right-of-way rules. Conversely, if the airfield is controlled, we expect that the ATC would be aware of the situation and will prioritize the UA above other traffic and take opportune actions to ensure separations. In the case of the UAS, it is up to the regulator to decide whether this emergency is to be considered catastrophic or if an emergency landing is deemed appropriate. In fact, it seems reasonable that different considerations may exist, depending on the UAS equipment (and, notably, on the capabilities of the S&A system in autonomous flight), the type of airfield, the airspace class, the weather conditions, etc. Thus, the behavior of the UAS in such an emergency will be conveniently programmed and known beforehand.

In both cases the proposed solution is to abort the procedure in execution. For an emergency landing, integrate the arrival holding pattern at a safe altitude for a predetermined time (allowing for a potential datalink recovery), while transmitting special emergency messages over the radio communications channel and setting the transponder (if equipped) into a special distress code. For takeoff procedures, abort the transition to the navigating phase and also integrate the arrival holding pattern corresponding to that runway. Then after a given time-out it will perform the predefined landing pattern procedure, assuming that all necessary emergency clearances have been managed by the PiC. If a flight termination is preferred, a similar holding pattern would be executed over the predefined FTZ, and if command and control communications are not reestablished after a given time-out, a flight-termination procedure would be initiated. Note, however, that if an emergency landing procedure is preplanned as a reaction to a lost-link situation, the UA will perform a highly predictable operation that cannot be changed into a flight termination unless some alternative communication mechanism exists.

IV. UAS System Architecture and Experimental Results

The proposed concept of operation has been implemented within a UAS specific system architecture called USAL (UAS service abstraction layer). This architecture has been introduced as a flexible, reusable and distributed architecture to support the development of UAS civil operations. The reader is referred to [24,25] for a more detailed description. This section briefly describes the flight-related services within USAL, the simulation environment designed to test all USAL systems, and concepts of operation and finally the results derived from some experimental excises used to evaluate the concepts proposed in this work.

A. USAL Flight Services

The absence of UAS civil (and commercial) applications has driven the development of UAS highly dependent on the type of mission to be accomplished and on the flight scenario expected for that mission. At present, there is an increasing amount of different autopilot manufacturers providing solutions for UAS (see, for instance. the survey done in [26]). Thus, very specific and nonflexible systems exist nowadays to control the desired flight profile, the sensor activation/configuration, the data storage, etc. The goal of the USAL architecture is twofold. On one hand, USAL promotes the development of advanced concepts of operation by implementing specific functionalities as integral part of the architecture. Relevant examples are the definition of enhanced flight plans [27,28], including contingency management, autopilot management, a mission control engine, support for payload management and data storage, etc. On the other hand, USAL provides flexibility for the development of additional systems required to implement the actual UAS mission, while reducing the development effort when creating a new UAS system. The USAL is designed as a set of *services* and their interrelations running on top of a communication mechanism, as a basic starting point for further development by users. Available USAL services have been classified into the following categories:

1) Flight services are responsible for basic UAS flight operations: autopilot, flight-plan management, basic monitoring, contingency management, etc.

2) Awareness services are responsible for the safe operation of the UAS related to terrain avoidance and integration with other airspace users.

3) Mission services are responsible for carrying out the actual UAS mission.

4) Payload services specialize in interfacing with the input/output capabilities provided by the payload onboard the UAS.

Both the flight and awareness services are directly related to the objectives of this work. Figure 10 depicts the fundamental components in both sets of services and the major relationships among them. The virtual autopilot system (VAS) manages the interaction

