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TÍTOL DEL TFC: Design of take-off and landing operational procedures for unmanned aerial vehicles

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

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Resumen

Un vehículo aéreo no tripulado (UAV por sus siglas en inglés), es un vehículo aéreo sin piloto. Esto es, un avión operado sin la posibilidad de intervención humana directa desde dentro o sobre el avión. Con la evolución tecnológica de los sistemas aviónicos, los UAVs se han convertido en una opción válida para llevar a cabo misiones civiles. Sin embargo, todavía existe una división entre aeronaves tripuladas y no tripuladas que está frenando esta evolución.

El grupo ICARUS está llevando a cabo el desarrollo de una capa de abstracción de servicios para estos vehículos (USAL por sus siglas en inglés), cuyo principal objetivo es minimizar costes y proveer al usuario de una capa de software estandarizada gracias a la cual el usuario podrá desarrollar sus aplicaciones sin importar la arquitectura del piloto automático embarcado. El estudio desarrollado en este trabajo de fin de carrera se enmarca dentro de la investigación que lleva a cabo el grupo ICARUS.

El objetivo de este trabajo es diseñar unos procedimientos de despegue y aterrizaje para UAVs que permitan a estas aeronaves desarrollar su cometido compartiendo espacio aéreo con el resto de tráfico aéreo. Esta definición debe tener en cuenta las diferentes reglas de vuelo así como la existencia o no de servicios de control de tráfico aéreo. Además, se establecen las bases para el futuro desarrollo de la interfaz hombre-máquina (HMI) para los procedimientos estudiados.

Se comienza estudiando los procedimientos que siguen las aeronaves tripuladas en los casos a estudiar y el citado USAL. Con esta información se desarrollan conceptualmente las operaciones para UAVs. Siempre intentando molestar lo mínimo posible al resto del tráfico. Mejorando estos procedimientos a la hora de diseñarlos para UAVs donde ha sido posible y siendo conservadores donde no lo era.

Una vez los procedimientos con sus parámetros y dependencias han sido desarrollados, se han establecido las líneas generales para el desarrollo del segmento de tierra del sistema tanto a nivel de pantallas como de interacción entre las partes involucradas.

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Overview

An Unmanned Aerial System (UAV) is an aerial vehicle with no onboard pilot, that is, an aircraft operated without the possibility of direct human intervention from, within or on the aircraft. With the avionics technological evolution, UAVs become a valid option to perform civil missions. But there still exist a division between the manned and unmanned aerial vehicles that is making this evolution a non trivial issue.

Group ICARUS is carrying out the development of an UAV Services Abstraction Layer (USAL), which main objective is to lower the economical costs and provide a standardized software layer so as to not depend on the on-board autopilot's architecture. The work carried out in this final degree project takes place within the framework research that ICARUS group is performing.

The aim of this work is to design such take-off and landing procedures for UAVs that could able these airframes to develop properly within manned traffic airspace. This definition should take into account the different flight rules and the existence or not of air traffic control services. In addition, the guidelines for the further development of the Human Machine Interface for these procedures are expected.

First, a study about the state of the art of the manned airspace and the system which occupies us is done. With the information provided we have developed the concept of operations for these procedures, always trying to bother as less as possible the other traffic. Improving where possible and being conservative where not.

Once the procedures with its parameters and dependencies have been set, the guidelines for the developing of the ground segment screens and interaction between the involved parts of the whole system has been established.

GLOSSARY

AAL	Above Aerodrome Level
AFIS	Aerodrome Flight Information Service
AGL	Above Ground Level
AIP	Aeronautical Information Publication
ATC	Air Traffic Control
CCW	Counterclockwise
CONOPS	Concept of Operations
CW	Clockwise
EDW	End Departure Waypoint
FPMS	Flight Plan Management Service
HMI	Human-Machine Interface
IAC	Instrument Approach Chart
IAF	Initial Approach Fix
ICARUS	Intelligent Communications and Avionics for Robust UAVs
IFR	Instrumental Flight Rules
LD	Lateral Deviation
NAVAIDS	Navigational Aid System
PiC	Pilot in Command
RVR	Runway Visual Range
RWY	Runway
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TDF	Touchdown Fix
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
ULM	Ultra Light Models
USAL	UAV Services Abstraction Layer
VAS	Virtual Autopilot Service
VFR	Visual Flight Rules
VLA	Very Light Aircraft
VMC	Visual Meteorological Conditions
WP	Waypoint

SUMMARY

INTRODUCTION

An Unmanned Aerial Vehicle (UAV) is an expression that identifies an aircraft that can fly without pilot. That is, an airframe and a computer system which combines sensors, navigation systems, servos and computer units. All these elements have to pilot the plane with no human intervention. Although there are several kinds of UAVs, this work is related to fixed wing and heavier than air ones.

At the beginning of this technology, it was limited to military objectives. However UAVs are increasingly gaining presence in our daily life because of their potential. UAV systems could be used to perform environmental applications, help in emergency situations, perform monitoring and surveillance operations, act as communication relays and even more. This explosive growth is explained with the fact that these platforms significantly reduce time and human costs, which is traduced into less monetary costs. [1]

With the advent of UAV's civil applications, UAVs are emerging as a valid option in commercial scenarios. But strong division remains stopping this evolution, and it is the fact that unmanned aerial vehicles are not prepared to behave as manned ones in the same airspace. This work addresses one of the issues that will arise if extensive civil UAV application became a reality in a near future, imagining a scenario where manned aircraft will coexist with unmanned vehicles. In particular, the integration of UAV in the depart, arrival and approach phases is assessed, taking into account all possible situations ranging from busy and controlled airspaces to remote and uncontrolled aerodromes.

This document works on developing a concrete part of the UAV Services Abstraction Layer (USAL) which is being developed by the group ICARUS. In fact, this document is expected to lay the basis of the take-off and landing procedures as well as the way of interaction between the pilot in command (PiC) and the UAV.

In order to design such procedures that UAVs could coexist with manned aircrafts, the regulations that apply to the last need to be known. Nowadays, in civil aviation, a set of procedures and standardized practices are followed in order to operate safely, efficiently 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 [ref pans-ops] 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.

Summarizing, the objective of this document is the design of standard arrival, approach and departure procedures to apply for each UAV in each aerodrome taking into account the other traffic, the air traffic control (ATC) services and the rules of the air which applies on the procedure. Additionally, guidelines for the design of the human-machine interface (HMI) for those procedures are provided.

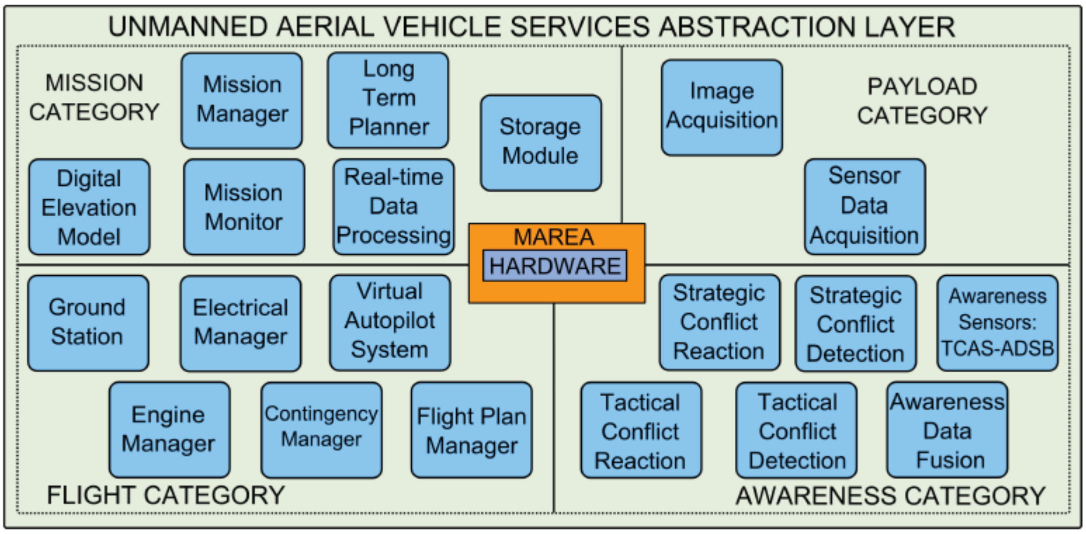
The organization of this document is as follows: Chapter 1 presents the ICARUS project going in depth with the concepts that could facilitate the understanding of the following chapters. In Chapter 2, a briefly study of the state of the art of VFR and IFR in both controlled and non-controlled aerodromes is done so as to develop procedures according to the current normative. Chapter 3 details the development of these procedures for UAVs, the computations made for this development could be found in Appendix 1. Once the development of the procedures is done and we could state what information and what level of interaction between PiC and the UAV is expected, in Chapter 4 we have stated the guidelines for the developing of the HMI that covers the screens and the flux of data between the parts involved. Finally, the conclusion summarizes and justifies the way in which the work has been developed.

1. SYSTEM OVERVIEW

In this chapter some background of the UAS system that is being developed for ICARUS group is given. The work proposed in this project will be integrated into the UAV Services Abstraction Layer (USAL) [2]. ICARUS group has proposed this Unmanned Aerial System (UAS) architecture with aim of having a platform which could be able to implement a variety of missions with little reconfiguration time and overhead.

1.1. Introduction

This service architecture is managed with a middleware in order to implement a distributed embedded systems. The UAS is composed of set of distributed elements, known as services, which operate at the same level on top of a middleware communication framework. In order to organize the USAL Services, they are divided in four groups [3] as could be seen in Fig 1.1



1.1 Overview of the USAL service-based architecture

Services are presented in a same group when they cooperate in the same main objective, such flight or mission or payload or awareness. We are going to focus on flight and awareness services (see Fig 1.1) which are in charge of the UAS flight operations and the safe operation of the UAV related to terrain avoidance and integration with shared airspace respectively.

1.1.1. Flight Services

The key parts of the flight services are the Flight Plan Manager Service (FPMS) and the Virtual Autopilot Service (VAS). The electrical, Engine and Contingency managers are auxiliary services whose task consists of monitoring engine and electrical parameters and, with this information, decide the reaction if some contingency is taking place.

The FPMS is in charge of processing the flight plan. Once the FPMS has received the current mission flight plan, it generates the necessary waypoints (WPs) so that the UAV performs the mission as expected. The FPMS works together with the VAS in order to direct the flight of the UAV. The VAS receives WPs continuously from the FPMS and computes the heading that leads to the current destination WP. Therefore, FPMS is a kind of translator that receives flight plan information [4] and sends WPs to the VAS which is the only information it can process. The FPMS also monitors the flight evolution indicating the current position within the flight plan and the destination WP to which the UAV is flying to.

Apart of the FPMS and the other auxiliary services, there is the VAS, which main duty is to act as an abstraction layer between the on-board autopilot and the WPs generated by the FPMS. As is the most important for our work it has been described in deep in the Section 1.2

1.1.2. Awareness Service Category

An UAV System is a highly instrumented aircraft and has no pilot on board. With these conditionings UAVs must rely on its instrumentation equipment to properly inform the PiC on the ground or substitute the pilot capacities. The awareness services are responsible of such functionalities. As commented above, Flight Services are in charge of the aircraft management in normal conditions while the Awareness Services are in charge of monitoring surrounding conditions and overtake aircraft management in critical conditions. In this case mission services com to a second priority, until flight conditions become again normal. These services are: the ‘awareness data fusion’, the ‘conflict detection’, the ‘tactical reaction’, and the ‘strategic reaction’ services.

Here we are going to comment those which we are interested on: the conflict detection and the tactical reaction services, for more info about the system, see [3].

The conflict detection service studies what is happening around the UAS and generates alert when detect something that could be dangerous. Furthermore, this service is in charge of classify how danger is the conflict detected. First, the conflict detection evaluates the hazard, and then the service decides if the conflict needs a tactical or strategic reaction in order to solve it.

The tactical reaction service generates reactions in case of a quick response is need. This reaction will have the maximum priority level in the whole system. This service will take virtual autopilot system control, and it will manage the UAS flight canceling the flight plan manager commands and solving the tactical conflict.

1.2. Virtual Autopilot Service (VAS)

Now that the USAL have been shown, we are going to describe more accurately one of the most important services for the whole system and the most relevant for the work presented in this document, the Virtual Autopilot Service (VAS).

First, this section will explain the VAS Functional Overview, then it will make comprehensive study of the concepts that we use in the following chapters.

1.2.1. VAS Functional Overview

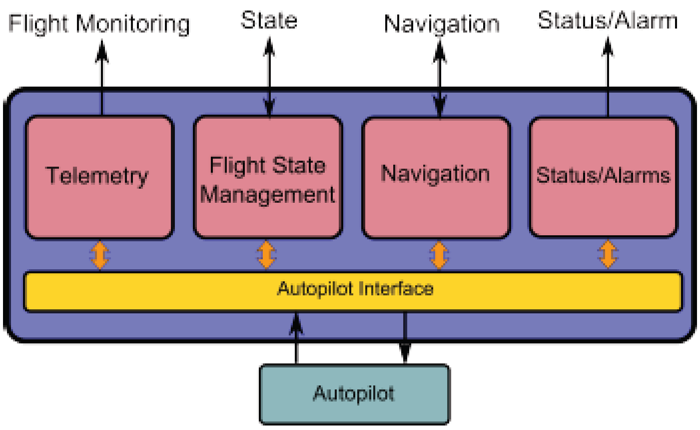
The Virtual Autopilot Service is the component that interacts between the autopilot and the rest of the components of the USAL. After studying several UAS autopilots, ICARUS group [4] saw that although their functioning and capabilities were very similar, their implementation details greatly differ. An improvement of the UAS flexibility was needed.

The VAS actuates in a UAV as drivers do on operating systems, abstracting away the implementation details from actual autopilot users. In fact, it is the only service with access to the on-board autopilot; it isolates the on-board autopilot from the rest of the system and works as the link between them. With this implementation, the UAS becomes independent of the autopilot and the changes to adapt another autopilot solution are restricted to the VAS.

The key to carry out a correct abstraction is to offer in the VAS interface the common functionality and data that can be found in any autopilot. This information will be organized in the following four groups:

- flight monitoring information (also referred to as telemetry),
- navigation information,
- status/alarm information, and
- flight state management.

The first group relates to the need of the autopilot to acquire and process attitude and position data. The second one is needed to determine the path that the aircraft will follow. The third, gives information about its current status and possible alarms. Finally, the last one is added to the VAS design to provide an increased level of functionality. This last group will change the autopilot states when necessary. Fig. 1.2 shows the different parts of the VAS service. As displayed in the figure, monitoring and status/alarms information are outgoing flows, while navigation and state management states have both input and output directions.



1.2 VAS Architecture

1.2.1.1. Flight Monitoring Services

There are several ways to expose the information generated by autopilot sensors. Usually, the autopilot manufacturer groups all this information in large packets of data, which are sent via radio modem at a certain frequency. In this service-based architecture, the VAS will offer this information over a LAN to all services that need this information. Information will be semantically grouped in a way that this information relates to parameters, situations or attitudes of the aircraft, independently of the real autopilot hardware and sensors [4].

1.2.1.2. Navigation Services

As mentioned in Section 1.1 the Flight Plan Manager System is in charge of generating the navigation commands to the VAS. In most cases these commands will take the form of waypoints or requests for changing the autopilot state. There are (as shown at Fig. 1.2 two types of Navigation Services, Output Navigation Services and Input Navigation Services.

The 'Output Navigation Services' basically says where the UAV is going to at any moment, in which direction is moving, which waypoint is flying and indicates the actual state of the VAS. State is reported each time the VAS switches from one state to another; and each time a state change is requested but cannot be fulfilled. On the other hand, 'Input Navigation Services' basically tells the VAS configuration parameters for the autopilot operation, as well as, and this is the most important for us in this work, parameters to configure the operative parameters of the states in which the VAS may operate.

1.2.1.3. VAS and Autopilot Status/Alarms

As being the interface between the autopilot and the rest of the system, the VAS is in charge of inform the status of the autopilot and its own status. An autopilot is a complex hardware that needs to be monitored every time. With this group of packets we can monitor the autopilot and the VAS status; when any part of these devices has a failure the VAS will send an alarm to the network as events for two reasons. First, because the alarms are very important for the system and it is needed that these notifications safely arrive to all the services that process them. Second, we will only need to know the status when something is wrong. They are not periodical information like the telemetry flows.

1.2.1.4. VAS Operational States and Parameters

As mentioned above, this is the point we are going to study more thoroughly. The aim of these states is to increase the VAS autopilot functionalities and give the same services without depending on the on-board autopilot (taking into account that not all autopilot are equal). So these mission states have been developed focusing on the mission instead of the UAS flight. In addition, we have to mention that if an autopilot does not have some state, this layer will simulate them for the autopilot so that the rest of the system could interact always with the same interface.

In this section, we are going to present first all these operational states to then focus in which we are more interested.

As can be seen in Fig. 1.3, the first states are the ‘**Start-up**’. These states take part at ground. It is UAS duty to carry out these states by itself. While in these states, all the systems and services needed to accomplish the mission are configured and checked to start the mission in optimal conditions.

