Airborne System for Self Separation in a Trajectory–Based Airspace

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***Abstract*—One way how to overcome the performance limitations of the current ATM systems is a partial delegation of the ATM tasks on aircraft equipped with appropriate airborne systems. The use of such an Airborne Separation Assistance Systems (ASAS) is envisioned both in the European Union (SESAR) and in the US (NextGen) for the 2025 timeframe. The primary goal of the EC FP6 project iFly is to identify safety and performance limitations of the airborne self separation during the en-route phase of flight. In addition, iFly aims to develop the airborne system requirements needed for safe self-separation operations. This paper presents the airborne system architecture drafted within the iFly's Concept of Operations and discusses its requirements on the global ATM environment, namely, on the information management services.**

***Index Terms*—ASAS, Avionics, Information Management, Trajectory Management**

I. Introduction

The current Air Traffic Management (ATM) system, still based on the principles adopted after World War II, reached its limits and is already unable to satisfy the current worldwide growth of air traffic. The known weaknesses include namely:

- Inferior information management
- Ineffective or missing automation–human task distribution
- Ineffective distribution of air–ground tasks and responsibilities.

The information management process is one of the main bottlenecks of the current ATM system. While the ATM tasks are performed by ground-based Air Traffic Control (ATC) centers, a lot of information about the actual situation is known only to the airborne side. For instance, ATC typically does not receive information about the instantaneous local conditions (local weather, aircraft state) as well as about aircraft's intended trajectory. On the contrary, the up-to-date global weather forecast necessary for better airborne trajectory planning is usually available only on the ground. As the ATM community is aware of this information management bottleneck, new information sharing systems are developed both in Europe (System-Wide Information Management (SWIM) within SESAR [1]) and in the U.S. (Net-centric Infrastructure Services within NextGen [2]). The existence of such information sharing services together with new airborne and communication capabilities are then key enablers for a more effective distribution of ATM tasks between air- and ground systems.

From an ATM perspective, the airspace can be divided into two types: the high traffic density areas around an airport (Terminal Maneuvering Area (TMA)), and the en-route airspace. Within TMA, the primary ATM goal is to ensure an effective use of the airport and the nature of the problem thus points to the use of a centralized control strategy. The main goal for the en-route airspace is to provide an effective flow of traffic which has no natural center of operations.

The airspace is further artificially split into sectors (horizontally as well as vertically) based on the need to overcome the limited capacity of ground-based human controllers. However, such sector-based approach has a natural performance limit: although it is possible to manage higher traffic density by reducing size of the sectors, this airspace management process increases the workload associated with the transfer of aircraft between sectors and with the inter-sector planning.

A possible way to overcome these major limitations is to replace (at least partially) the centralized ground-based control by a distributed control system using advanced airborne avionics [3]–[5].

The iFly project aims to provide safety and performance analysis of an advanced en-route self separation[1] ATM system. In this context it continues in the theoretical work performed within the project HYBRIDGE[2] [8] and the validation experiments in the Mediterranean Free Flight (MFF) project [9]. For this purpose two design cycles are envisioned: while the first design cycle (Autonomous Aircraft Advanced (A3) Concept of Operations) is confined on the autonomous aircraft concept, i.e., flight operations completely without ATC interventions, the second design cycle aims, apart from a further refinement of A3, to study how A3 equipped aircraft fit within the SESAR environment.

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[1] *Self separation* is a new separation mode in which aircrews are the designated separator for a defined segment of flight during which they shall assure separation from all other aircraft [1].

[2] At this INO workshop, some other innovative results that have been obtained with the help of the HYBRIDGE developments are presented in [6] and [7].

This paper aims to present a functional overview of the airborne self-separation system drafted in the iFly A3 Concept of Operations [10] with emphasis on its requirements for the global ATM environment, in particular, considering information sharing services.