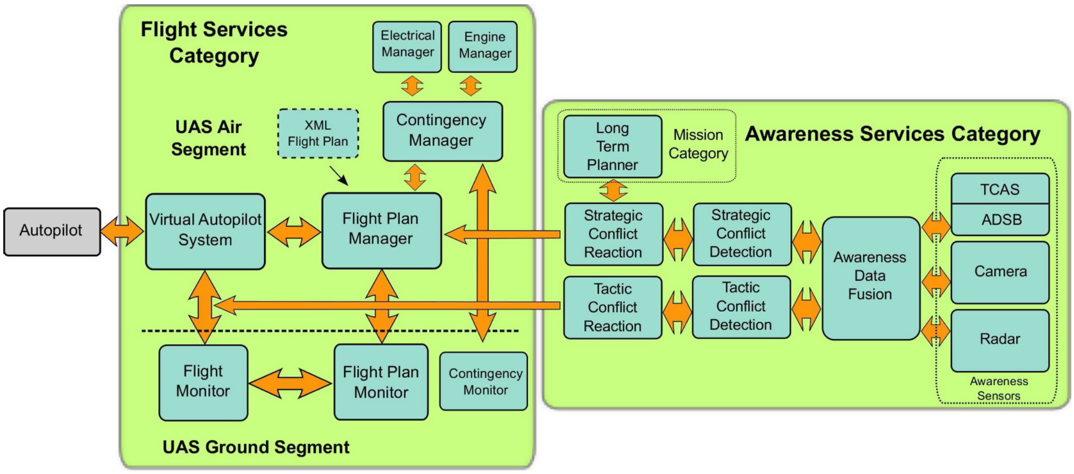

Fig. 10 Overview of the flight and awareness services within the USAL.

with the selected autopilot and abstracts its peculiarities providing a uniform view [25]. The VAS offers a number of information flows to be exploited by the USAL, but at the same time retains a number of critical flight aspects such as those related to manual flight and automated takeoff/landing operations. Alongside the VAS, we have developed a flight-plan manager (FPMa) that implements much richer flight-plan capabilities on top of the available capabilities offered by the actual autopilot [27]. The FPMa offers an almost unlimited number of waypoints, waypoint grouping, structured flight-plan phases with built-in emergency alternatives, mission-oriented legs with high-level semantics such as repetitions, parameterized scans, and, in particular, the set of properties/parameters needed to perform takeoff and landing operations following the proposed concept of operation.

Within the USAL architecture all the PiC human–machine interfaces (HMIs) have been divided in two coordinated interfaces: a classical pilotlike interface and a flight-plan-oriented interface. Generally speaking, current UAS autopilots offer manual and/or assisted piloting plus basic waypoint navigation support. The design of the USAL HMIs maintains such manual piloting and waypoint navigation capabilities through the VAS, and provides them to the ground through the flight-plan monitor (FPMo) service; e.g., manual piloting, basic flight monitoring, contingency management, navigation support including heading-based and waypoint-based, and takeoff and landing support.

The 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. As previously mentioned, the FPMa executes a mission-oriented flight plan designed to implement high-level operation structures and to allow dynamic flight updates decided by the onboard mission systems of by the PiC through the offered HMIs. When the UAS develops a complex mission using the USAL, the flight plan itself will contain all the required landing and takeoff parameters necessary to implement the proposed concept of operation. At each stage of the flight, the FPM will notify the VAS and the FPMo, which should be the actual usage of those parameters. This flexibility is necessary because the actual landing site may change according to the actual mission development or due to the existence of potential in-flight emergencies. 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 sent later to the VAS/FPMo for their implementation by the PiC.

Flight services in USAL also incorporate a service that it is in charge of managing potential contingency situations. This component is called the contingency manager and is responsible for collecting status information related to multiple sources as autopilot, engine, electrical, fuel, communications, etc.; identifying potential contingency situations; and determining the most appropriate reaction from a preplanned set of reactions [29].

B. Experimental Simulation Environment

A simulation environment was set up to test the proposed operational concepts while using the modular UAS architecture presented above. Figure 11 shows the different components created around the main USAL flight services. Only the relevant flight services within the USAL architecture are shown in the figure: the VAS and the FPMa and their equivalent HMIs. In the architecture proposed above the autotakeoff will be performed by the VAS, and once at the EDWP, the FPMa takes care of the navigation that follows. On the other hand, once the UA has integrated the arrival holding pattern, the control of the aircraft will transition from the FPMa to the VAS before starting the approach procedure.