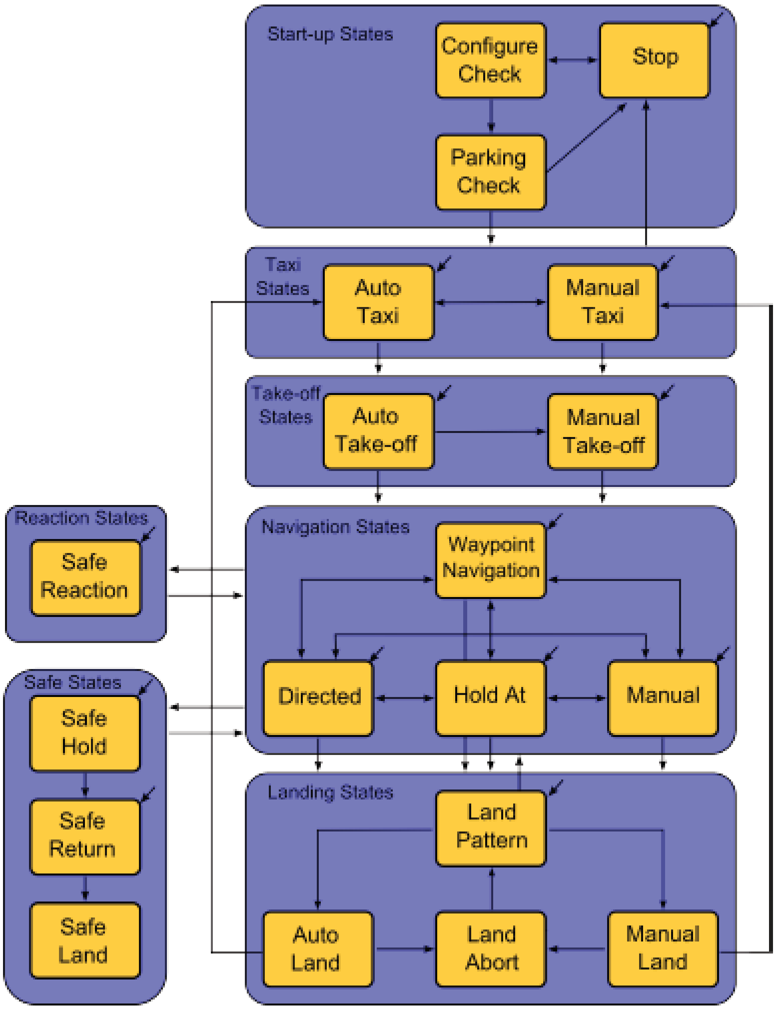
Once the UAS is configured and checked it is the time to select and go from the parking to a good runway to start the mission. These states are called as ‘**Taxi**’ and could be done both automatically and manually[1].

The mission starts with the ‘**Take off**’ states and they are the responsible for carry the UAV to a secure altitude where change to the ‘**Navigation**’ states. Take off states can be developed both manually or automatically[9]

The ‘**Navigation**’ states are where the mission should be developed, so they are thought in order to follow the waypoints that are feed to the VAS; go ‘direct’ maintaining bearing, airspeed and altitude; do a hold around a previously updated waypoint; and finally control manually the UAS.

As shown in Fig.1.3 if any failure occurs during the navigation states, the VAS can switch to the safe states [3]

[1] In all states that can be done both manually or automatically. If the UAS starts automatically and any contingency happens, the operator can take the UAS control to solve the problem.



1.3 VAS Operational States and Transitions

Finally, the UAS must prepare the land procedures. In order to carry out this task, the UAS switches to '**Landing**' states. First, an approximation pattern is done in order to prepare the landing. After this state as in the previous cases, the PiC can choose auto landing or manual landing. In both cases, the UAS can switch to the land abort state. In case of abort, the UAS climbs up to a secure altitude and goes back to land pattern state so as to try again. If the landing has been achieved successfully, the UAS will be braking on the runway. When the UAS speed is on range in order to go by the ground the UAS will switch to the parking state again and will arrive to the parking to finish the mission.

1.2.1.5. Take off and Landing

Once we have presented the VAS operational states and transitions, we are going to present the guidelines of that we have tried to improve: take-off and landing states. These guidelines are developed in the Chapter 3'CONOPS'. The aim of all the ideas is to decrease the workload of the pilot in command.

1.2.1.5.1. ‘Take-off’ states

Before this work, the take-off was thought as the state which carries the UAS up to a certain (safe) height. Our point of view is that we must define several end departure waypoints which allow the mission designer to start his designs from a finite number of waypoints, defined for different departure areas (see Section 3.3). These end departure waypoints are thought to depend on the traffic pattern so the safety is guaranteed.

Additionally, we propose a third state: ‘Take off abort’, which will allow the UAS to automatically switch to the ‘auto land’ and will carry the UAS to the beginning of this state with a safe maneuver, taking into account the possible traffic.

1.2.1.5.2. ‘Land’ states

Something similar occurs with the ‘Land’ mode which, as default, ends with the UAV stopped[2] at the runway but could be aborted at anytime by the PiC or at some critical points where the VAS has the capability of deciding to pass to ‘land abort’ mode. The ‘Land’ mode also takes into account the chance of being extended so as to not bother other aircrafts. Landing states are still being the same stated above: land pattern, land abort, auto land and manual land.

The ‘land pattern’ state we present in the Chapter 3 is thought in such a way that the UAV does not bother other traffic approaching to the same runway.

We have also thought in the chance of having clearance to join the traffic pattern (‘auto land’ state) in some advanced leg avoiding then the land pattern state. All possible traffic patterns are covered within this work.

And as the last of the autonomous states we have the ‘land abort’ state, maybe the more interesting because of its hinge function between the rest of landing and navigation states. This mode will have a different behavior depending on which was the previous state and, within each state, it will have different behavior depending in the procedure being carried out while the ‘land abort’ state is activated.

Finally, within landing states we find also the manual landing state as the last resort.

[2] When the UAV speed is low enough, the VAS will switch to the Taxi state again and will continue to the hangar to finish the mission.

2. STATE OF THE ART

2.1. Introduction

In order to know how the operation of aircraft is done nowadays, this chapter reviews the state of the art of the principal regulations for visual and instrumental flights for take-off and landing procedures.

We have split this chapter in four sections in accordance with the case study that we are proposing in this work. These cases come from the difference between the rules of flight: Visual Flight Rules (VFR) and Instrument Flight Rules (IFR); and depending on the existence or not of Air Traffic Control (ATC) at the airfield. And a fifth section where we study the chances of change between flight rules before joining the approach procedure.

All the information provided in this chapter is extracted from different Aeronautical Information Publications (AIP). Namely, they are the French AIP [5][6], the US AIP [7], the New Zealand AIP [8][9], the and the Australian AIP [10],

2.2. VFR operations in non-controlled aerodromes

We call non controlled aerodromes those on which neither air traffic services nor information and alerting services are ensured for aerodrome traffic.

These kinds of airfields are nowadays operated in a regional basis. In addition they usually have short runways so they are not prepared to receive large range aircrafts. Because of that, it is the scenario where more discrepancies could be found between the legislation of different countries.

For example, while in New Zealand's AIP we could read that Pilots in uncontrolled airspace may carry out a visual approach provided the pilot can maintain visual reference to the terrain.[3] In the French AIP we see that in a Non-Controlled airfield IFR operations are also considered.

On the other hand in New Zealand, for night visual approaches, it is essential that the pilot has the runway in sight. Sighting only of the aerodrome beacon, Runway End Identification Light (REIL) or approach lights is insufficient.

2.2.1. Terminology

This is the terminology adopted as standard and has been extracted from [2]:

Upwind leg. A flight path parallel to the landing runway in the direction of landing.

[3] See [8] ENR 1.5 pag 35 2.24

Crosswind leg. A flight path at right angles to the landing runway. or its takeoff end.

Base leg. A flight path at right angles to the landing runway or its approach end and extending from the downwind leg to the intersection of the extended runway centerline.

Final approach. A flight path in the direction of landing along the extended runway.

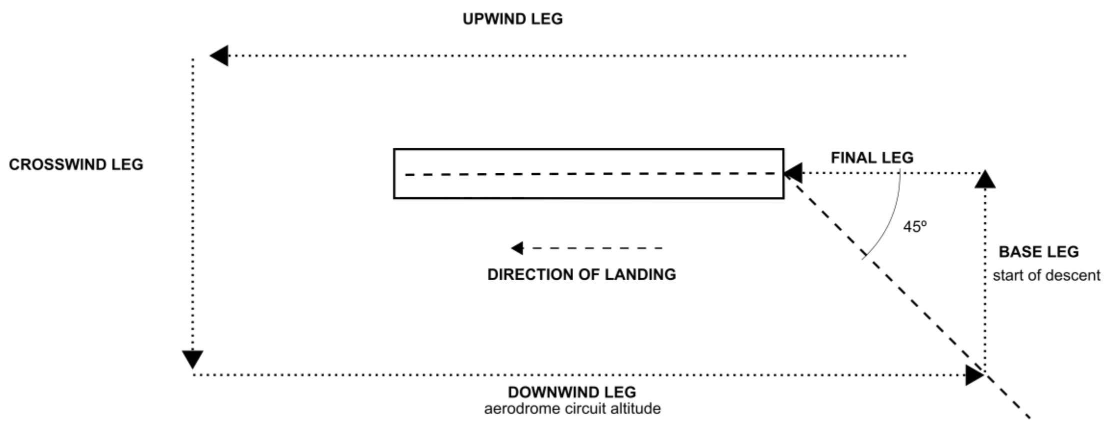


Fig. 2.1 Components of a Traffic Pattern

2.2.2. Different circuits

On an aerodrome, different traffic circuits on the ground and aerodrome circuits specific to planes, gliders, ULM, helicopters can be established. Any aircraft using an aerodrome must comply with the aerodrome and ground traffic circuit according to the type of aircraft used (airplane, glider, ULM, helicopter, etc.) when they are defined. The existence of these different circuits is often related to the different, and significant, performances that can exist from one type of aircraft to another.

2.2.3. Typical circuit pattern

As a general rule aerodrome circuit dimensions are not strictly defined. It is the captain's duty to fly his aircraft within its maneuvering limits according to circumstances so as not to bother other aerodrome traffic or traffic in the vicinity. Even if there does not exist any specific regulation concerning the circuit shape and dimensions, a more or less standardized aerodrome traffic pattern is accepted internationally with the following characteristics (see figure 1.1):

- Fly the downwind leg at 300 meters (1000 ft) AAL. Being out of clouds; pilots under training may use a different height provided that they do not bother other aerodrome users;
- Make left hand turns;
- The base leg is generally one minute length at the approach speed
- Extension of the downwind
    - The base leg starts when the extended runway centerline forms a 45 degree angle with the line joining the aircraft and the landing runway threshold.[ref]
    - The downwind to final turn should be completed at least ¼ mile away from the runway threshold [2].
- When going around (in a missed approach maneuver), not to make any maneuvers which could bother other circuit traffic.

However for noise abatement reasons, obstacle clearance or air traffic management purposes, some remarks may apply in a specific aerodrome and it is possible to ask the pilot to:

- Avoid overflying certain noise sensitive areas; and/or
- 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.

2.2.4. Circuit joining procedures

Circuits must be joined in accordance with traffic already in the said circuit but also in accordance with traffic which may be in the other aerodrome circuits.

On a non controlled aerodrome an aircraft in the aerodrome traffic which is aware of an inbound IFR flight must, unless 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 order to accomplish these guidelines in a safe way, the pilot must inspect the possible traffic already doing the circuit pattern before joining it. To do so, an initial and circular holding pattern is done at the vertical of the signaling area[4]. This holding is done with left hand turns so the pilot could see better the ground[5]. Once the PiC considers that it is safe to land and join the traffic, he leaves the hold directing the aircraft to the downwind leg.

This joining maneuver is done maintaining the hold altitude until passing through the extended runway centerline so as to not bother possible departure

[4] In the signaling area there is a wind sock that provides visual information about the direction and strength of the wind. There is also a designated space where different visual signals can be placed in order to warn the pilots that possible restrictions may apply at the aerodrome.
[5] The pilot sits at the left, so if he does left hand turns, he could see what is happening below his vehicle.

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.

It is also 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 giving them the right of way if the pilot in command estimates[6] that this maneuver is safe and is not bothering other aircraft already in the circuit. (See Section 2.2.4).

2.2.4.1. Non powered aerodyne

In the case of a non powered aerodyne, on arrival, if the captain cannot fly in such a way as to adhere the previous dispositions, he must make a glide landing taking into account the parameters of the aerodyne and other aircrafts which are already in the aerodrome traffic.

2.2.5. Take-off

First, the aircraft should arrive 500 ft and then it must go direct to navigation. In the case that the destiny were just in the opposite direction, the usual maneuver done is to join the traffic pattern, continue climbing and leave the circuit pattern at the end of the downwind leg.

2.2.6. Overtaking

An aircraft may only overtake another one in the aerodrome circuit provided that he does not bother or delay the landing of the aircraft which he has overtaken in addition to the other aircraft which may be in the different aerodrome circuits.

2.2.7. Separation due to wake turbulence[7]

In aerodromes without air traffic services, each pilot must fly in such a way as to avoid all incidents due to wake turbulence. Vortex visualization and avoidance procedures during VFR operations must be exercised by the pilot using the same degree for concern as in collision avoidance [7][5]

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[6] According to French AIP[5], "*A 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;*
- *If he already knows the wind direction and velocity and what signals are displayed on the signaling area and taxiways"*

[7] Wake turbulence is caused by a pair of counter rotating vortices from wing tips. The vortex from larger aircraft pose problems to encountering aircraft. For instance, the wake of these aircraft can impose rolling moments exceeding the roll control authority of the encountering aircraft. [7]

2.2.8. Auto-information

Auto-information reports must be transmitted by aircraft equipped with radio communications equipment whilst flying in aerodrome traffic when there is no air traffic services organism.

2.2.9. Taxiing

Unless otherwise instructed, an aircraft may not wait at either end of the runway in use or the turnaround areas, when another aircraft is landing on the runway in question. When there are no holding points or their markings are not visible, and unless otherwise stated in the aerodrome remarks for the use of the aerodrome, aircraft must wait at a distance from the edge of the runway at least equal to:

- 30 m for a paved RWY whose length is less than 1000 m or an unpaved RWY;
- 50 m for a paved RWY whose length is equal to or greater than 1000 m.

2.2.10. Dispositions relating to radio communications

2.2.10.1. Frequencies

When, on an aerodrome having a control tower or an AFIS organism these organisms are not on duty, the assigned frequency of these organisms must be used.

When there is no organism, the auto information frequency assigned to the aerodrome must be used. When the aerodrome does not have its own frequency the common frequency 123.500 MHz is to be used.

2.2.10.2. Procedures

The captain of an aircraft fitted with radio communications equipment must make reports on his position, state his intentions and transmit any subsequent changes to the AFIS organism or, in default, on auto information:

- On arrival:
  - Before joining the aerodrome traffic,
  - On downwind leg,
  - On base leg,
  - On final approach,
  - Clear of runway
  - On the ramp.

- On departure:
  - On the ramp before moving,

- At holding point(s) before going on to a runway,
- When lined up before taking off,
- When he leaves the aerodrome traffic.

2.3. VFR Controlled

2.3.1. Take off

See Section 2.2.5 ‘Take-off’

2.3.2. Taxiing

See section 2.2.9 ‘Taxiing’

2.3.3. Separation due to wake turbulence

The controllers will provide to VFR aircraft with whom they are in communication and which in the tower’s opinion may be adversely affected by wake turbulence from a larger aircraft. After issuing the caution for wake turbulence, the airport traffic controllers generally do not provide additional information to the following aircraft unless the airport traffic controllers know the following aircraft is overtaking the preceding aircraft [7]. However, whether or not a warning or information has been given, the pilot is expected to adjust aircraft operations a flight path as necessary to preclude serious wake encounters. Behind any doubt exists, pilots should ask the control tower for updates on separation distance and aircraft groundspeed.

2.3.4. Clearances

On a controlled aerodrome, any aircraft must be given clearance before:

- going on to or taxiing on the ramp;
- going on to the runway;
- taking off;
- joining aerodrome traffic;
- landing.

2.3.5. Disposition relating to radio communications

To join or fly in aerodrome traffic of a controlled aerodrome, an aircraft must be able at any given time to transmit and receive the necessary messages required by air traffic services.

The pilot in command must report his position on arrival before joining the aerodrome traffic, on departure before leaving the ramp and at any other typical position, on request of the control tower.

And finally, the captain must be aware of data transmitted to him by means of radiotelephony: on departure, before leaving the ramp; and on arrival, before joining aerodrome traffic.

2.4. IFR Non-Controlled

The responsibility of the pilots in command in the absence of APP service, the pilots in command must secure their separations with the other IFR traffic according themselves together and respecting specified procedure for missed approach, if necessary; and transmit their positions reports and say their intentions:

- Before beginning the approach;
- At each distinctive point of the IFR procedure.

2.4.1. Take-off

Take-off is only permitted if an aerodrome can be used as take-off alternate or if an instrumental approach procedure exists and can be executed at the aerodrome departure. The take-off minimum must be above the crew's landing minima. During nighttime take-off is only permitted with operating runway lights. Low visibility take-off operations (RVR < 400 m) are not permitted.[jeppesen y doc IAC]

2.4.2. Approach

The instrument approach procedure is only permitted if there exists a station designated to provide QNH[8] or an automatic data information system (STAP)[9], and the aerodrome is open for such operations, however in such a case Visual Maneuvering is mandatory.

The approaches procedures are compulsorily followed with visual maneuvering for which minima are possibly increased and published. By night, an operator agent should have to be at the aerodrome to carry out scheduled air public transport operations and should to get approval instructions from the suitable air traffic service enabling him to trig the safety plan of aerodrome and emergency phases if necessary.[6]

[8] Quasi-Non-Hydrostatic. It is a pressure setting used by pilots, ATC and low frequency weather beacons to refer to the barometric altimeter setting which will cause the altimeter to read altitude above mean sea level within a certain defined region.

[9] STAP transmits meteorological data required for landing and take-off when ATC is unavailable. It could be activated by the pilot.

2.4.3. Joining aerodrome pattern

As we could read in French AIP, on aerodrome not provided with a control tower (TWR) or AFIS and where instrument approach is authorized, only a circling is authorized with the aircraft joining the aerodrome circuit and complying with the rules applicable to VFR flights, If the aerodrome pattern does not meet the conditions laid down for a standard pattern (left hand turn and height 1000 ft), the needed information is provided in the 'observations' box of IAC.

2.5. IFR Controlled

In controlled airports where IFR procedures exist, different STARs are used and published in function of the aircraft category. Therefore, the UAV will follow the procedures that fit 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. With the future introduction of DataLink between the controllers and the aircraft [ref paper] the UAV can easily become fully autonomous. In the actual concept of operations, with voice communications, the pilot in command will interact with the ATC, who will not have to distinguish between manned and unmanned traffic, and transmit the orders to the UAV.

However, we have to mention that our study is based on the operations from where the ATC gives clearance for continue under VFR, so all the information needed is already commented in the previous sections.

2.6. Changes between flight rules

As it was mentioned previously, there exists the chance of change between flight rules before the approach procedure. In this section we briefly[10] expose these casuistic.

2.6.1. VFR to IFR

In the case of arrival to an aerodrome where the visibility is under the minimal for VFR operations [16], it is possible to change to IFR if the aircraft has the needed instruments and the required qualification.

In the scenario where ATC is present, clearance to do it is needed.

2.6.2. IFR to VFR

[10] For more info, see OACI Annex 2: Rules of the air [13]

If no ATC services are provided, it is possible to change to VFR always taking into account the previously mentioned VMC minima.