The goal of this system is to enable a safe[3] and efficient autonomous flight through an en-route airspace. This en-route phase of flight is ended by a flight constraint (3D point with a time interval) at the entry point of the destination TMA. Such a flight is enabled by the following functionalities of the system:

- **Separation Management** which prevents the loss of separation (according to the applicable minimum separation standards) between the own aircraft and the surrounding traffic
- **Trajectory Management** that takes advantage of the flexibility provided by an autonomous aircraft concept for an efficient airborne flight optimization
- **Information Sharing** that enables a good predictability of the own flight trajectory for other airspace users.

Due to the fact that within A3 more tasks and responsibilities will fall on the operating crews, the whole airborne system is designed as a pilot's supporting tool. This implies that a certain amount of automation is a vital necessity. The system automatically collects the information needed for flight optimization (weather, obstacles, ...) and about surrounding traffic and helps in detecting potential conflicts. The aircrew is provided with all information which is necessary to build a high level of traffic situation awareness any time during flight in order to enable the aircrew to make even critical decisions in a timely and accurate manner. In this sense the automated functions are geared to leading the aircrew to safely perform safety critical work conditions, instead of taking them out-of-the-loop. It will support the crew in the decision making process by providing possible solutions in form of maneuvers/trajectory presented to the flight crew through a suitable Human Machine Interface (HMI). The parameters which supplied the solutions are alterable according to the flight crew needs and when finally a maneuver is accepted, it can be executed using automated guidance system (FMS, autopilot) or manually.

This paper is organized as follows: First, we discuss some general aspects of the trajectory information sharing and how this information can be communicated to maintain traffic situation awareness during autonomous operations. Subsequently, a functional description of the A3 airborne system is provided as well as its role within the iFly project framework.

II. Information Sharing Environment

Safety and performance limits attainable by a self separation airborne system are directly affected by the information available onboard of an autonomous aircraft. For instance, the safety aspects are critically depending on the completeness of the traffic information. For autonomous aircraft concept it means to ensure that an aircraft and its crew know at any moment about **all** flights in its vicinity. In addition, the capability to predict time evolution of the air traffic situation is reliant on the availability of information about intended trajectories of neighboring aircraft. Yet further information is then needed for the trajectory optimization tasks.

A. Flight Trajectory Information

There are two fundamental levels of the trajectory information: data about the current state, and the planned trajectory. A range of the planned trajectory may differ according to its purposes. For example within the FMS the trajectory is always generated up to the final destination.

Within ATM, trajectory information is typically used for the following purposes:

- Strategic planning of the load of the resources (airports, sectors or, more generally, arbitrary parts of airspace)
- Detection of conflicts with other aircraft.

The current ATM system is typically based on the use of state information (and its extrapolation) for conflict detection and the flight plan, which contains a sequence of navigation waypoints with estimated take-off and landing time, for strategic planning. In the future, it is anticipated that for strategic planning purposes a more detailed and up-to-date trajectory, a so-called Reference Business Trajectory (RBT) in SESAR [1], will be provided by each aircraft. In addition, the use of a limited amount of the trajectory data is also envisioned for conflict detection. Consequently, the following three types of trajectory information are considered for ATM purposes:

- State information (e.g., position, speed, …)
- Intent information (a part of intended 4D trajectory usable for conflict detection purposes)
- RBT (planned trajectory for strategic resource load planning)

Distinct purposes of each level of flight information impose different requirements on their accuracy and reliability. For instance, Conflict Detection (CD) applications require more accurate information than load planning of airspace and airports. An aircraft can also provide more accurate trajectory for a shorter look-ahead time where the accurate information from its onboard sensors (mainly about wind) can be used. On the contrary, longer trajectory predictions depend on the availability of a global weather forecast whose accuracy is considerably lower. Although modern aircraft guidance and navigation systems are in principle able to follow a predefined 3D+ trajectory (3D trajectory with time constraints on specified points), this capability should be used with care as the price for compensation of the Trajectory Prediction (TP) inaccuracies (especially considering time dimension) may be high.

[3] The iFly approach to the safety analysis of self separation operations is discussed, e.g., in [11].