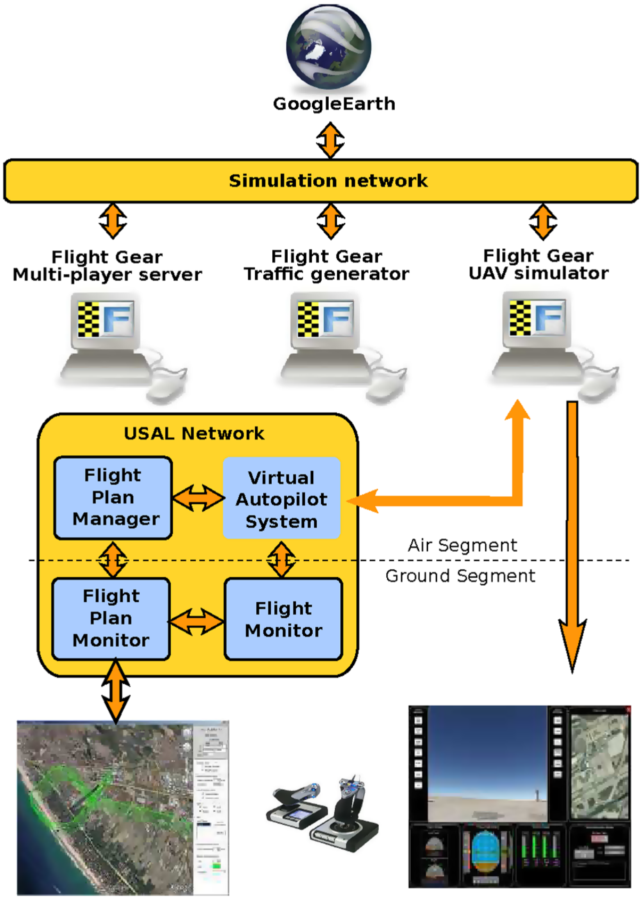

Fig. 11 Schematic representation of the simulation environment.