On the other hand, if ATC services are provided, the PiC needs the clearance before joining the approach procedure. While the ATC does not provide that clearance, the aircraft must remain doing holds at Initial Approach Fix, IAF. However, under pilot request, it is possible to do a visual approach (they are usually shorter).

3. CONOPS

The purpose of this chapter is to present a concept of operations (CONOPS) in order to operate UAVs in the current air traffic scenario. In following sections we present our proposals and explain how to apply them.

However, to assure that these proposals could be developed in a safe way, several computations and designs have been made, resulting in the needed parameters to obtain the desired waypoints. In order to illustrate this work, an example for Sabadell is provided in Appendix 1.

All this commented parameters needed for the construction of the procedures have been grouped in a diagram provided in Appendix 2. The objective of this Appendix 2 is to serve as guideline for the further developing of an xml file which should be embedded into the ground segment so as to automatically compute all the waypoints and procedures which evolve within the take off an landing procedures.

3.1. Introduction

We have computed the maneuvers that we propose to avoid asking the UAV to do any impossible maneuver. These computations are shown at Appendix 1.

In this section, the suggested procedures (always taking into account all possible restrictions such as entry and exits points, altitudes, etc.) are briefly presented and explained in detail though sections 3.2 to 3.4.

Thence, we have grouped the whole aerodrome procedures into the two VAS states that concern us: take off and landing states. The order we have followed is justified with the fact that take off procedures are defined in function of the traffic pattern, which is developed in the landing states section.

3.1.1. Landing states

For the landing states our proposal is to receive the control of the UAV from the FPMS in a concrete point at enough altitude in order to do an evaluation of the traffic over the aerodrome. Then the UAV should join an ideal traffic pattern (which will depend on the performances of each UAV).

The land abort state will allow the PiC to select ‘return to auto land’ (by default), go to waypoint navigation or even pass to manual control.

3.1.2. Take off states

We have thought that the better way to ensure a safe procedure to carry the UAV from the runway to any point where the Flight Plan Manager Service could assume the control is to set up five known exit waypoints. And establish then how to arrive at each of them from the traffic pattern.

We have also introduced a third state within the take off states, the ‘abort take off’ state, which is developed in Section 3.3.3

3.2. Landing states

3.2.1. Land pattern state

First of all, an evaluation[11] of the situation is done by doing a holding over the aerodrome’s vertical or centered in a point which we could set. By default this point will be the center of the runway. The UAV will overfly the airfield at a height greater than the highest of the aerodrome (1500 ft). At this point, the aircraft will be able to wait at a safe altitude before joining the aerodrome traffic pattern. Even if a go-around is done by any aircraft in the aerodrome, the UAV will be safe at the vertical of the field (or another safe point chosen by the pilot in command) 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 maneuver which could bother other traffic.

Once the pilot in command considers that it is possible to join the traffic, he will demand the UAV to do so. He can use predictions computed by the UAV (4D trajectories) 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 start the maneuver.

This maneuver must end at the beginning of the downwind leg already at the aerodrome circuit altitude, so 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 UAV to the downwind leg. However, to avoid bothering departure traffic, the UAV must not start descending until it arrives to the Integration WP (which is placed over the extended runway centerline). Another point is to select the circuit pattern sense and direction. In order to select them, the pilot in command must order the UAV to join the predefined circuit A or B, as well as the sense, as could be seen at Fig. 3.4

[11] See section 2.2.4, ‘Circuit joining procedures’

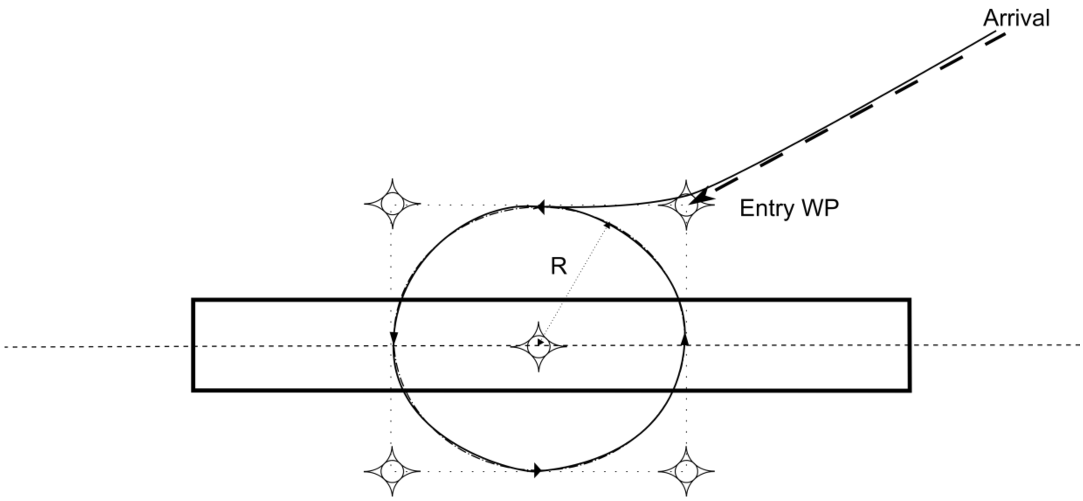


Fig. 3.1 Holding

3.2.1.1. Initial holding

In order to have an omnidirectional arrival (which is the simplest), we've thought in a five waypoints holding pattern (4 in a square + center WP). Those points are automatically computed by setting the coordinates of the center and the holding speed.

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.

But this is only the ideal scenario. In the real one, we will have wind and the performances of the plane wouldn't follow the theory. To avoid having problems caused by the real-world, we are going to introduce a 1.5 factor in the computation of the ideal pattern, so we do not have ideal circumferences anymore. The UAV will follow a non-ideal holding like it is shown in Fix 3.2.

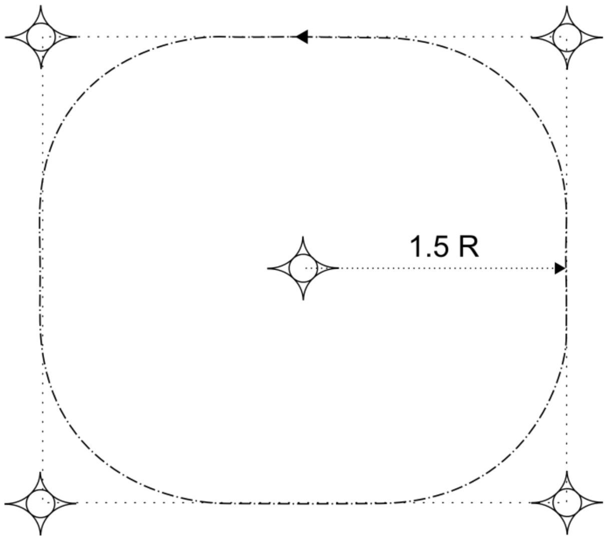


Fig. 3.2 Non-Ideal Holding

Another point that we must take into account while thinking about aerodromes is the fact that holding waypoints must be referenced to the holding's center WP and the heading of the selected runway. All this parameters and computations can be seen in Appendix 1.

3.2.1.2. Transition from initial holding to the traffic pattern

Once in the holding, the pilot in command must select the circuit pattern. It cannot be selected before because of the fact that he must realize how the rest of the traffic is doing it. To do so, he must choose the 'Exit WP', the 'Integration WP' and the 'Initial downwind WP'.

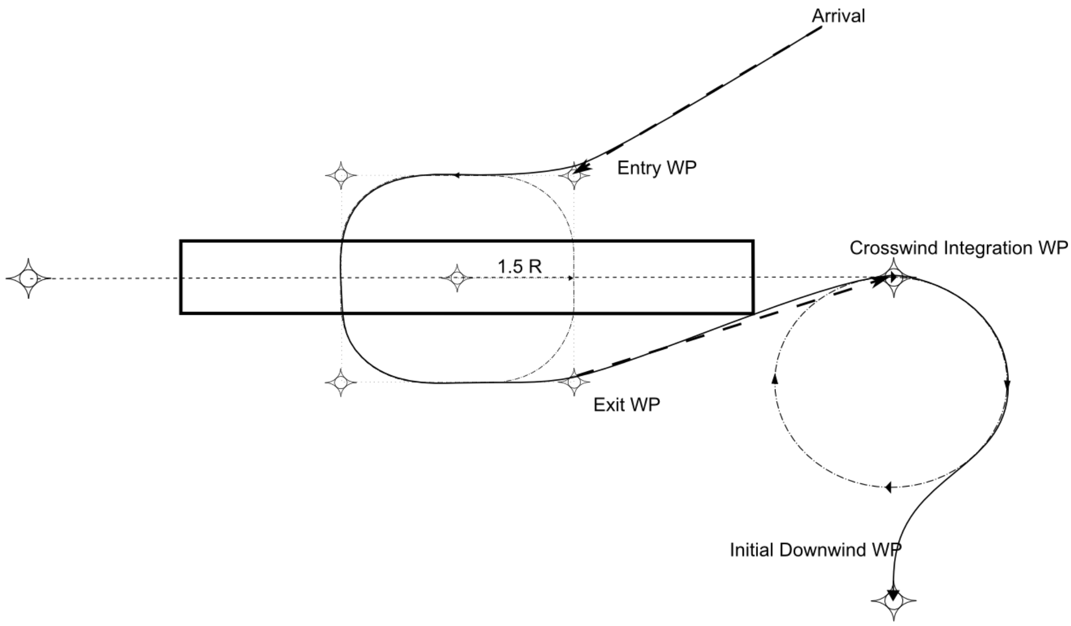


Fig. 3.3 Holding to Circuit

This maneuver is very important in order to arrive at the correct height and the correct heading to the downwind leg, where all the traffic must follow the queue in a safe way. As stated at USA AIP [7], “Entries into traffic patterns while descending create specific collision hazards and should be avoided.”

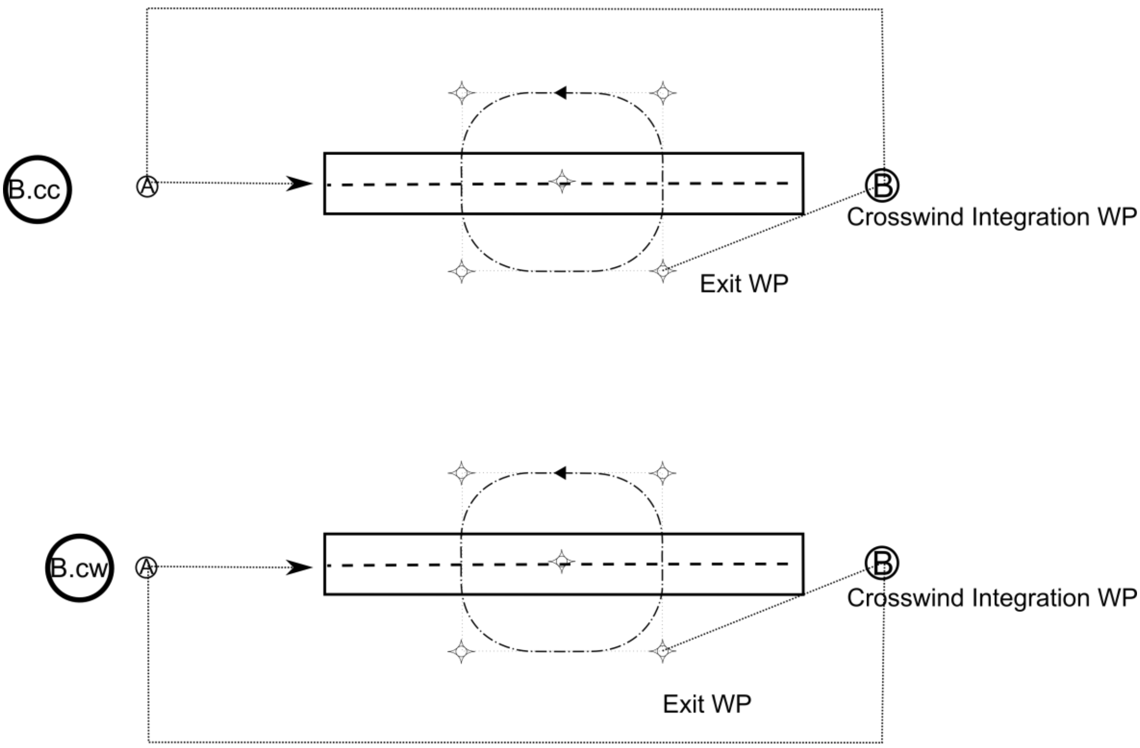


Fig. 3.4 Selection of Circuit Pattern

3.2.2. ‘Auto land’ state

The next point is to follow the downwind leg, which must be flown by all the air traffic at the same altitude, usually 1000 ft above ground level (AGL). It is done in that way so all the aircraft could see the one which precede them. The pilot in command will be able to make adjustments on the length of the downwind leg or do a hold at the end of the downwind leg in order to ensure the separation from other traffic. In the first case, the only parameter affected by these changes is the angle of descent of the final leg, whereas in the case of a hold, any parameter is affected.

At the end of the landing procedure we have the final leg and the touchdown fix (TDF), computed by the autopilot.

3.2.2.1. Traffic pattern

According to the French AIP [1], aerodrome circuit dimensions are not strictly defined. So if there is a published chart, the UAV, as all the other traffic, should follow the indications of this chart. As commented in section 2.2.3 there is a more or less standardized aerodrome traffic pattern which is accepted internationally. This is the traffic pattern which we will apply to the different aerodromes unless there is a specific and well defined one.

We have chosen the parameters commented in section 2.2.3 in order to define our standard traffic pattern. The only difference that we take into account the chance of doing the traffic pattern making left handed (CCW) and right handed turns (CW).

Here we have found two different scenarios: ‘There is a published chart for the chosen aerodrome’ and ‘There is not a published chart for the chosen aerodrome’. For the first one our proposal is to follow only what chart states .If there is no chart, we purpose to follow whatever of the two ideal circuits: Clockwise (CW) and Counter Clock Wise (CCW). If the traffic pattern provided is not standard [11], is work of the dispatcher to introduce the traffic pattern in the UAV's database and select how the UAV will arrive to the mentioned EDW.

In all the cases, it could be possible to define different circuits for UAV that have performances much more limited than general aviation aircraft, like nowadays is done for ULM or gliders.

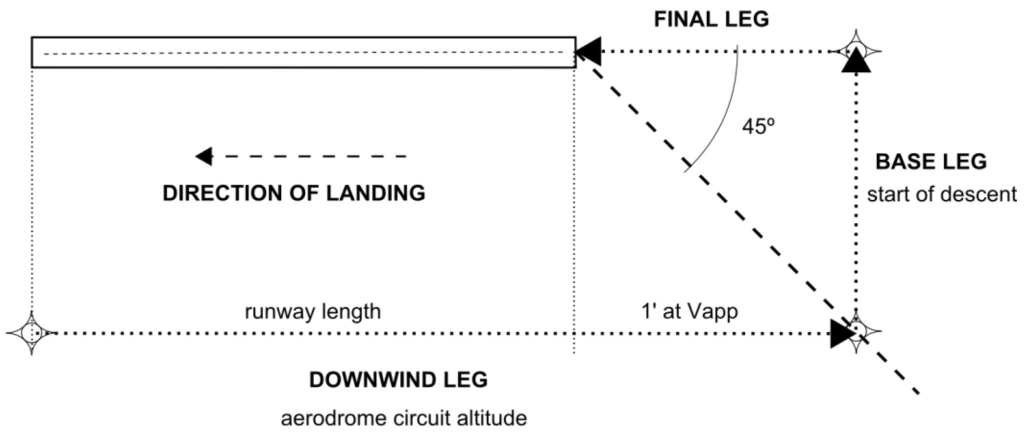
3.2.2.1.1. Downwind leg

The definition of downwind leg that is usually taken as follows:

- Is parallel to the runway

- The distance from the runway is equal to the distance which the UAS cover at V_{app} during one minute plus the length of the runway

- It starts where a perpendicular line which passes by the threshold intersects the line stated above.
- It finishes (as default) where a 45º angle line (the angle is formed by the runway and the line and the vertex is at the end of the final leg) intersects the downwind leg.



3.1 Traffic pattern construction

All traffic has the obligation to follow the established circuit pattern, but we must take into account that previous traffic could be slower than predicted, (some problem with other traffic or with the runway could exist[12]) We have thought in two ways in order to augment the downwind leg time and not bother the other traffic:

3.2.2.1.1.1. Hold

As we have mentioned, the PiC will have the possibility of do a hold during the downwind in order to gain some extra time if a problem has been reported on the runway or if the previous traffic is slower than expected and there is not traffic behind the UAV[13].

If what is wanted is to do a hold during the downwind leg, a process similar to the mentioned above for the holding pattern is done. The only parameters that changes are the center WP and the speed. These parameters could be entered in the airport database before flight in order to decrease PiC workload. If the PiC asks the UAV to do a hold there, it will do it one time unless the opposite is explicitly asked by the PiC (see Chapter 4 Human Machine Interface).

[12] There could be some punctual problem on the runway; some traffic conflict as if the PiC finds out that the UAV is doing a right-hand traffic pattern and someone is doing it left-handed
[13] If there is, an extended downwind maneuver is suggested.

If the PiC asks the UAV to do more than one hold, he should have the chance of ‘cancel’ that hold at anytime. When he cancels it, the UAV should return to the same point of the downwind leg where the hold started.

3.2.2.1.1.2. Extended downwind

It will be implemented by a variable which could be managed into certains limits which must be reflected in the aerodrome characteristics xml file. Taking into account the selected circuit speed, we could be able to manage this variable as a time variable. Having a time variable should be more intuitive for the pilot in command. Our purpose is to increment that leg in steps of 30 seconds and when the PiC decides to start the ‘base’ leg, the extended downwind could be aborted. It is not necessary to wait until the 30 seconds period finishes.

It is possible that for one or other reason the UAV was not allowed to do one of these maneuvers (because of restricted areas, obstacles, etc.) and this is why we have thought in providing the pilot in command the chance of choose between these two maneuvers. (See example in Fig.4.10)

3.2.2.1.2. Base leg

According to section 2.2.3, the ‘Base’ leg has the length which results from go during 1 minute at V_{app}. Is at this leg where the descent begins.

We have to mention that, if otherwise stated in the approach chart, the ‘Base’ leg is always perpendicular to the ‘Downwind’ and its length is the distance between that leg and the extended runway centerline.