A very important research parameter is the optimal time horizon of the intent information (usually referred to as a Mid Term timeframe) as it determines the effective time horizon of the corresponding Conflict Detection & Resolution (CD&R) tools. Although it is affected by multiple factors the accuracy of the available trajectory information (influenced by stochastic factors and equipment limitations) and trajectory reliability (with longer look-ahead time, the probability that the trajectory will be a subject of an ATM intervention increases) are crucial characteristics. Unfortunately, the second aspect cannot be in principle evaluated without the validation of the whole ATM system. The Mid Term timeframe considered within the current ATM research is usually affected by the typical size of the current ATC sectors (typically about 20 minutes of flight). The most suitable intent timeframe for distributed control system can be different (e.g., 10 minutes used in NASA research [12]). It is essential that both airborne and ground-based applications are considered in developing intent communication standards for future ATM system.

B. Traffic Situation Awareness

The critical requirement of an airborne CD&R is to guarantee that every aircraft will continuously have information about all traffic in its neighborhood. Usually, it is assumed that this goal can be achieved through a reception of the datalink broadcast of other aircraft (e.g., ADS-B). However, a distributed system based uniquely on this type of communication may be considerably affected by technology limitations. First, the range and reliability of a broadcast transition may be insufficient for the requirements of airborne CD&R.

Another issue emerges in the case when an aircraft does not communicate at all, or information transmission fails, e.g., due to interference problems. Within the current ATC system the continuity of monitoring of all aircraft is guaranteed by the transfer procedure between sectors.

Within the A3 ConOps this problem is solved by a SWIM ground application which monitors all traffic and periodically provides each aircraft with a complete list of flights in its vicinity. The aircraft's area of interest is described by so-called **Mid Term Awareness Zone** defined to cover all traffic that could potentially cause a conflict within the timeframe considered for trajectory-based CD (Mid Term). The traffic list is dynamically compiled using up-to-date RBTs available in SWIM.

In addition, an aircraft can obtain information about other flights using any of the following communication services:

- Reception of (periodical) broadcasts of other aircraft (e.g., ADS-B)
- Direct querying another aircraft (e.g., an Air – Air equivalent of ADS-C)
- Querying ground infrastructure (e.g., SWIM).

While the broadcast is still considered as a primary source of information, there are two additional possibilities to query information about aircraft on the traffic list for which the broadcast communication fails: Air – Air datalink and ground systems (see Figure 1).