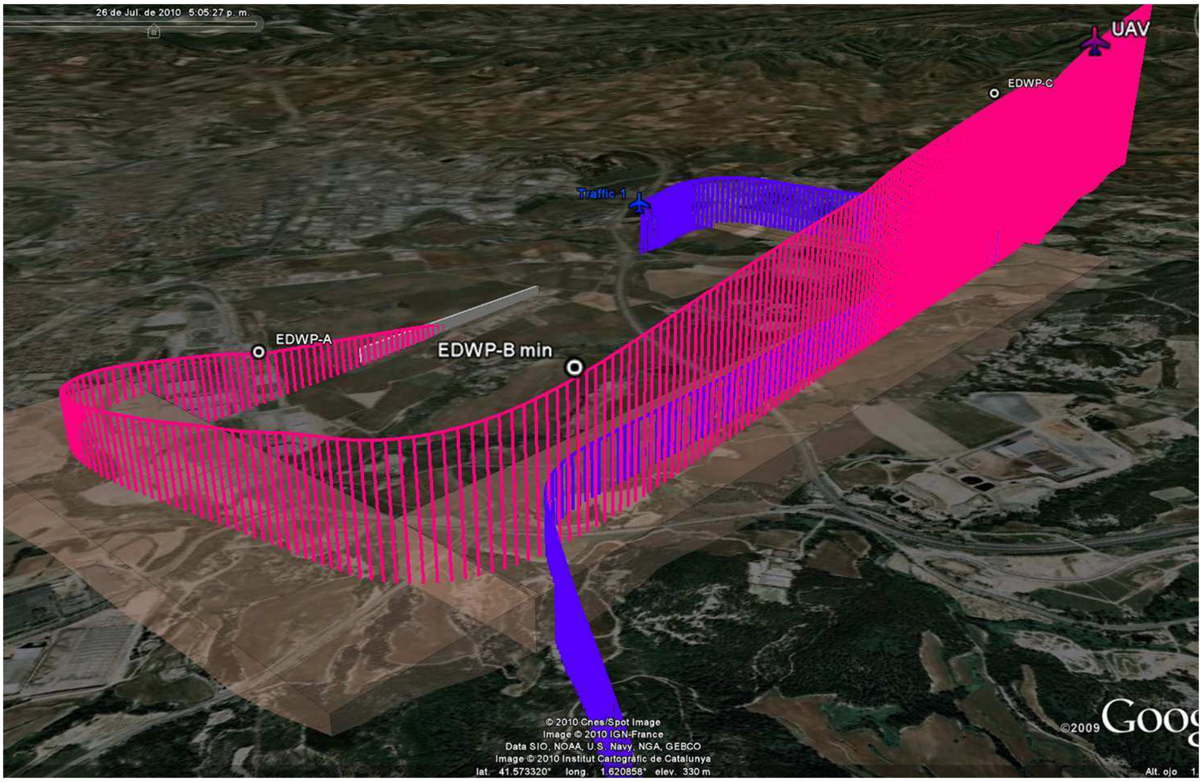

Fig. 12 Example screenshot for the simulation of takeoff operations.

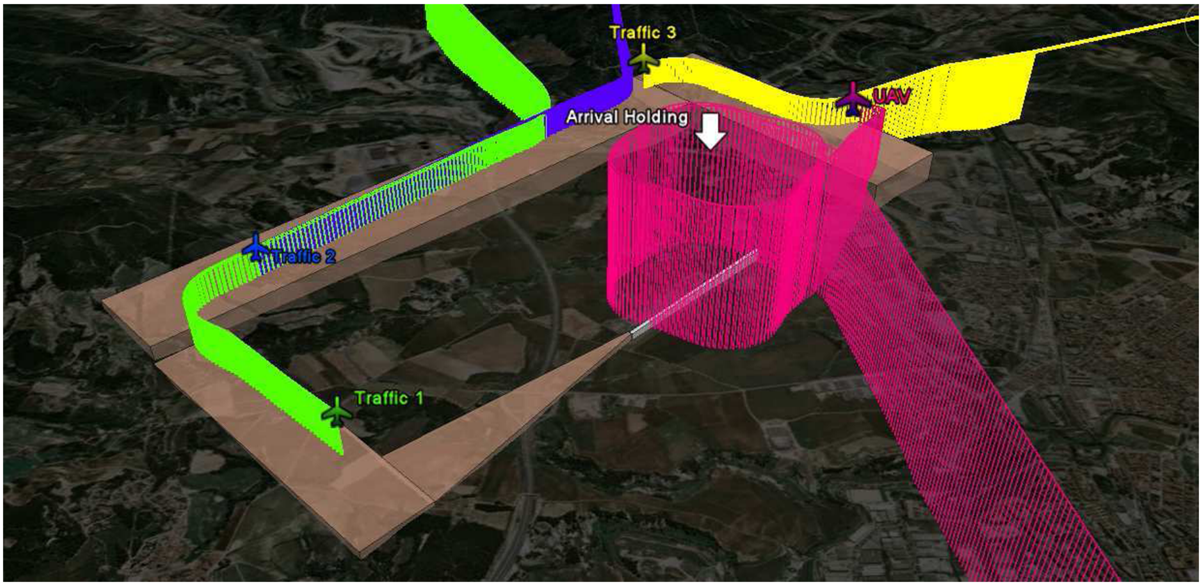

Fig. 13 Example screenshot for the simulation of arrival operations.

To provide a realistic real-time simulation scenario, the dynamics of a UAS platform were simulated using the FlightGear flight simulator software,[‡‡] and therefore a VAS service has been implemented to interface with its build-in autopilot. This flight simulator was also used to produce a synthetic pilot view that was used in the flight monitor HMI pilot display. Airfield departure and approach operations were simulated in an hypothetical scenario with the presence of surrounding traffic. In this preliminary simulation, the other aircraft were generated by an independent computer and followed specific preprogrammed flight trajectories.

The flight intentions for these emulated traffics were not known beforehand by the PiC of the UAS, which had to deal with them according to the procedures and tools presented in the previous section. The remaining components of this simulation environment support the multivehicle scenario environment and a Google Earth visualization and tracking tool, allowing us to store and reproduce the trajectories of all involved aircraft.