3.2.2.2. Landing

The landing maneuver is formed by a single leg which angle of descent is automatically computed by setting the last waypoint of the ‘Base leg’ and the touchdown fix.

This is the most-delicate maneuver. A problem in this maneuver should entail the loss of the vehicle. This is the reason why we need to know the difference between the Desired Touch-Down Fix (DTDF) and the real one (RTDF). In addition, some information about the lateral error is also required. If any part of the system feels that the maneuver could not be managed within safety limits, the missing approach procedure should be started without delay.

3.2.2.2.1. Landing restrictions

3.2.2.2.1.1. Touch Down Fix (TDF)

We have defined the autopilot's predicted Touch-Down Fix as desired TDF, DTDF[14] and we suggest applying a margin[15] over the runway with acceptable real TDF, RTDF (see Fig. 4.11). From our point of view, it is essential to calculate in real-time during the descent the real descent pattern and the difference between it and the previously computed as ideal by the AP. If the VAS determines that this difference is excessive[16] taking into account the margin, it should start the missed approach maneuver by passing to abort state.

3.2.2.2.1.2. Lateral Deviation

Aside from the TDF and following the same idea we have defined the 'Lateral Deviation' LD which we will use to provide the VAS information about its lateral error. We suggest applying (like in the previous case) a margin about the Ideal Lateral Deviation ILD based on the navigation systems (GPS, gyros, etc.) and the Real Lateral Deviation, RLD. As in the TDF case, this information will be provided to the VAS so it could determine if a missed approach procedure has to be started.

3.2.2.2.1.3. Pilot in command

Finally, the PiC should have the chance of change to the 'Abort' state at any time. This chance is justified to avoid the situation where he is informed by radio about a problem appeared over the runway.

3.2.3. 'Land abort' state

In the case of having to abort in both the 'auto land' and the 'manual land' states, the UAV should follow the procedures stated in this section. Here we consider the chance of change from the 'auto land' state to an independent one. This 'land abort' state takes into account the previous procedure (e.g. 'downwind leg' or 'final leg') so as to carry a safe maneuver automatically. Each time the land abort state is started, a default maneuver begins. However the PiC has the chance of ask the UAV to do another one or change to manual state.

---

[14] This point must be set in the aerodrome characteristics datasheet. It is also the point which the AP should have as objective during the final leg in order to compute the parameters related to the descending maneuver (velocities, headings, etc.)
[15] This margin must depend on the runway length and the performances of the UAV.
[16] This computation will be done at certain (enough) frequency from the beginning of the final leg to certain decision altitude. This altitude is usually computed in function of the error of the navigation system and the 'Height Loss' of the UAV, which is the height that an aircraft looses from the point where it decides to go up to the point where it really does it.

The 'land abort' state, as we have stated above, will actuate as a hinge between the landing and other states (e.g. from auto land to waypoint navigation). That is why we need to define very accurately how it is going to behave in function of the different points from where the land abort state could be activated.

3.2.3.1. Abort from 'land pattern' (initial hold)

First of all we must mention that although we have contemplated this case, we think that it is not complex enough to embed it in the land abort state.

This procedure could be used in case of arrival to an aerodrome where there is an important problem at the runway, or if it is very congested or any other reason which could make the PiC take the decision of abort the initial holding and return to the 'Navigation' mode.

The safer mode to carry the UAV another time to the navigation mode is by going directly to the waypoint navigation state from wherever in the initial holding pattern. The UAV will be at enough altitude so as to not bother other traffic and any other maneuver may be more dangerous than the suggested one.

3.2.3.2. Abort from 'auto land'

If during the traffic pattern (even at the final segment) the PiC or the VAS determines that a safe landing cannot be accomplished for any reason, the landing maneuver must be discontinued and the missed approach procedure must be initiated immediately (see Fig. 4.11).

The procedure should be initiated by changing from the auto land state to the land abort one. Once in the land abort state, the PiC will have the chance of giving the control to the FPMS in waypoint navigation state (through the auto take off state), return to the land pattern state or return to the auto land state (set by default).

All these maneuvers should be done following the traffic pattern as accurately as possible.

3.2.3.2.1. Abort causes

The land abort state could be started automatically if any of the following situations takes place:

- The real touchdown fix (RTDF) is out of the margin applied to the desired touchdown fix (DTDF). See section 3.2.2.2.1.
- The real lateral deviation (RLD) is out of the margin applied to the desired lateral deviation (DLD). See section 3.2.2.2.1..
- The UAV goes out of velocity margins.

- The UAV goes out of height margins.
- The UAV goes out of rate of descent margins.

3.2.3.2.2. Return to 'Land'

This procedure will be the one set as default, (the PiC will always have the chance of switching to the other mentioned procedures, even taking manual control of the UAV). It will consist of joining the downwind leg at circuit altitude. In order to do it, the UAV should climb up to circuit altitude and do the rest of the procedure at this height.

We have thought about the chance of having some other traffic joining the circuit pattern. In order to avoid a conflict with this traffic, we propose to have the possibility of extend this first missed approach leg with the same philosophy as in the downwind extended maneuver.

3.2.3.2.3. Go Navigation

Our proposal is to change to the auto take off state (see following section) in order to arrive to a safe WP. As default EDW will be the WP_A (arrive to 500 ft), but the HMI will allow the PiC to change this parameter.

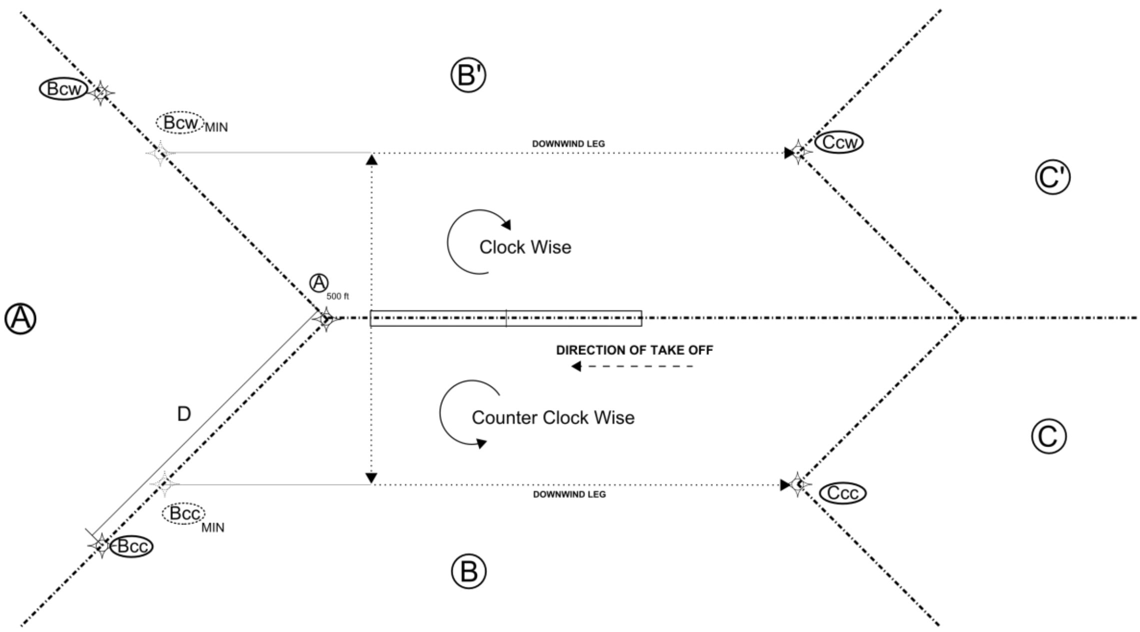
3.3. Take off states

In this section the developments of the 'take off' states are done. Firstly we analyze in depth the structure of the 'auto take off' for then continue with the 'abort take off' state.

In order to ensure a safe way to carry the UAV from the runway to the 'End of Departure WP'[17] (EDW) we have defined a five WP diagram which would be applied to all the runways. As shown at Fig. 3.3, these waypoints delimit five departure areas. For each airfield, some of these WP can be cancelled if they fall over restricted areas or the flight dispatcher decides that they are not operational for that particular scenario.

The aims are to arrive to one of the defined EDW without bothering (where possible) the other traffic and to provide the FPMS enough departure waypoints to cover all possible destinations.

[17] This WP is the link between the Departure procedure and the Mission Flight Plan,



3.2 End of Departure Waypoints (EDW) definition (no published traffic pattern)

3.3.1. Auto take off state

3.3.1.1. Construction of the diagram

Following the idea of bother as less as possible the other traffic, we propose a diagram defined in function of the 'Traffic Pattern' and built in base to it. Some operational facts have been taken into account in order to define the limits of the areas.

Details about the points, its restrictions and the departure areas are detailed below:

3.3.1.1.1. End Departure Waypoints and Areas

WP_A :

- It is the point where the UAV reaches 500 ft AGL[18] (section 2.2) following the heading of the runway and since which the UAV is allowed to start maneuvers. If this altitude is reached before the end of the runway, the WP_A is translated to the runway threshold.

- This waypoint should be selected if the flight plan starts in the area "A", which is the area limited by 45º from the heading of the runway.

[18] This altitude has been selected according to sec. 2.2.5. In addition, some APs do not let UAV to do any maneuver before arriving at this altitude.

- From the WP_A the UAV will be allowed to go directly to WP_{Bcc} and WP_{Bcw}

WP_{Bcc} and $WP_{Bcw:}$

- These points must be placed at least at a distance '$1.5 \cdot D_{min\ turn}$'[19] and doing with the WP_A a 45º angle each one. If these points fall within the traffic pattern they must be placed at least in the intersection between the downwind and the 45º angle line from WP_A(Bcw_{min} and Bcc_{min} at Fig. 3.3).

- These waypoints should be selected if the flight plan starts in the "B" or "B' "areas. The limits of these areas are the other areas and the runway.

WP_{Ccc} and $WP_{Ccw:}$

- These last points are placed at the intersection between the downwind and base leg of the traffic pattern.

- With these waypoints and the extended runway centerline we are able to define the "C" and "C'" areas.

- The suggested track to arrive at WP_{Ccc} and WP_{Ccw} is to follow the traffic pattern. The ideal or the published depending on the charts (See Fig. 3.3 and Fig. 3.4).

Area limits:

45º limits for the different areas have been defined to avoid excessive turns and operational problems it may cause[20].

3.3.1.1.2. Other parameters

Altitudes and velocities:

UAVs 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.

Cancellation of waypoints:

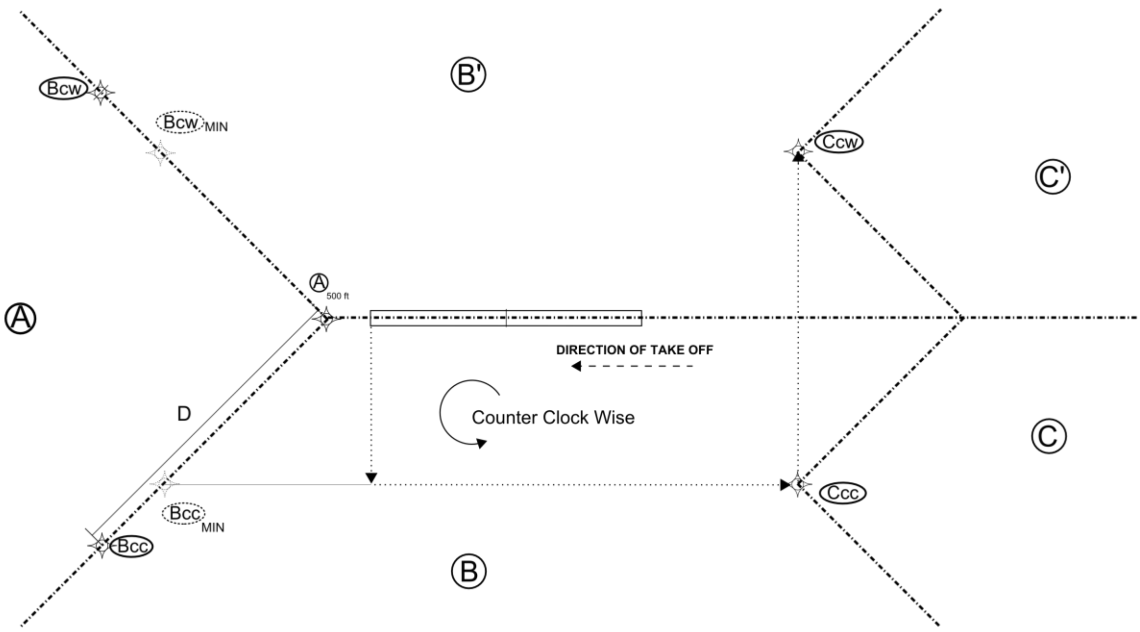
[19] See Annex 1: Computations
[20] Typical problems: never arrive to the 'next' waypoint and remain describing circumferences or 'Eight Patterns'

As stated above, if some waypoint falls over a restricted area, it may be cancelled for that airfield, cancelling then the corresponding area too.

3.3.1.2. Different patterns

Our proposal is to generate two standard traffic patterns (clockwise 'CW' and counterclockwise 'CC') for each runway. And then apply eventual restrictions to them.

As mentioned in section 2.2.3 'Traffic Pattern', if there is a published chart, it could restrict our traffic pattern in its sense or establishing a different one [11]. In the first case, our proposal is to do only the traffic pattern in the sense published, while in the second case we propose to allow the dispatcher to configure a non-standard traffic pattern and select how to arrive from it to the EDW[21].



3.3 End of Departure Waypoints (EDW) definition (traffic pattern published in counter clock wise sense)

3.3.2. Manual take off

In this state, the PiC is who has all the control over the UAV. This state could be activated in order to fight against any eventual contingency.

3.3.3. Take off abort state

[21] For more details about Traffic Pattern, see Section 2.2.3 'Traffic Pattern'.

If we start our reasoning from an UAV that is already flying (without taking into account the take-off), the selection of the 'Abort' mode will mean that for one or other reason the PiC has stated that the UAV must not enter in the 'Navigation' mode. So the UAV will join the traffic pattern and change then to the 'Land' mode.

This change of mode allows us to assure a safe landing of the UAV if a problem has been detected during the take off procedure.

In order to avoid bothering traffic joining the traffic procedure, this maneuver could be extended in the same way as the downwind leg so as to gain some extra time.

3.4. Different scenarios

In the previous sections, we have proposed some procedures to be included into VAS states. Within this section we will make a crossover between those commented in previous sections and the current state of the art studied at Chapter 2

The main difference between scenarios is the fact that in some cases the ATC, in some others navigation aids (NAVAIDs) will provide the PiC enough information to avoid some states or start them in different points.

3.4.1. VFR Non-Controlled

If the UAV should land on or take off from an airfield without any type of air traffic control or information services[22] and without IFR procedures published for that particular aerodrome we are dealing with a VFR non-controlled aerodrome.

This case is the more restrictive, so any kind of information is provided. In this scenario the UAV will use all the states and procedures:

3.4.1.1. Landing states

First, as commented above[12], an evaluation of the situation is done by doing a holding over the aerodrome (land pattern state) so the PiC could inspect the aerodrome and contact by radio with other possible traffic in order to obtain information about (for example) the sense of the traffic pattern, the wind direction, etc.

Then the UAV should join the traffic pattern at the beginning of the downwind leg. This is where the auto land state starts. After that, the UAV should follow in this state until stop at the runway or change to the land abort state.

[22] The particular case of an AFIS or another information providers are contempled in section 3.4.1.3, 'Aerodrome information is provided'

The ‘land abort state’ is followed until re-joining the traffic pattern, the auto land state (by default) or arriving at one of the EDW predefined for that aerodrome.

3.4.1.2. Take off states

In VFR non-controlled aerodromes, the auto take off state will be the state selected as default, and will carry the UAV from the runway to an EDW in a safe way. Then, the waypoint navigation state will be started. In the case of having any contingency during the take off, the abort take off state could be enabled in order to guide the UAV to the traffic pattern (auto land state) with the aim of returning to the runway as quickly as possible.

3.4.1.3. Aerodrome information is provided

However, in the case of having some information service (AFIS) or someone related with the operation of the UAV at the landing aerodrome who could provide essential information[23] to the PiC (even the PiC could assume that role), this information will help the PiC in the way that could let him avoid some maneuvers as start the whole approach procedure from the traffic pattern or even at the final leg.

3.4.2. VFR Controlled

If the UAV operates in a controlled aerodrome where non IFR procedures have been published, and only after ATC clearance, it is possible to directly integrate the traffic pattern in any of its segments.

However, the default procedure will be the same as commented in previous section: ‘VFR Non-controlled’. With the only difference that the PiC will require clearances for the maneuvers as if he was the PiC of a manned aircraft. (See Section 2.3.4‘VFR Controlled: Clearances’.

3.4.3. IFR Non-Controlled

The case of an UAV operating an aerodrome that has published instrumental procedures is as simple as follow these procedures. However, the coordination with other aircraft became an issue in non-controlled aerodromes.

In order to deal with this problem, we propose the same solution as seen in the French AIP [6] and already studied in section 2.4, which could be summed up by saying that the PiC should accord themselves together and transmit essential information. Moreover, IFR traffic, like the UAV one, will have priority

[23] This information could be: if there is some other traffic arriving (or taking off) at the aerodrome, what is the sense of the traffic pattern, existent meteorological conditions (wind, visibility, clouds, etc.).

over VFR traffic and thus conflicts will be minimized [11]. In all the cases, the approach should end in a circle to land approach

3.4.3.1. Landing states

Although the whole process is well described in charts, all published approach procedures have a certain height or waypoint from where the aircraft should follow visual flight rules (excepting those certified ILS Cat. III C, which are not common[24]). This part of the procedure will be managed as VFR Landing (see section 3.4.1) but taking into account only the procedures that the chart indicates to be done under VFR.

The land abort state will also be used but its default mode will be to carry the UAV to $EDW_{A.}$ From where the UAV could go direct to the begin of the published missed approach procedure.

3.4.3.2. Take off states

For the take off states, our proposal is to state the ‘A’ EDW[25] as the end of these states and follow from there in waypoint navigation state. The abort take off state in this scenario will mean to join the abort take-off procedure computed for that aerodrome for the flight dispatching service of the UAV.

3.4.4. IFR Controlled

In the case of operating to or from an airfield with IFR procedures published and ATC services available, we suggest following those published procedures but always taking into account that what ATC says is mandatory.

In both landing and take-off states we propose the same as in the previous section always considering the ATC obligations.