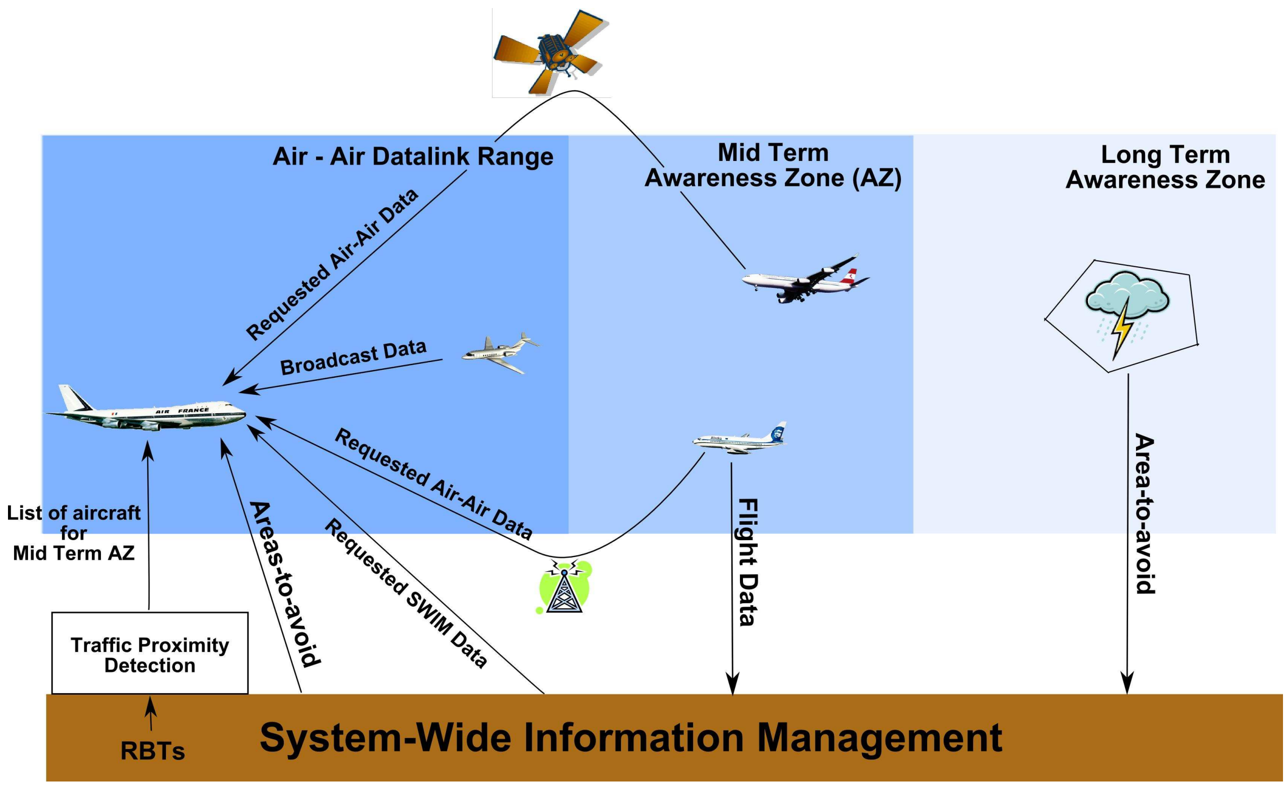

Figure 1: Overview of communication services considered for maintaining the onboard situation awareness.

C. Onboard Flight Planning

One of the most important advantages of the autonomous aircraft concept is a higher flexibility for dynamic optimization of the flown trajectory. An essential prerequisite of such trajectory optimization is a sufficient knowledge of the weather forecast, flight obstacles, airspace restrictions and other strategic factors. In the future ATM systems, the access to these information is anticipated through a ground-based information sharing systems, such as SWIM. The aircraft's area of interest considering this kind of information is defined in A3 as a so-called **Long Term Awareness Zone** covering the neighborhood of the actual RBT up to the predefined time horizon/range or for whole self-separation part of flight (up to the TMA entry point).

Potential risks are represented in terms of areas-to-avoid. They may include restricted areas, weather hazards, terrain, etc. Furthermore, within the A3 Concept of Operations it is considered that this information can be complemented by a strategic information about air traffic in the form of congested areas (detected by an automated ground system).

D. Communications Overview

Figure 1 depicts the overview of the communication channels anticipated for maintaining the airborne traffic situation awareness. This figure represent a single-track view on the data transfer problem, namely, only data potentially used by own aircraft are shown.

III. AIRBORNE SYSTEM DESCRIPTION

The architecture of the A3 airborne system discussed in this paper is shown in Figure 2. The purpose of this chapter is not to describe a possible implementation of such a system but rather to provide a high level analysis of needed functionalities. The whole system can be divided into five functional units:

- Information Management
- Conflict Detection
- Conflict Processing
- Conflict Resolution
- Trajectory Update Management (Trajectory Synthesizer and Trajectory Management)

A. Information Pre-processing (Information Management Unit)

As discussed in the previous chapter, an Airborne Separation Assistance System (ASAS) is dependent on the information sharing technologies and procedures. However, the typical development cycles of avionics and the global communication standards are quite different. The goal of the Information Management Unit is to hide technological and operational details of the communication services from the remaining parts of the airborne system. For this purpose it manages the communication channels to collect and process all required information.

In particular, the Information Management Unit is responsible for the following tasks:

1. Process all incoming data broadcasted from surrounding aircraft
2. Periodically process the list of neighboring traffic (obtained from an automated ground tool) and detect missing information traffic
3. Complement missing traffic information by querying the corresponding aircraft or SWIM
4. Process areas-to-avoid information and weather forecast data uploaded from ground and provided by onboard sensors (weather radar, Ground Proximity Warning System, etc.)
5. Monitor the conformance of surrounding aircraft to their intended trajectory (if available).