C. Experimental Results

A number of simulations were performed in order to validate the proposed concept of operation. All specific maneuvers were fully automated and initial HMIs were offered to the PiC. Various

[‡‡]See http://www.flightgear.org.

Fig. 14 Example screenshot for the simulation of extended downwind operations.

scenarios were tested, from the UAS operating standalone within nominal parameters to scenarios with a limited number of conflicting traffic so that the deconflicting operations have been commanded from the PiC in order to guarantee separation.

Figure 12 shows a screenshot during a takeoff in which EDWP-C was selected by the PiC (see Fig. 3). As seen in the figure, with this procedure the altitude of the UA when overflying the downwind leg is higher than the airfield traffic pattern altitude, thus reducing possible conflicts with other traffic. Moreover, the fact that the UA is overlaying the downwind leg until EDWP-C is reached improves the situational awareness of the other users. An arrival procedure is shown in Fig. 13, where it can be seen how the UAS integrates to the arrival holding defined over the runway, while other traffic integrates the downwind leg of the traffic pattern. When the PiC judges that it is safe to continue with the approach, the UA leaves the holding and integrates to the downwind leg after the preceding aircraft. Finally, Fig. 14 shows a case in which the PiC decides to extend the downwind leg in order to increase the safety distance with the preceding traffic.

V. Conclusions

Unmanned aircraft systems (UAS) have great potential to be used in a wide variety of civil applications. The development of flight control systems coupled with the availability of other commercial off-the-shelf components is enabling the introduction of UAS into the civil market. However, much work remains to be done to deliver systems that can be safely integrated to standard aeronautical procedures used by manned aviation. In this paper we have discussed the integration of civil UAS operations in departure and approach operations. Manned flights under visual flight rules (VFR) rely on the pilot's ability to see and avoid terrain and other surrounding traffic. Even if VFR environments exist from the very beginning of aviation, and have therefore been proved safe, they present a big challenge for the integration of UAS operations, due to their lack of predictability, precision, and repeatability. On the other hand, the high levels of automation in UAS make it possible to easily execute flights under instrumental flight rules (IFR) with the ability to achieve high degrees of transparency with the air traffic control services and the other airspace users. Not all the airports offer IFR procedures, however. Thence, this paper proposes some standardized operations for UAS evolving in such VFR environments.

All of these operations are based on the standard airfield traffic pattern, which is a widely used procedure in VFR operations. Regarding departure procedures it is proposed to predefine some initial standardized waypoints around the airport before starting the navigation phase. Conversely, approach operations are supposed to always start with a holding pattern before joining the traffic pattern. All of these procedures do not significantly differ from current manned VFR operations in noncontrolled airfields. However, manned operations do not always systematically follow these default paths. This is mainly due to the high flexibility inherent in all VFR flights and to the ability to override some legs in the presence of ATS or when the pilot considers it is a safe decision. Conversely, we believe that if the UA is always systematically executing the same set of procedures, the situational awareness will notably increase, and in short, we will be adding a significant procedural safe layer on top of all the separation and collision-avoidance mechanisms. Moreover, they are conceived in such a way that the UA will interfere as little as possible with other aircraft, while providing high levels of predictability in the trajectories and decreasing the workload of the UAS flight crew. We believe that these procedures would be useful in all VFR operations, either in controlled or in noncontrolled airfields. They are also generic enough to serve as baseline procedures, which can always be modified and adapted to specific scenarios and according to particular UAS equipment.

Moreover, we have considered that the UA has flight performances that are similar to those of the other aircraft flying in the same airport. It is clear that for UA flying significantly slower than the other aircraft, separate airfield traffic patterns may be considered (such as is done nowadays in airfields with low-performance ultralight aircraft or gliders). Finally, it is worthwhile mentioning that the example simulations given in this paper are preliminary results for the proof of these concepts. Work is underway in setting up a new simulation environment with several human pilots on flight simulators sharing the same scenario, along with the UAS. Therefore, the proposed procedures will be tested against different situations, ranging from nominal operations to different emergency situations, along with unexpected behaviors from other traffic. Finally, and in the near future, some test flights with a real UA platform are also foreseen.

Acknowledgments

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