3.4.4.1. Radar vectoring

Indeed, in the case of Radar Vectoring it will be duty of the FPMS to carry the UAV following the indications of the controller until the point that he states. But the PiC must ask the ATC not to guide until intercept NAVAIDs (e.g. until intercept ILS at RWY 07) but to a concrete point or even a intersection between two computable lines (e.g. ‘the current heading’ and ‘extended runway centerline’). The HMI should allow the PiC to compute these intersections on the screen.

[24] ILS Cat III C: Runway Visual Range (RVR) less than 150 ft (50 m)
[25] Is the point where the UAV arrives to 500 ft AGL or the end of the runway if it arrives to 500 ft AGL before the runway threshold. (see Section 3.3.1.1.1)

4. HUMAN MACHINE INTERFACE

4.1. Introduction

The main idea of an UAV is to minimize the Pilot in Command workload. But in order to achieve that objective, we have to design a helpful Human Machine Interface (HMI). That is why we have designed different interfaces for each scenario.

4.1.1. The Interface

It is clear that the interface should be very intuitive and should present in the most relevant information. This information should be presented in such a way that just looking at the interface, the PiC could know if all the parameters are within the limits and actuate if necessary.

Radio equipment is also required so as PiC could communicate with the other traffic or the ATC in addition of a first person view with which see other possible traffic and the state of the aerodrome.

The name of the workstation being developed is Flight Monitor Service, and it is split in two screens: Pilot Screen and Multifunction Screen. The main is the Pilot Screen and there is where the first person view is shown (as well as other information studied at [18]). The Multifunction Screen is a secondary tactile screen. In the following sections we are going to establish the main guidelines of this secondary screen for the VAS states studied in the Chapter 3 (CONOPS), takeoff and landing.

4.1.2. The info packages

During the procedures, a flux of data has to be managed. Here we will discuss the way that it will be done in the scenarios mentioned in the previous chapters.

The (sub) system where we are going to move is formed by the PiC, the FPMS and the VAS. For our proposals three are the directions for the data flux (in both senses): PiC-FPMS, PiC-VAS and FPMS-VAS. However, because of we are dealing with the VAS states, the main one will be PiC-VAS.

4.2. Multifunction Screen

As mentioned above, the Multifunction Screen is a secondary tactile screen where schematic information is shown in an intuitive way.

The ‘Multifunction Screen’ will be split into three main parts (See Fig. 4.1): The ‘Differential Display’ (DD), which will present ‘differential information’; the ‘Main Display’ (MD) where we will find the more relevant information in each procedure, and the ‘Interaction Display’ (ID), which is the part of the screen where the PiC will have the tools to interact with the UAV. Two secondary parts are also suggested: parameter summary box and a console which would act as a phraseology reminder in controlled scenarios.

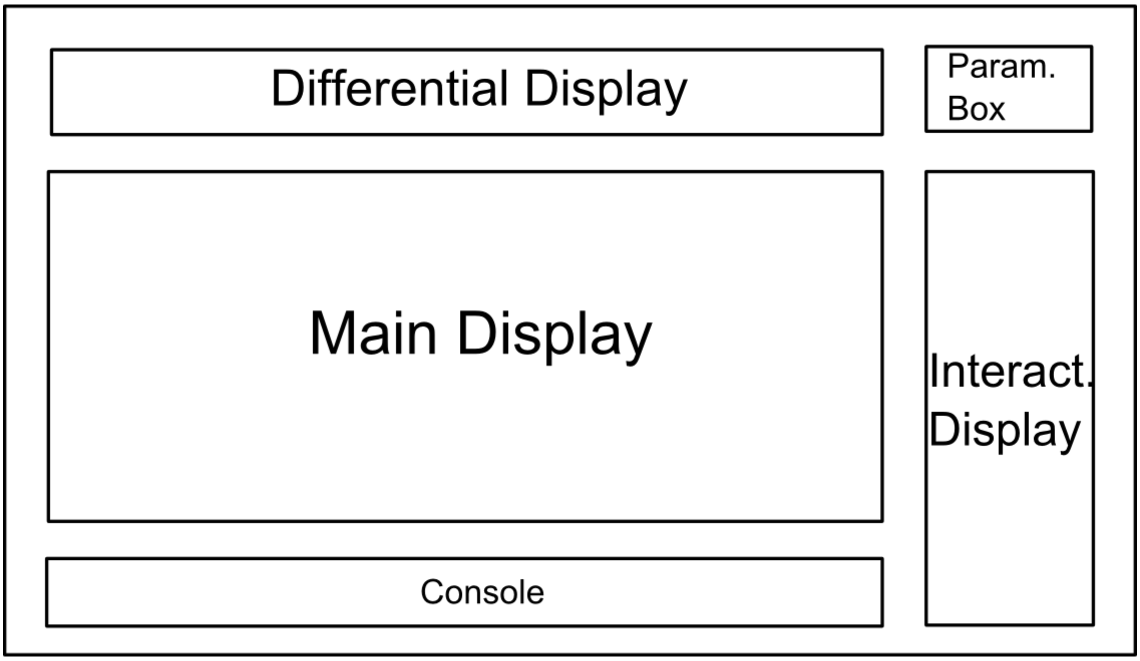


Fig. 4.1 Multifunction Diagram

In the case of change to manual operation, the interface will actuate as a support device to the PiC.

NOTE: In the figures of the following sections, all noted with an asterisk (*) are only explanations about what is drawn.

4.2.1. Main Display

For each procedure, the most important view of the situation is shown in this display. For example, in the ‘land pattern’ state the most important view is the ‘plant’ while in the last view of the ‘auto land’ the cross section gives more info (see Fig.4.2).

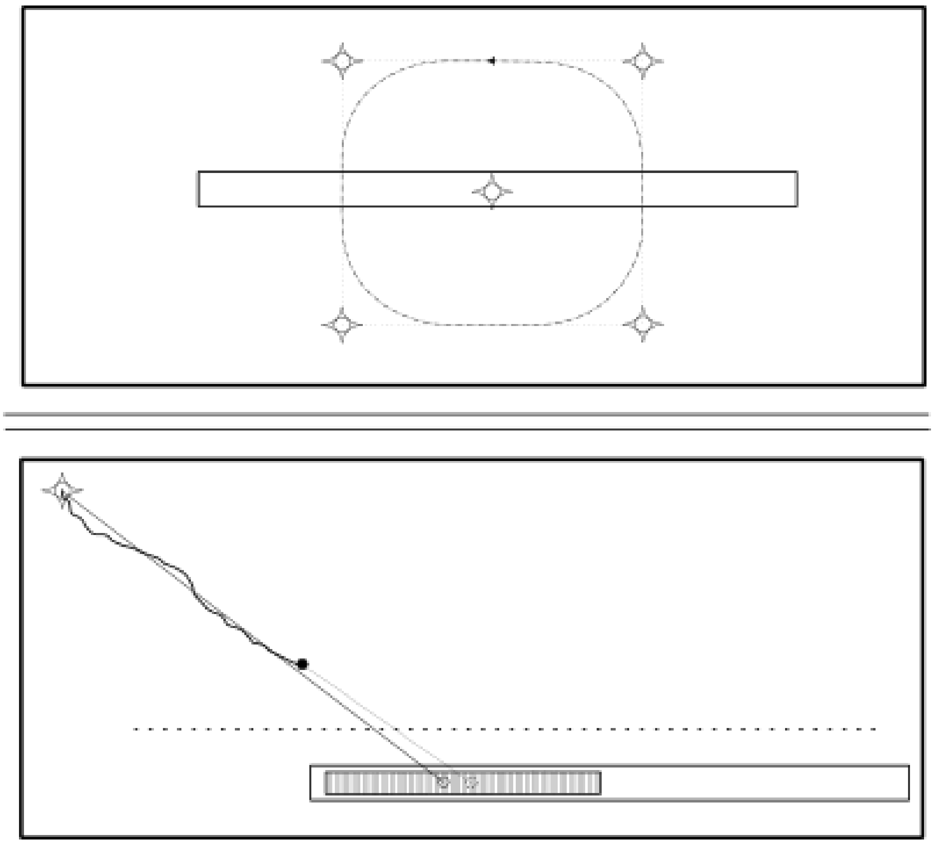


Fig. 4.2 Main Display Examples: Initial Hold (upper) and Final Leg

4.2.2. Differential Display

All the parts in which this display is split would present the desirable value, the current value and a margin of acceptable values for different parameters. The information needed for the construction of these diagrams is at aerodrome's xml file or is related to the UAV performances.

In Fig. 4.3 we present the construction of these differential diagrams with an example for the velocity. It is formed by a margin of acceptable velocities, a desirable one (which could be tuned by the PiC), the real (or measured) with its tendency direction and module. All the words in the figure are only descriptive, no one of them would appear in the workstation, and Magnitudes into square brackets are suggested to appear in number.

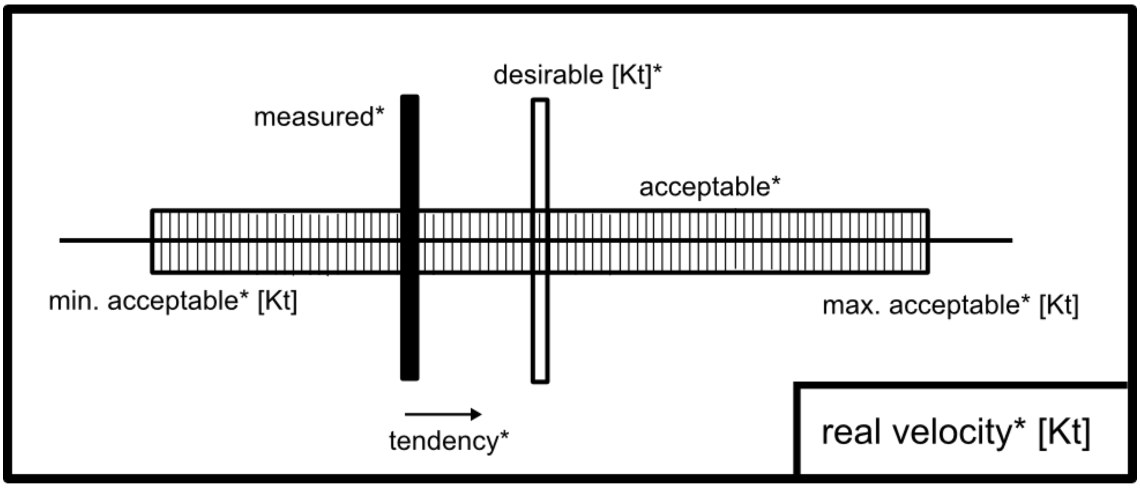


Fig. 4.3 Differential Display Detail: Velocity

In the following sections the differential display will be only described, the diagram of what is shown will follow the guidelines stated in this section.

4.2.3. Interaction display

The main idea of the interaction display is to decrease the workload of the PiC. In order to achieve that objective, we have thought in a display such that the minimum interaction is required.

The main buttons (and its evolutions) that will appear in this display are briefly commented below:

Selection button:

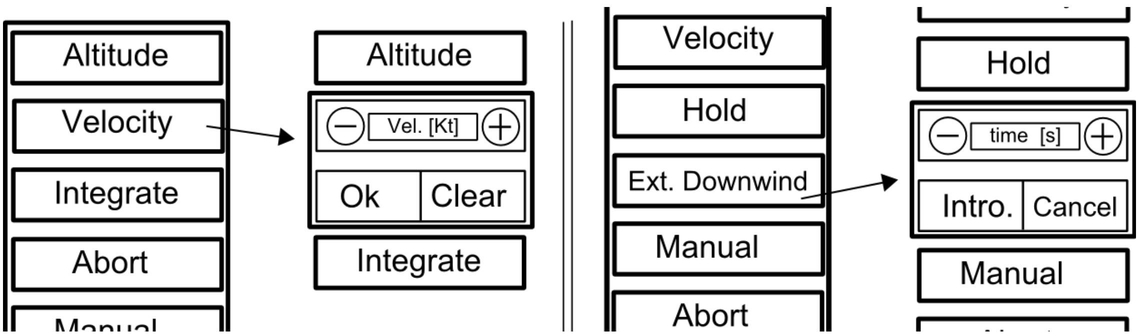


Fig. 4.4 Interaction Display detail: Selection Button examples

This button should be applied to magnitudes as altitude, velocity, or time. In the two first, once the Ok button has been pushed, the screen comes back to the previous appearance. The changes applies to the desired values, it is AP duty to take into account the performances of the UAV so as to achieve the desired value.

In the case of the Extended Downwind, to distinguish between 'selected time' or 'time being selected', before pushing the 'Intro.' Button the numbers should tilt.

Change state button:

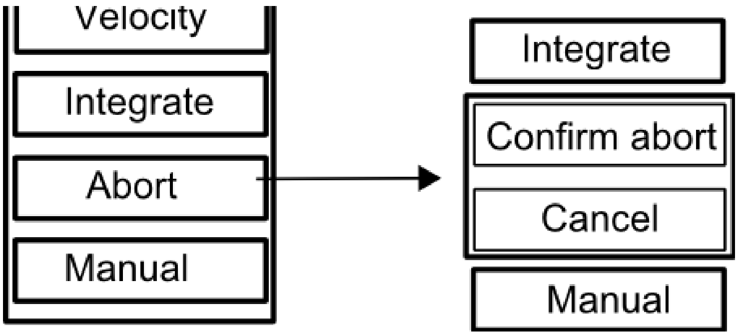


Fig. 4.5 Interaction Display detail: Confirm change of state

It is important to note that a semantic distinction have been done between 'cancel' and 'abort'. The mean of cancel is to leave the present procedure and return to the previous one, whereas abort has connotations of change of state.

We suggest putting always Abort and Manual buttons in the same place for ergonomic reasons. This will help the PiC to quickly actuate in view of eventual contingencies.

4.2.4. Secondary displays

Our proposal is to provide some extra information which could help the PiC to remind parameters or procedures. In order to achieve that objective, we suggest the Parameter Box, the Console and the Radio Indicator.

4.2.4.1. Parameter Box

Within the Parameter Box, fundamental magnitudes for a safe flight should be displayed. These parameters could be: current velocity, height and heading/ bearing.

4.2.4.2. Console and Radio Indicator

These two indicators are thought for aiding the PiC in the radio communications. The radio indicator turns on when someone is talking on the selected frequency (for the radio communications a radio interface is required). And main function of the console is to remind the PiC the phraseology in the different cases. A button should be provided in order to skip the phrases. It could also be used as console or reminder in other cases.

4.2.5. Landing states

In this section, the guidelines to develop the multifunction screens for the landing states are provided. This section is split into five parts. In the first one we comment the procedure to select where of the landing states the UAV is going to join the standard traffic pattern proposed. The following sections correspond with the landing states with the exception of the 'Final leg' which although it is not a state, is complex enough to have a sub-section.

4.2.5.1. Before join the landing states

Although this selection is suggested to be done before the flight, we present this screen to cover the case where for one or other reason this plan could not be followed[26]:

Before joining the landing states, the PiC (in function of the flight rules, ATC indications and information of the aerodrome provided), should select one of the nine points[27] shown at Fig 4.6 Each one of these waypoints has different parameters (altitude, velocity and heading) that must be accomplished before the waypoint.

A screen similar to the one presented below is suggested for that cases.

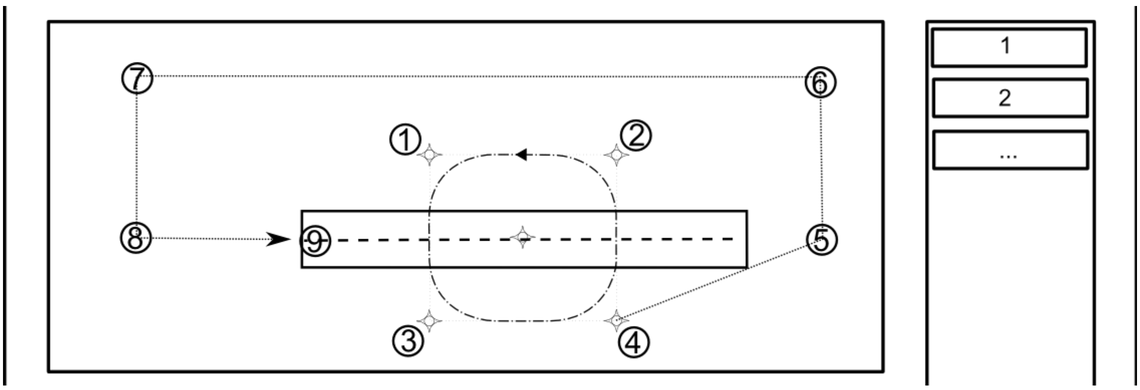


Fig. 4.6 Selection of initial approach WP (MD and ID)

[26] Our proposal is to do all the flight (where possible) under IFR. But the HMI must be prepared for deal with eventual contingencies.
[27] Before this screen, there should be another one where the PiC could select the runway and the sense of the traffic pattern (if he knows it).

4.2.5.2. Land pattern

On arriving to the aerodrome, there are two main aspects that we must check before joining the aerodrome: wind speed and direction and information about other possible traffic. These data must be shown in the Main Display.

For the data about wind we have thought in a compass rose. But present information about other traffic is only possible if both the UAV and the other traffic have a system capable of know the other's position, heading and velocity. Nowadays it is very difficult to imagine such scenario. That is why our proposal is try to see the other traffic with the on-board camera doing a hold over the aerodrome or contact them by radio.

In this scenario, to present the other traffic in the Multifunction Screen will be difficult. Our proposal is that coordination with the other traffic should be done by radio.

An action of the PiC is required when this screen appears (Fig 4.7): to confirm the default center of the hold or to select the alternative center of the hold (by touching the alternative center on the screen).

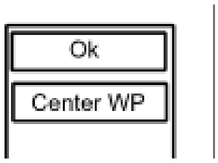


Fig. 4.7 Detail of the Interaction Display

Once the center of the initial hold has been selected, the 'Land Pattern View' is shown in Fig 4.8.

Now, what the PiC will see in the main display is the initial hold diagram over the runway with its different waypoints and the current UAV position and direction. In the differential display, the suggested indicators are: velocity, height, vertical speed and heading. And finally, in the interaction display, the PiC will have the chance of change the altitude and velocity (always within the limits), see the integration view (described in the following section), abort (go navigation) and change to manual mode.