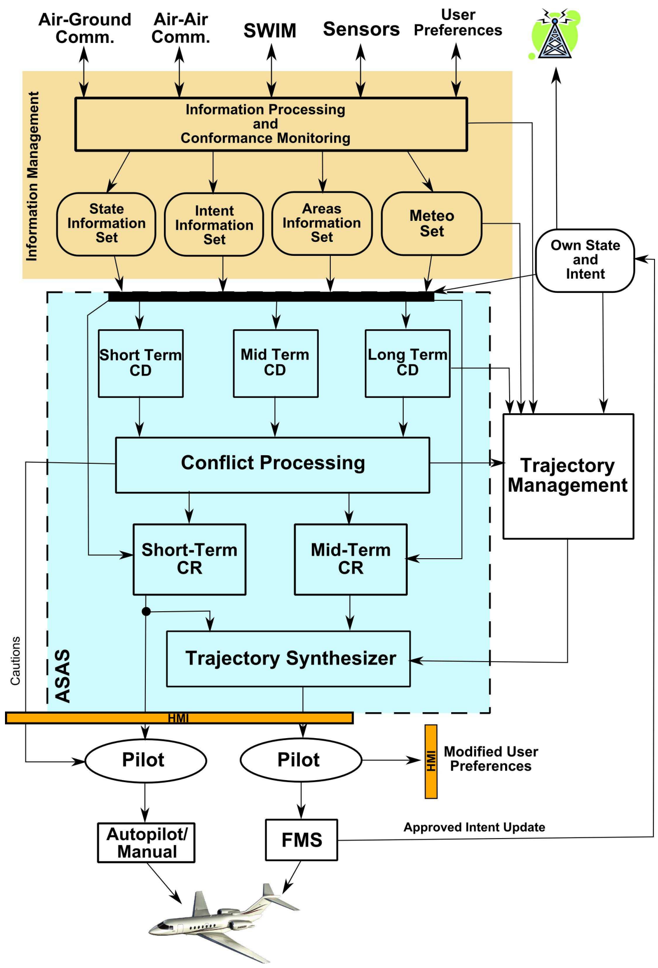

Figure 2: Functional overview of the airborne system architecture drafted within the iFly A3 Concept of Operations.

The output of this information management process is represented by four information sets:

- **State information set** will contain all up-to-date state information obtained from the broadcast of surrounding aircraft.
- **Intent information set** will contain the best estimate of intended trajectories of all aircraft within the Mid Term Awareness Zone. This

information will be complemented by conformance parameters obtained through a comparison of state and available intent information.

- **Areas information set** will contain information about all areas-to-avoid (e.g., restricted areas, weather hazards, congestion areas, etc.).
- **Meteo set** will contain up-to-date information about the weather forecast.

The primary goal of the Information Management Unit is to ensure that the airborne system has intent information about all aircraft inside its Mid Term Awareness Zone and an efficient data fusion.

B. Conflict Detection

In the system, there are three CD functions which are running in parallel and independently. All detected conflicts are provided to the integrative Conflict Processing function which ensures the overall situation analysis and determines the appropriate actions.

- **Long Term CD** detects conflicts with areas-to-avoid provided by a ground support and onboard sensors. This kind of conflict is used both for Trajectory and Separation Management.
- **Mid Term CD** module represents the key part of the CD process for Separation Management. As the intent information set contains the best available estimate of the trajectories of neighboring aircraft, the majority (ideally all) of the Separation Management tasks should be performed within this timeframe. In addition to a detection of potential Losses of Separation, it is anticipated that this module will also detect situations that could potentially represent a risk for system's CR functionality. Two possible approaches are considered: a detection of the situations with high traffic complexity [13] or the situations that reduce significantly aircraft's flexibility of maneuvering [14].
- **Short Term CD** module uses an extrapolation of the state information for a short look-ahead time (the parameter to be determined but typically about 2 minutes) and plays a role of the Separation Management safety backup.