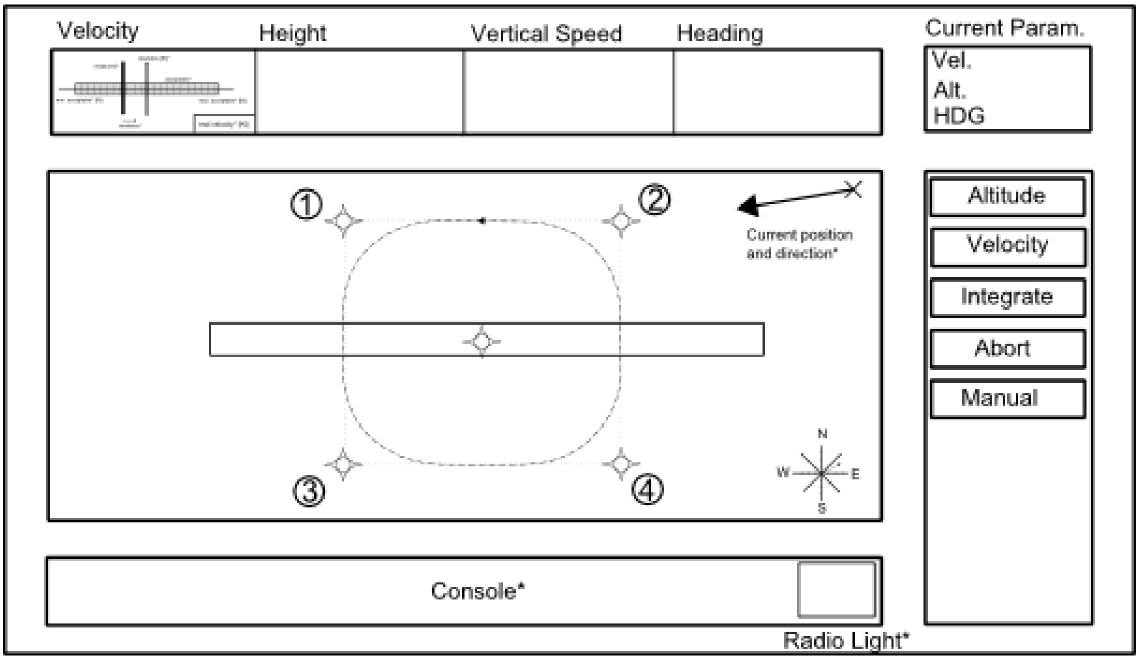


Fig. 4.8 Multifunction Screen: Land Pattern View

4.2.5.2.1. Integration View

While in the integration view, the main display should show something similar to Fig 3.3 and/ or Fig. 3.4 as well as the time that the UAV would take to go from where it is at the moment to the different points[28]. The interaction display will give the PiC the chance of select if possible (see Section 3.2.1.2)the runway and the sense of the traffic pattern. As well as the Abort and Manual buttons.

4.2.5.3. Auto land

At this point, the autoland view should be displayed (Fig. 4.9).

In this view, the main display should present information about the current position (black dot on Fig. 4.9) and the time that the UAV will take to arrive at relevant waypoints. Another point (for further development) is to present information about other traffic in the aerodrome. As stated above in ‘Land pattern’ section, it is difficult to have such scenario that the workstation could have necessary info to print the position, direction and velocity of other traffic.

The ID should show the buttons of Fig. 4.9. The evolution of these buttons has been already commented at section 4.2.3. Interaction Display. The evolutions of the main display for ‘extended downwind’ and ‘downwind hold’ maneuvers are detailed below:

[28] This information could be very important in order to communicate the ATC or the other traffic how long it would take the UAV to join the traffic pattern.

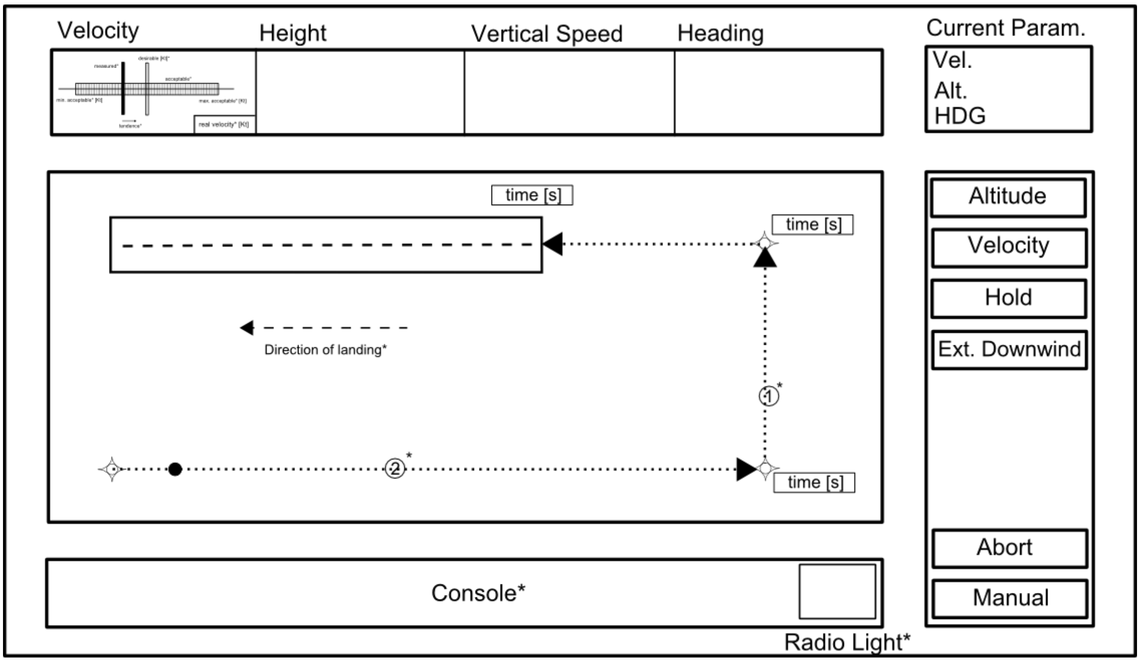


Fig. 4.9 Multifunction Screen: Traffic Pattern View

4.2.5.3.1. Extended downwind

For this maneuver, the 30 seconds steps extension should be drawn. The times and the trajectory should be actualized after pushing the 'Intro.' button. What happens with the ID is detailed as example in the corresponding section (4.2.3 Interaction display).

4.2.5.3.2. Hold

For the hold we have two cases, do the hold 'Now' or specify where by selecting on the screen where (always tangential with the downwind and out of area inside the traffic pattern) to do it. There should also be some limits within the hold could be done. These limits are moved with the downwind when it is extended

.

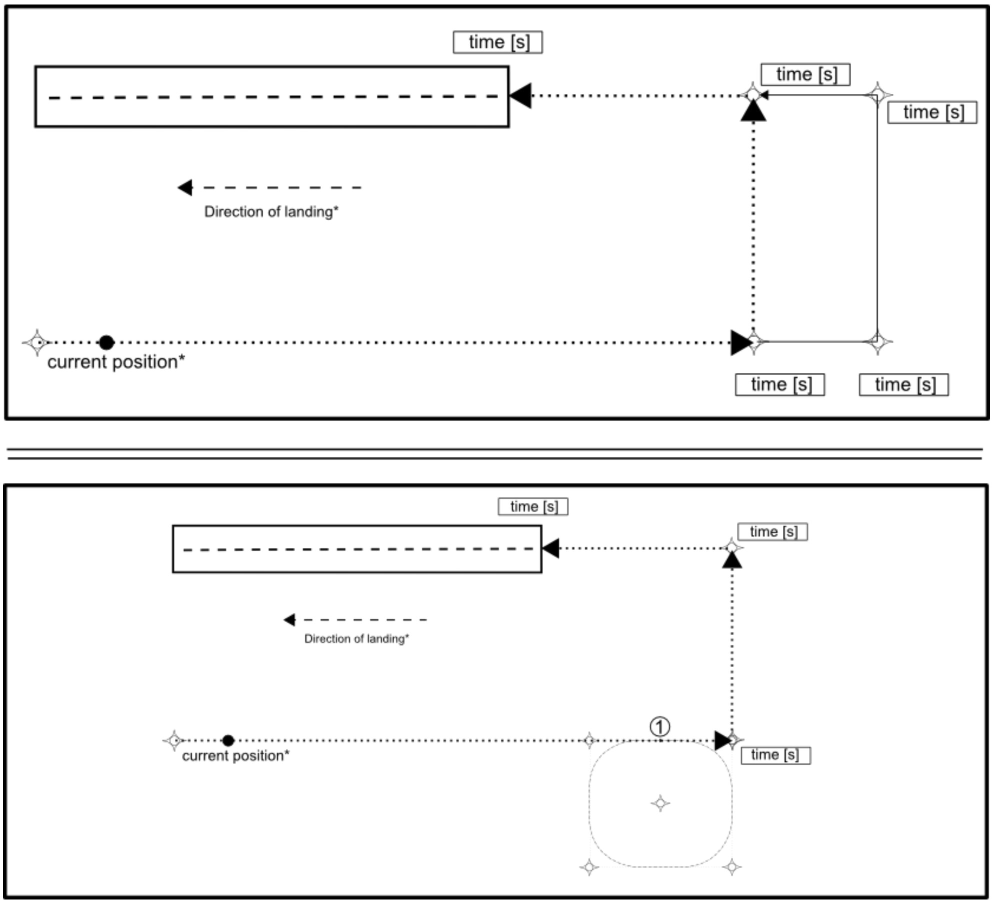


Fig. 4.10 Main Display: 'Extended downwind' and 'Hold' maneuvers[29]

4.2.5.4. Final Leg

The final leg is usually the most critical leg of the land procedure. In this section we develop our proposal so the PiC could have all the info that he could need.

To describe the view in a better way, we are going to lean on the following figure:

In the differential display we will have some horizontal indicators and some vertical indicators. The touchdown fix indicator should be more accurate than the presented in the main display. Meanwhile in the interaction display only abort and manual buttons will be available. The procedure is so critical that only the VAS or the PiC should be able to interact. Interaction between these two and the AP would result too slowly.

[29] The circled 1 is the limit which the text refers to in the 'Hold' section.

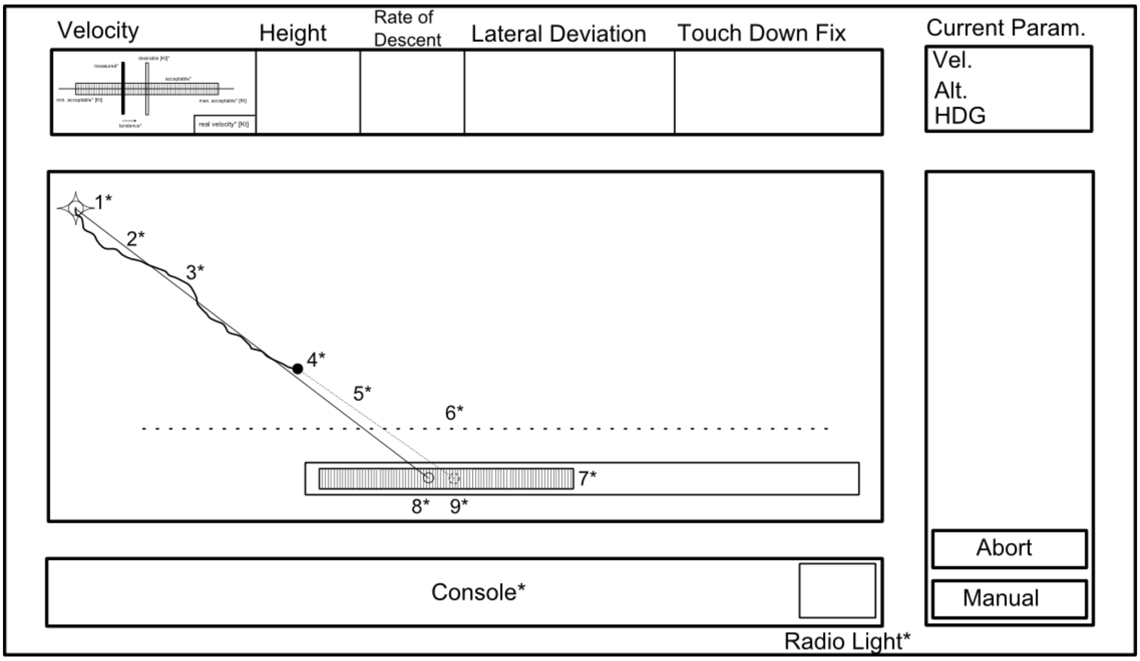


Fig. 4.11 Multifunctional screen: Final leg view

In the main window we will have the following (all distances –height and length- should be proportional):

1* Initial base leg waypoint.
2* Straight line between 1* and the DTDF (see Section 3.2.2), ideal slope.
3* Course that the UAV has followed, real (or measured) slope.
4* Current position.
5* Ideal slope from the current position
6* Decision height
7* Acceptable TDF
8* Desirable TDF
9* Computed TDF from current position

4.2.5.5. Land Abort

The land abort actuates as a hinge state, and its function is to carry the UAV in a safe way from the 'abort point' to the begin of another state.

4.2.5.5.1. Abort from land pattern

As mentioned, the abort from the land pattern means a return to the waypoint navigation state. Therefore, it is out of the scope of our work to describe it.

4.2.5.5.2. Abort from auto land

If an abort from autoland state is done, the default evolution of the screens will be that when the UAV were below 500 ft, the final leg view's main display (Fig. 4.11) is shown, whereas over 500 ft, the main display will show something like the traffic pattern view.

The differences between the commented main displays and the abort ones will be that selected abort procedure should be drawn. In addition, the interaction display should change its buttons. The buttons should allow the PiC to change to the different states commented in section 3.2.3.2 as well as change to manual.

4.2.6. Take off states

In this section, the guidelines to develop the multifunction screens for the takeoff states are provide. First we are going to comment the chance of change the defined EDW while in the start-up states (see Fig. 1.3). Next, we are going to develop the screens for the auto takeoff state and finally we will talk about the take off abort state screens.

4.2.6.1. Before takeoff

As with the landing entry waypoint, we suggest that end departure waypoint to be selected before the take off. However, we have designed the guidelines of this screen to cover the case wherein for one or other reason the PiC must change the selected EDW.

In the interaction display, the chance for change the altitude of those points should be taken into account.

4.2.6.2. Auto takeoff

This view should have two main display screens, one for the time between the end of the taxi and the arrival to the EDW_A and another for after achieving that WP.

The first one should be similar to the final leg view, but only with the real (measured) position and the ideal in function of the performances of the UAV. Meanwhile the second should display the traffic pattern, the runway and the EDW (Fig. 3.4) with the time to arrive there.
In this view, only the runway, the EDW_A and the time to arrive there should be shown in the main display.

4.2.6.3. Take off abort

As commented in section 3.3.3 Take off abort state', The objective of this state is to carry the UAV back to the autoland state. That is why if the UAV were below 500 ft, a screen similar to the final leg should be shown, whereas in the case of being over 500 ft, the main display should display a screen where the traffic pattern and the maneuver to achieve it should be drawn.

In addition, in the interaction display, the option of extend the joining traffic pattern should be given to the PiC following the same philosophy as in the extended downwind maneuver.

In the case of flying below 500 ft, in the differential display, the desirable altitude should ever be 500 ft. So the most of the AP does not let the VAS operate the UAV below that altitude. [3]

4.3. Different scenarios

As commented in section 3.4 Different Scenarios', we have grouped the whole aerodrome procedures into the two VAS states that concern us: take off and landing states. Here we are going to comment the main differences between operate in one or another scenario.

4.3.1. VFR Non-controlled

The VFR Non-Controlled is the worst scenario for the Pilot in Command. It is the way it is because of the lack of references or guided tracks to follow. Here the PiC should have a more guided HMI with more data and maybe more interaction with the UAV, but always keeping in mind that our objective is to have the less interaction possible between PiC and UAV.

As we have already mentioned, all the screens and operations are thought for the most restrictive case: VFR Non-controlled aerodrome. That is why here we should all the screens detailed in the previous sections.

4.3.2. VFR Controlled

(See section 4.3.1)[30]

4.3.3. IFR Non-Controlled

(See section 4.3.3 'IFR non-controlled')[31]

[30] The main difference between the controlled and non controlled VFR workstation screens is the phraseology aids in the console.
[31] The charts should be part of the Flight Plan, so it is not VAS duty to deal with the IFR published charts.

4.3.4. IFR Controlled

(See section 4.3.4 'IFR Controlled')

4.4. Information Flow

As commented at the beginning of this chapter, here we are going to give some guidelines about the information flux that will exist sent between the VAS, the FPMS and the workstation within our study cases.

This section is divided according to the mentioned paths: VAS-workstation, VAS-FPMS, and workstation-FPMS; additionally, a fourth section has been added in order to deal with the automatic aborts and its actors.

4.4.1. VAS-workstation

All the parameters that the ground segment needs to compute the different procedures and waypoints (see Appendix 1) should be provided by the Flight Monitoring Information Service. After that, the ground segment should act as FPMS by computing all the WP and updating this WP with extra information (velocity, height, etc.) to the Virtual Autopilot Waypoint Array.

In addition, the workstation will be subscribed (see chapter 1, System Overview) to the mentioned Flight Monitoring Information System so as to know all the parameters which could affect the airframe and in function of these parameters compute if the UAV is within the expected limits or start an abort state. All these computations should be done, as commented above in the ground segment.

4.4.2. VAS-FPMS

In order to allow the FPMS to change the VAS system to the landing states or automatically link the EDW with the waypoint navigation state, it is necessary to include in the definition of the last flight plan WP and the EDW the needed information so as to change the VAS state once this WP is cleared.

4.4.3. Workstation-FPMS

Before beginning the approach procedures, it will often occur that the ATC ask the PiC to change the predefined arrival (under IFR) that would result in arriving at different Final Approach Fix (FAF) [32]; ATC or other information provider could allow the UAV to join the traffic pattern in different points (under IFR/VFR).

[32] Depending on the importance and the supported traffic, the aerodromes have more or less SIDs and STARs at important aerodromes.

These changes must have an effect in where the FPMS should pass the controls to the VAS and the workstation. Even could introduce the first waypoints and parameters to the virtual autopilot waypoint array in order to reduce PiC workload.

4.4.4. Abort

The fact of define what part of the system is in charge of change to an abort state is a difficult issue. On one hand we have that there are several actors which could adapt this role: the Awareness Service, the Contingency Manager, or even the ground segment.

However, the solution to this problem is quite easy: depending on the precedence of the fail one part or another of the system should take part and switch the state.

If the problem is caused by an external problem (as wind or other traffic), it will be Awareness Service’s duty to manage the change, whereas if the problem comes from a mistaken within the computed parameters it will be the ground segment the part in charge of deal with the problem. Besides, if the problem comes from the airframe (engine, control surfaces, etc.) it is work for the contingency manager.

CONCLUSIONS

This document presents a proposal for integrate Unmanned Air Vehicles (UAV) in civil airspace with coexisting manned aircraft. In order to achieve this objective, the authors have tried always the solution which interferes as less as possible with the other possible traffic and Air Traffic Control (ATC) procedures.

In order to appreciate the problem in all its scope, we have split the casuistic of manned aircraft operations (on aerodromes) into four branches. This division has been made taking into account the flight rules and the existence or not of air traffic services. As a result of this study we have concluded that operating under visual flight rules without air traffic services is the most challenging case and is there where the work has been focused.

In addition, as a result of the study of the system and the current state of the art, we are able to conclude that the last part of the landing procedure is always done like a visual approach. On the other hand, instrument arrivals could be managed as automatic flight plans for the UAV. With all these information our proposal has been to define the whole visual procedure with all its possible maneuvers being able to join it in different points depending on the aerodrome information provided and the type of approach in use.

To describe the procedures, there are some parameters about the aerodrome and the performances of the airframe that must be known before doing any computation. These data needed for the construction of the procedures have been grouped.

Once the procedures with its parameters and dependencies have been set, the guidelines for the developing of the workstation screens (for the studied cases) and the interaction between the different parts of the system has been established.

The main contribution of this work is the decrease of PiC workload in approach and departure procedures that the system should achieve when these improvements will be embedded. This objective has been achieved due to the mentioned procedures and the way to compute its waypoints and distances as well as to the establishment of the main views and buttons that the workstation should have and the flow of information between the related parts of the system.

Future work includes the creation of a database of aerodromes with all the procedures described; final design of the workstation screens; the link between the different abort causes, its managers and the way in which this manager behaves; the parameterization of the decision altitude on landing and the development of an automatic system of communication between the UAV and the ATC.

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APPENDIX

APPENDIX 1. WAYPOINT COMPUTATION

In this Appendix we present all the computations done in order to avoid the UAV do an impossible or dangerous maneuver. Where possible we have taken official OACI parameters [16]. An example with a visual approach to the airport of Sabadell is done too with the aim to illustrate these computations.

1. LANDING STATES

1.1.1. Land pattern (initial hold)

First of all, the turn parameters will be computed. Let us suppose a coordinate turn with no altitude change. We define our reference frame as the Cartesian couple [X,Y] with the origin at the center of mass of the aircraft, the Y axis parallel and with the opposite sense than the local gravity and the X axis perpendicular to Y and along the right side of the aircraft (see figure A1.1).

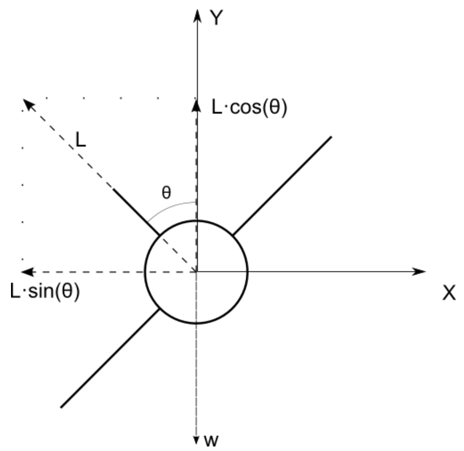

Fig. A1.1 Forces Diagram

Initially we have to determine our forces system, which is composed by the Lift (L), and the weight (W). If we express these forces into our reference system:

$$L \cdot \cos(\theta) = L_y \qquad \textbf{(A1.1)}$$

$$L \cdot \sin(\theta) = L_x \tag{A1.2}$$

$$W = m \cdot g \tag{A1.3}$$

Where θ is the bank angle, m the aircraft mass and g the local gravity module. If the aircraft is in equilibrium (horizontal flight) L_y must be equal to the weight and therefore:

$$L_y = W \tag{A1.4}$$

And L_x must be equal to the Centrifuge Force that allows the aircraft to describe a circumference:

$$F_c = m \cdot \omega^2 \cdot R \tag{A1.5}$$

$$L_x = \frac{m \cdot v^2}{R} \tag{A1.6}$$

Where v is velocity, R is the radius of the described circumference, ω the angular velocity. Then, if we divide equations A1.1 and A1.2, we have:

$$tan(\theta) = \frac{V^2}{g \cdot R} \tag{A1.7}$$

Equation A1.7 is the relation between the radius of our hold and the 'bank angle' of our UAV for a certain velocity.

1.1.1.1. Typical Holding speed

There is a typical holding speed which consists in describing a hold in two minutes. With that premise, we could compute this typical holding speed as:

$$\omega = \frac{V}{R} = g \cdot tan(\theta)/V = \pi/60 \leftrightarrow 180^{o} turn \rightarrow 60\ sec. \tag{A1.8}$$

With that premise and a typical value for θ of 25º [16], we could compute this typical holding speed as:

$$V = \frac{g \cdot tan(\theta) \cdot 60}{\pi} = 87\frac{m}{s} = \ 170\, Kt \qquad \textbf{(A1.9)}$$

However, the work carried out in this final degree project is done from the scope of small UAVs, which may not arrive to that velocity. In our computation example, we have chosen 80 Kt as hold and traffic pattern velocity. This velocity is typical for Cat A aircrafts in the traffic pattern procedure [16].

1.1.1.2. Computing the waypoints[33]

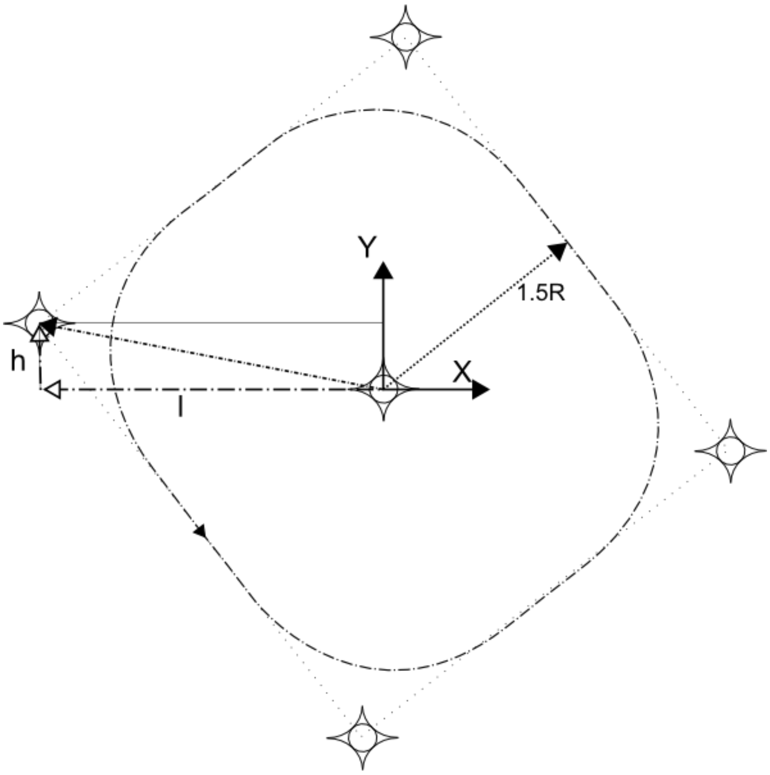

Fig. A1.2 Holding

Taking into account the previous computations, we have:

$$tan(\theta) = \frac{V^2}{R \cdot g}, \qquad V = 80\ kt; \qquad \textbf{(A1.10)}$$

[33] x,y are the coordinates of the center WP (center of the hold)

$$R = \frac{V^2}{g \cdot \tan(25º)} \qquad \textbf{(A1.11)}$$

$$R_{V=170kt} = 370\ m \qquad \textbf{(A1.12)}$$

$$1{,}5\ R_{V=170kt} = 555\ m \qquad \textbf{(A1.13)}$$

Now we could compute ‘l’ and ‘h’ as the distance (in meters) that we have to add to our reference point (the center of our hold) in order to compute our four WP:

$$l = cos(HDG + 45^o) \cdot 1{,}5 \cdot R \cdot \sqrt{2} \qquad \textbf{(A1.14)}$$

$$h = sin(HDG + 45^o) \cdot 1{,}5 \cdot R \cdot \sqrt{2} \qquad \textbf{(A1.15)}$$

$$WP1\ (x + l, y + h) \qquad \textbf{(A1.16)}$$

$$WP2\ (x + h, y - l) \qquad \textbf{(A1.17)}$$

$$WP3\ (x - l, y - h) \qquad \textbf{(A1.18)}$$

$$WP4\ (x - h, y + l) \qquad \textbf{(A1.19)}$$

Then, just applying the previous mathematics we have:

$$l = \ cos(128^o + 45^o) \cdot 1{,}5 \cdot 555 \cdot \sqrt{2} \qquad \textbf{(A1.20)}$$

$$h = \ sin(128º + 45º) \cdot 1{,}5 \cdot 555 \cdot \sqrt{2} \qquad \textbf{(A1.21)}$$

$$|l| = 1168\, m \qquad \textbf{(A1.22)}$$

$$|h| = 143\ m \tag{A1.23}$$

And we can easily arrive to the following points:

$$WP1\ (x + 1168, y + 143) \tag{A1.24}$$

$$WP2\ (x + 143, y - 1168) \tag{A1.25}$$

$$WP3\ (x - 1168, y - 143) \tag{A1.26}$$

$$WP4\ (x - 143, y + 1168) \tag{A1.27}$$

Fig A1.3 shows these four waypoints for the case of Sabadell's aerodrome:

Fig. A1.3 Initial hold at Sabadell aerodrome for an UAV at V=80kt

1.1.2. Max. Holding Speed

We are able to compute the maximum holding speed by taking into account the distance from the runway of the downwind leg (Fig. A1.4)

$$D = V \cdot 60 \qquad \textbf{(A1.28)}$$

And the condition that this distance D must be higher than the radius of our hold;

$D > R \rightarrow If\ D < R, the\ UAV\ wouldn't\ be\ able\ to\ achieve\ the\ 'Circling\ entry\ WP'$

$$V \cdot 60 > (V\hat{}2)/(g \cdot tan(\theta)) \qquad \textbf{(A1.29)}$$

$$60 \cdot g \cdot tan(\theta) > V \rightarrow typical\ bank\ angle = 25^{o}\ [16] \qquad \textbf{(A1.30)}$$

$$V < 274\ m/s\ =\ 533\ Kt\ is\ the\ maximum\ holding\ speed. \qquad \textbf{(A1.31)}$$

That maximum holding speed is enough since the holding speed proposed by OACI [16] (in turbulence conditions) is 280 kt .

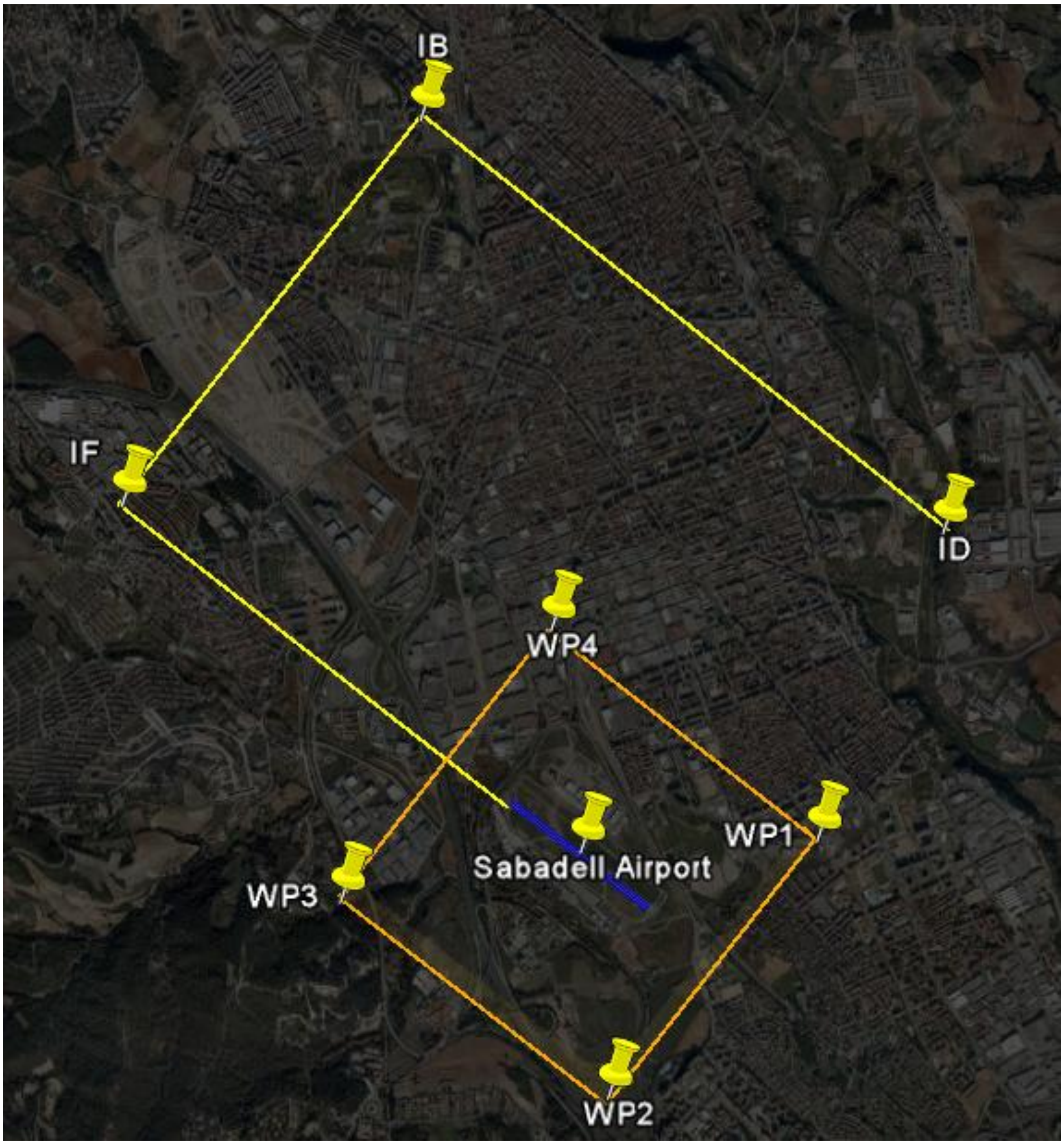

Fig. A1.4 Initial hold and traffic pattern

1.2. Autoland

1.2.1. Traffic Pattern

In order to describe the traffic pattern we must take into account that the main parameters to compute it are:

- Fly the downwind leg at 300 meters (1000 ft) AAL.
- The base leg is generally one minute length at the approach speed
- The base leg starts when the extended runway centerline forms a 45 degree angle with the line joining the aircraft and the landing runway threshold.
- When going around (in a missed approach maneuver), not to make any maneuvers which could bother other circuit traffic.

With these parameters[34], the following mathematics are required to compute the WP[35]:

$$60s\ 80\ kt\ =\ 2474\ m \qquad \textbf{(A1.32)}$$

Length of the different legs follows:

$$Downwind\ Leg: 2474 + RWY\ length\ [m] \qquad \textbf{(A1.33)}$$

$$Base\ Leg: 2474\ m \qquad \textbf{(A1.34)}$$

$$Final\ Leg: 2474\ m \qquad \textbf{(A1.35)}$$

Altitude of the different legs:

$$Downwind\ Leg: Aerodrome\ circuit\ altitude\ (1000\ ft) \qquad \textbf{(A1.36)}$$

$$Base\ Leg: Initial\ 1000\ ft, 500\ ft \qquad \textbf{(A1.37)}$$

$$Final\ leg: 500\ ft;\ Final\ at\ ground\ level. \qquad \textbf{(A1.38)}$$

[34] 1m/s=1,943 kt
[35] We are taking 80 kt as V_{app} to do these computations.

For these computations our origin of coordinates is the center of the runway,

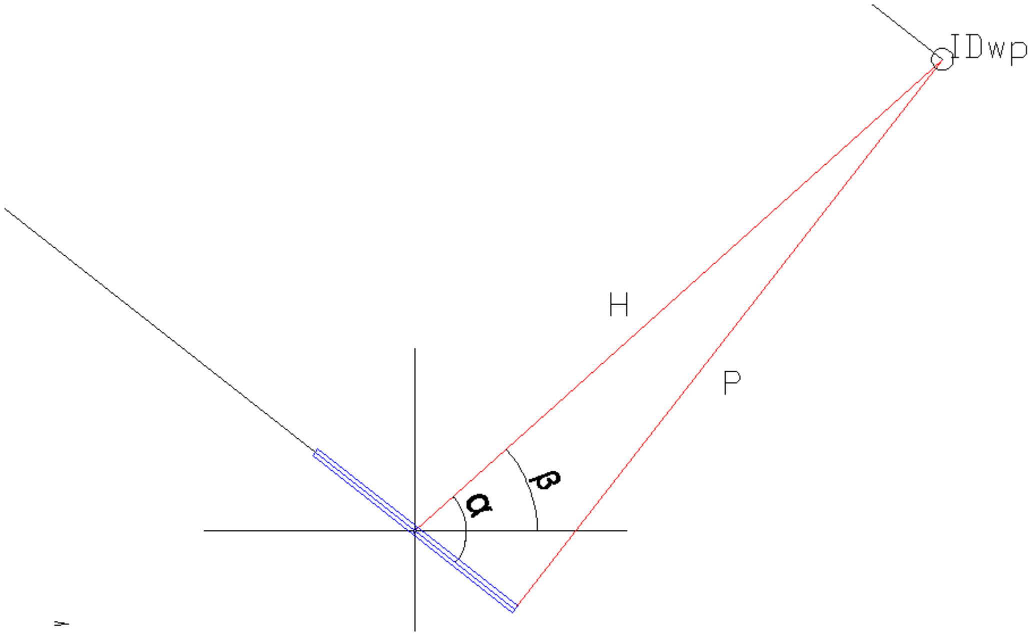

Fig. A1.5 Initial Downwind WP computation

1.2.1.1. Initial Downwind (ID) WP computation

In order to carry out this computation, we call H the distance between the center of the runway and the ID WP; P the distance between the RWY threshold and the same WP and alpha the angle between H and the RWY heading.