A simplified overview of the described CD process is shown in Figure 3.

C. Conflict Resolution

Depending on the urgency of the conflicting situation there are two different Conflict Resolution (CR) functions able to generate possible solutions. The urgency of a conflict is reflected by the execution delay parameter, which defines the maximum delay in starting the execution of the resolution maneuver. The execution delay is necessary for the flight crew to assess and understand both the situation and the proposed solution(s) and to prepare its execution.

It is anticipated that the system can generate two kinds of the flight trajectory changes:

- *Closed maneuver* which can be described in terms of a new consistent trajectory up to the destination. This is a preferable method in order to solve conflicts as the up-to-date trajectory information may be immediately provided to other airspace users.
- *Open maneuver* solves a detected conflict situation but a continuation of the flight after the maneuver is not considered. This method is used only for urgent conflicts when a short time-to-conflict exclude more optimized closed solutions. The A3 airborne system is designed to minimize the delay before an open maneuver is completed and transformed into a closed one.

Apparently a consistent update of the trajectory (closed maneuver) typically requires a more complex situation assessment than a single open maneuver. These considerations are reflected in the two CR modules included in the system:

- **Short Term CR** generates open maneuver solutions with an execution delay typically about 30 seconds (exact value to be determined).
- **Mid Term CR** provides closed maneuver solutions with an execution delay (research parameter) typically about 1-2 minutes.

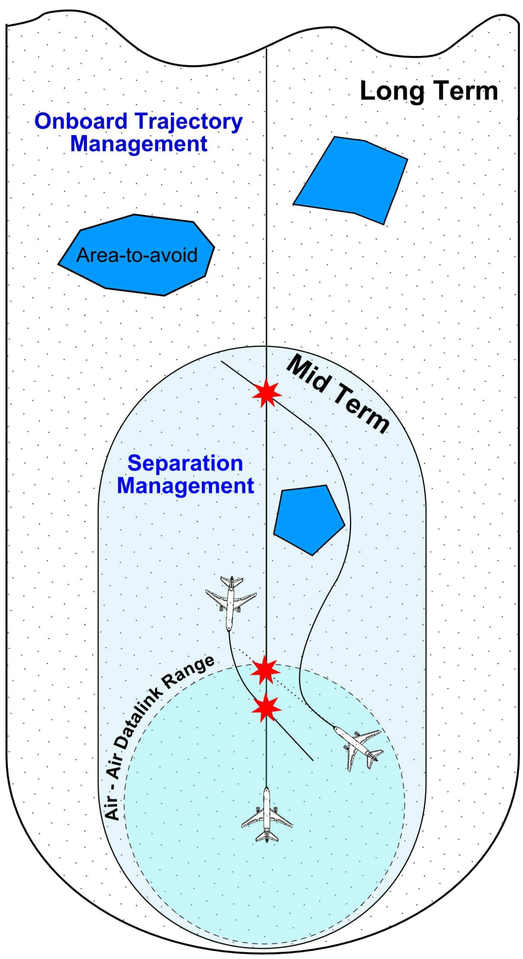

Figure 3: Overview of the Conflict Detection Process.

An important operational issue of any airborne distributed control system is a coordination of the conflict resolution maneuvers among the conflicting aircraft. Usually three possible types of coordination are considered: explicit coordination based on the negotiation among conflicting aircraft, implicit coordination based on the compatibility of algorithms (typically geometrical) ensuring a mutual complementariness of the CR maneuvers applied by conflicting aircraft, and priority rules. The advantages and drawbacks of different approaches are discussed, e.g., in [15]. The A3 operational description is based on the use of priority rules for closed CR maneuvers and implicit coordination for open CR maneuvers.

D. Conflict Processing

The Conflict Processing module is the heart of the A3 airborne system. It processes information coming from all three CD functions and determines the appropriate action(s). It is performed by prioritizing detected conflicts and balancing the safety and the false alarm rate aspects. In addition, this module controls information displayed to the flight crew to maintain its situation awareness.