Known values are P and the runway length.

$$Tan(\alpha) = P/(\frac{RWY_{length}}{2}) \quad \textbf{(A1.39)}$$

Doing the arctan we are able to compute alpha, with this value and the arcsin of

$$Sin(\alpha) = P/H, \quad \textbf{(A1.40)}$$

we obtain H.

Now, and in order to compute beta (the angle between H and the x axis),

$$\beta = HDG - 180^o - \alpha \qquad \textbf{(A1.41)}$$

And now we are able to compute the position of ID

$$l = cos(\beta) \cdot H \qquad \textbf{(A1.42)}$$

$$h = sin(\beta) \cdot H \qquad \textbf{(A1.43)}$$

$$IDwp\ (x + h, y + l) \qquad \textbf{(A1.44)}$$

Initial Base and Initial Final waypoints (even the extended) could be computed following similar reasoning.

1.2.1.2. Hold at Downwind

Similar computations than in section A1.1 are done:

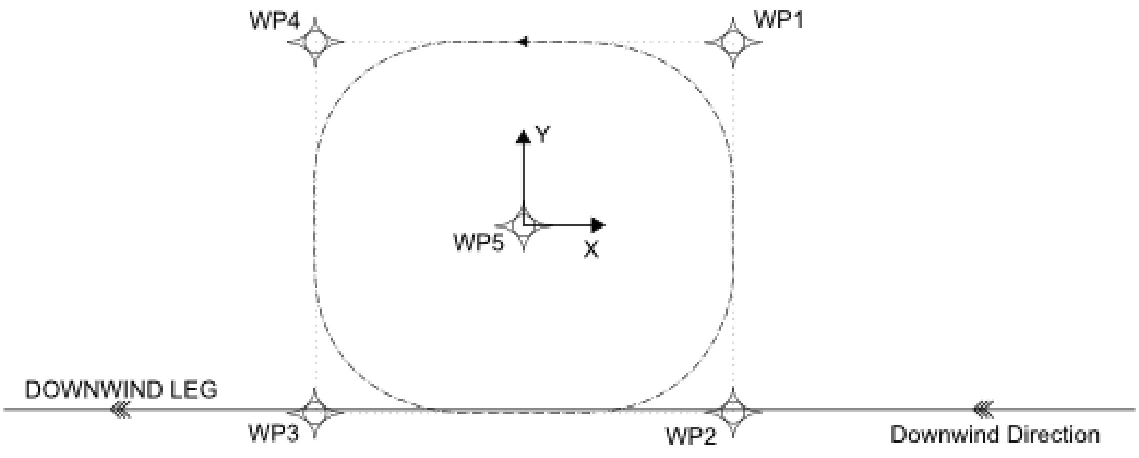

Fig. A1.6 Hold at Downwind

$$1{,}5\ R_{V=170kt} = 555\ m \qquad \textbf{(A1.45)}$$

$$l = cos(HDG + 45^o) \cdot 1{,}5 \cdot R \cdot \sqrt{2} \qquad \textbf{(A1.46)}$$

$$h = sin(HDG + 45^{o}) \cdot 1{,}5 \cdot R \cdot \sqrt{2} \qquad \textbf{(A1.47)}$$

We know that

$$WP1\ (x + l, y + h) \qquad \textbf{(A1.48)}$$

So,

$$WP5\ (x_{current} - h, y_{current} + l) \qquad \textbf{(A1.49)}$$

$$WP2\ (x_{current}, y_{current}) \qquad \textbf{(A1.50)}$$

$$WP3\ (x - l, y - h) \qquad \textbf{(A1.51)}$$

$$WP4\ (x - h, y + l) \qquad \textbf{(A1.52)}$$

$$l = \ cos(128^{o} + 45^{o}) \cdot 1{,}5 \cdot 555 \cdot \sqrt{2} \qquad \textbf{(A1.53)}$$

$$h = \ sin(128^{\underline{o}} + 45^{\underline{o}}) \cdot 1{,}5 \cdot 555 \cdot \sqrt{2} \qquad \textbf{(A1.54)}$$

$$|l| = 1168\,m \qquad \textbf{(A1.53)}$$

$$|h| = 143\ m \qquad \textbf{(A1.54)}$$

$$WP1\ (x + 1168, y + 143) \qquad \textbf{(A1.55)}$$

$$WP2\ (x_{current}, y_{current}) \qquad \textbf{(A1.56)}$$

$$WP3\ (x - 1168, y - 143) \qquad \textbf{(A1.57)}$$

$$WP4\ (x - 143, y + 1168) \qquad \textbf{(A1.58)}$$

1.2.1.3. Extended downwind

The placement of the IB is computed by adding (at least) 0,25 NM after the threshold of the runway.

The placement of the IBA is computed by adding steps of 30seconds to the downwind length.

The placement of WP3 and WP3A are derived from the stated above.

The angle of descent is computed by the VAS by knowing the current position and the desired TDF and TDS (Touch Down Speed).

Taking all these into account, the only parameter that we must compute is the placement of the WP2A and the placement of the WP3A:

Taking 80 Kt as our approach velocity, we could compute the next WP or just maintain HDG and velocity the steps of 30 seconds that the PiC requires.

In next figure we show the example for Sabadell:

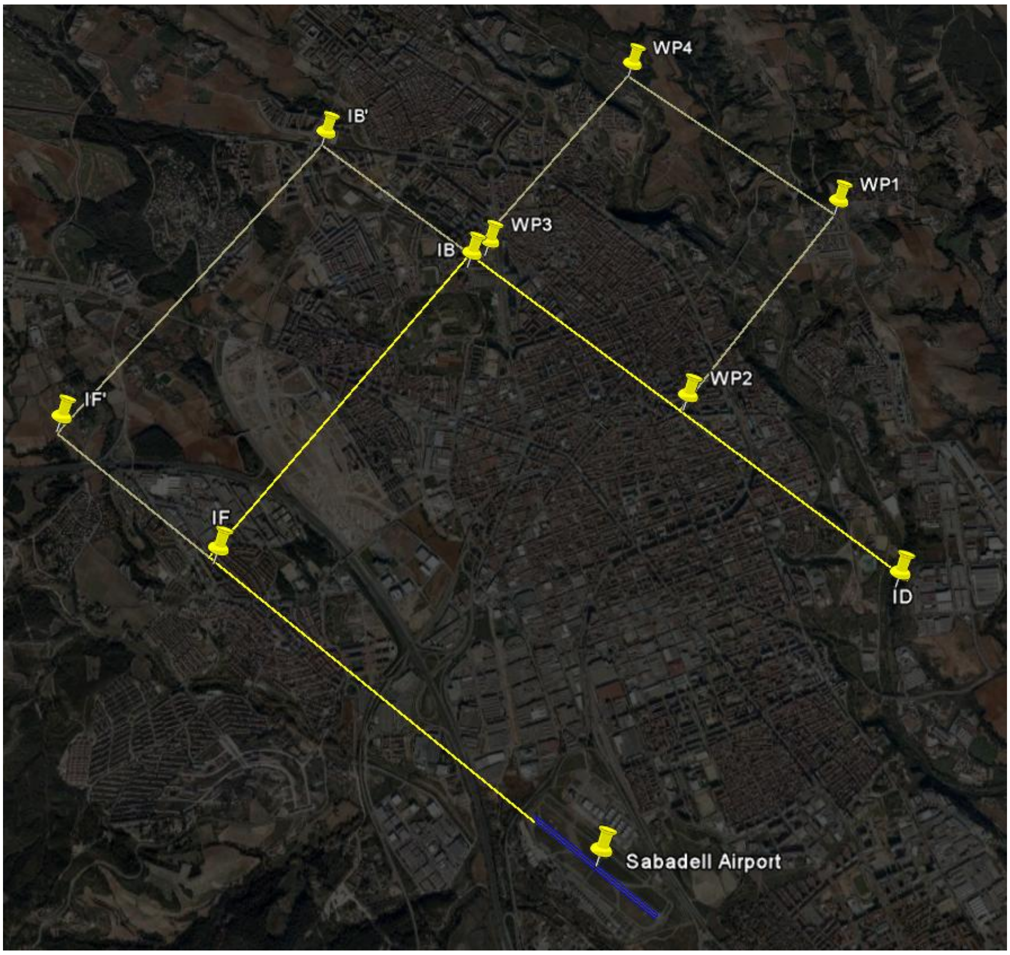

Fig. A1.7 Hold and Extended Downwind procedures and Traffic Pattern for Sabadell

1.2.2. Landing parameters

1.2.2.1. Slope

The airspeed at threshold V_{at} is the V_{s0} x 1.3, where V_{s0} is the stalling speed in landing configuration at maximum certificated landing weight [8]. In order to have this airspeed at threshold we have to mention that the UAV should reduce its airspeed velocity during the previous maneuvers.

1.2.2.2. TDF Margins

The margin which applies with the TDF will be set by subtracting the Stop Distance (SD) to the length of the runway and applying a 0,8 security factor to the margin distance. As this margin depends on the SD is very closely linked to the performances of the UAV. Positioning error has to be taken into account.

1.2.2.3. LD Margins

The LD is the distance from the UAV to the extended runway centerline. Positioning error has to be taken into account.

The estimation and comparison between the DTDF/DLD and RTDF/RLD is done until the UAV touches the ground. And it could change to the 'Abort' mode until the last moment.

1.3. Land abort state

There are no waypoints used only in the land abort state.

1.4. Departure

To compute these points we need data from the aerodrome[36] (RWY length, HDG[37] and coordinates of one of the thresholds[38]) and from the UAV's performances (V_{app}). And the following mathematics:

Doing similar computations than above and taking into account the diagram presented (Fig. A1.6)

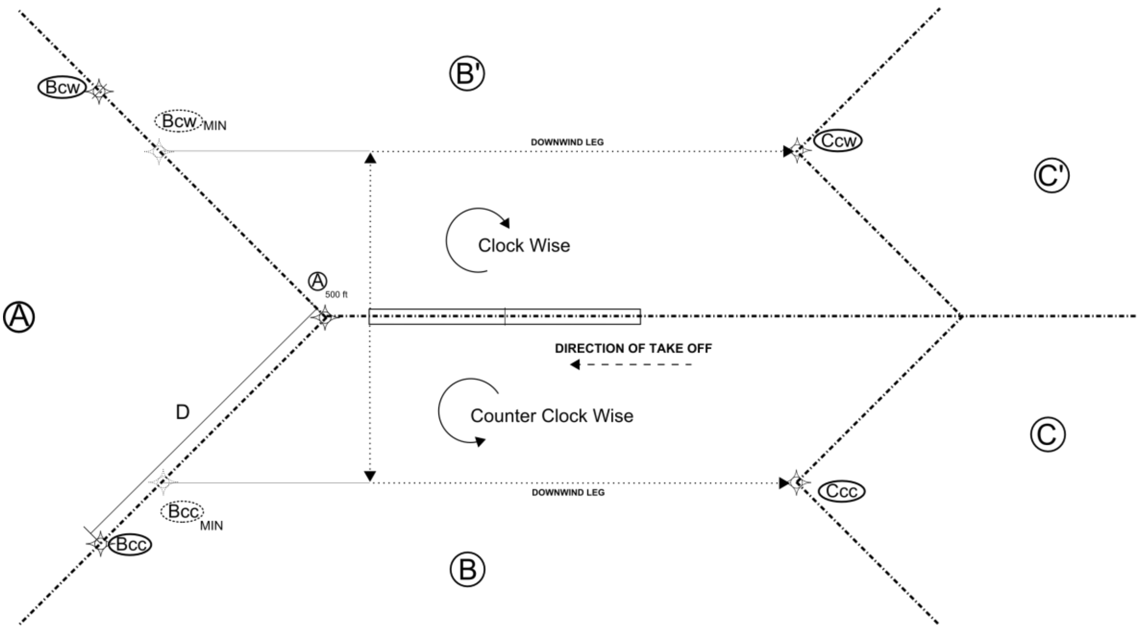

Fig. A1.8 Departure WP diagram

In order to assure the capability of the aircraft to arrive at both Bcw and Bcc, with the commented distance of radius computed for the hold we propose that distance so as to mark the position of these points. However, if taking into account this computation, they fall within the traffic pattern area, to avoid bothering other traffic, our proposal is to limit the placement of these WP to the extension of the downwind leg (see Fig A1.7).

With this diagram and those stated in section 3.3.1.1 'Construction of the diagram', we are able to present this example for Sabadell aerodrome in next figure:

[36] Here we are computing only the EDWs, to know more details about the 'Traffic Pattern' see Section 3.2.2.1
[37] The HDG is measured from the North (0º) in clockwise sense. The addition and substraction of angles in the following sections are computed according to that rule.
[38] We will use one threshold coordinates as our coordinates origin

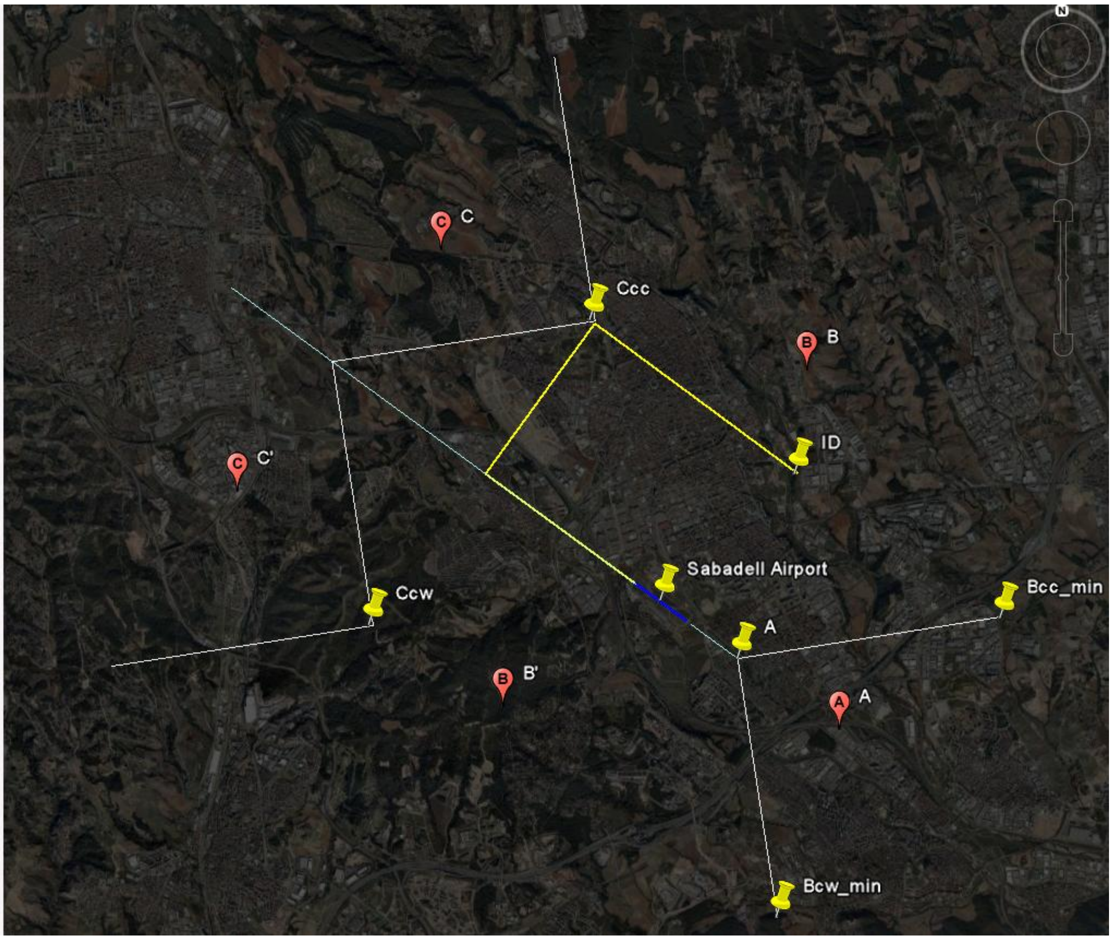

Fig. A1.9 End Departure Waypoints and Areas

APPENDIX 2: PARAMETERS

Here we present the needed parameters to compute the stated procedures as well as the way in which these parameters should be structured so as to aid in the computation of the following waypoints. This appendix is expected to mark the guidelines of an xml file which must be included in the ground segment of the system.

This data file takes into account both performances of the airframe (e.g. maximum and minimum velocities) and runway parameters (e.g. runway length) needed in the computation of the different procedures or waypoints.

Some of the waypoints have more than just the coordinates attribute. These attributes must be taken into account in order to compute safe procedures.

In this document, Coordinates are the position relating to the world geodesic system taken into account in the three axis as well as the velocity that the UAV should carry at the arrival to that waypoint

- Landing
- Sequence
  - Holding
    - Height
      - Max
      - Min
      - Preferred
    - Center WP
      - Coordinates
    - WP1
      - Coordinates
    - WP2
      - Coordinates
    - WP3
      - Coordinates
    - WP4
      - Coordinates
    - Entry WP
      - WP1/ WP2/ WP3/ WP4
    - Exit WP
      - WP1/ WP2/ WP3/ WP4
    - Sense
      - Clockwise/counterclockwise
    - Vapp
      - Max
      - Min
      - Preferred
    - Go_Traffic Pattern

Yes/No
Traffic Pattern
- Vapp
- Structure of Traffic Pattern
  - Initial WP
    - Coordinates
  - Downwind
    - WP2
      - Coordinates
      - Hold
        - Limits[39]
        - Do? (Yes/No)
          - Waypoints
            - Coordinates
              - Return?(Yes/No)
  - Extended
    - 30secSteps
    - WP2A
      - Coordinates
      - Limit
        - Coordinates
  - Base
    - WP3
      - Coordinates
    - Extended
      - WP3A
        - Coordinates
        - Limit
          - Coordinates

Landing
- Airport
  - RWY
    - Threshold
      - Coordinates
    - TDF
      - Coordinates
      - Margin
      - DTDF
  - LD
    - DLD

Missed Approach
- Safety Height
- Angle of ascent

Departure
- WPA
  - Height

[39] Limit: Final Downwind WP– 2·1.5RHold

500 ft
Coordinates
WPBcw
Min
Coordinates
Null (Yes/No)
WPBcc
Min
Coordinates
Null (Yes/No)
WPCcw
Coordinates
Null (Yes/No)
WPCcc
Coordinates
Null (Yes/No)