The main goal of the Conflict Processing function is to determine if the situation requires a modification of the current trajectory. In this case one of the corrective actions is selected:

- Short Term CR (short execution delay)
- Mid Term CR (longer execution delay)
- Trajectory Management for (area) conflicts beyond Mid Term timeframe.

Some situations may not represent a conflict at the moment but there is a possibility that they can evolve to a dangerous situation under specific conditions. In this case some of the surveillance actions can be taken:

- Situation is registered and further analyzed during following iterations
- A caution is provided to flight crew.

E. Trajectory Update Management

As discussed in the previous chapter, the key requirement of the information sharing airspace is that all aircraft provide up-to-date information about their intended trajectory. The goal of the Trajectory Synthesizer module is to manage all flight changes and ensure that a consistent RBT update is available (and shared) as soon as possible. For instance, when an open CR maneuver is executed, the Trajectory Synthesizer immediately initiates a generation of the suitable maneuver continuation in order to obtain a closed trajectory updates. For these purposes it can call other system functions (not shown in Figure 2).

The Trajectory Synthesizer also manages the optimization-driven updates generated by the Trajectory Management module. These updates are generated periodically, on-demand, or on the event-basis (e.g., updated weather forecast). The related trajectory modifications affect only the trajectory beyond the Mid Term timeframe in order not to interfere with the separation management functions.

IV. CONCLUSION

The idea of an autonomous aircraft concept is not new [3]. The main obstacle to its realistic flight testing and a potential implementation is its critical dependence on the reliability and efficiency of the Air – Air communication and on the availability of information in general. This is also reflected in the anticipated implementation timeframe within the SESAR [16] and NextGen [17] frameworks, as the Air – Air datalinks are deployed later than Air – Ground communication services. However, as discussed within this paper, a lot of information requirements (especially trajectory related) are common for the ASAS and the ground-based automated tools (in particular Medium Term CD&R). In this context, it is desirable that both airborne and ground applications are considered in developing relevant communication standards, e.g., for the flight intent.

The proposed system aims to maximally benefit from the communication technologies and information sharing services anticipated in the future ATM system. However, it is also designed in the scalable way allowing to reflect the situation where the information sharing services are degraded. Similarly, it is possible to envision several airborne capability levels. For instance, general aviation or aircraft flying in low density airspace may rely completely on the availability of the state information obtained from broadcasts of surrounding aircraft. A key research question is to determine and classify performance limits (respecting valid safety criteria) of the airborne system for different levels of available information and available information management support.

The iFly project has two main objectives: to assess the highest level of en-route traffic demand in which well equipped aircraft can safely self separate, and to develop the airborne system requirements that must be met to ensure the safe operations in our future airspace (2025+).

Additional requirements result from the mixed equipage operations. Currently both SESAR and NextGen consider a possibility that IFR and self separating aircraft are flying simultaneously within the same part of airspace. Even if this topic is out of the iFly scope, the trajectory focused approach adopted in the design of the presented system should considerably simplify such mixed operations as well as limited delegation aspects (ASAS separation).

The airborne system presented in this paper aims to provide separation and trajectory management functionalities. In the current form it does not consider the Collision Avoidance capability that essentially prevents a collision in the case of a Loss of Separation. The A3 Concept of Operations assumes the presence of such a system (e.g., TCAS) onboard in the role of an independent safety backup.

Some of the presented functionalities are completely missing in the existing avionics, others are at least partially implemented in the current systems (e.g., partial trajectory optimization in FMS). The discussion whether required functionalities should be implemented as an enhancement of the existing systems or as a completely new system is out of scope of this paper.

The iFly project began its work in May 2007, and will run for 39 months. The public deliverables and other results will be available at **http://iFLY.nlr.nl**.

ACKNOWLEDGMENT

Thanks to the whole iFly WP1 team, in particular to Frank Bussink (NLR), Ignacio Echegoyen (former Isdefe), Gustavo Cuevas (Isdefe), and Aavo Luuk (University of Tartu), for the fruitful and pleasant teamwork on the A3 Concept of Operations and to all iFly partners for their valuable comments.

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