Safe, airborne self-separation operations in tomorrow's airspace?

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Abstract

Autonomous aircraft, responsible for self separation from surrounding traffic and other conflict areas, are part of the future air traffic management system envisioned by both the European Union (EU) and North American government agencies for the 2025 time frame. The objective of the EU-funded iFly program is twofold: to assess the highest level of enroute 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 operation of these autonomous aircraft in our future airspace. This paper will discuss the future environment and the advanced airborne equipage of autonomous aircraft, the uncertainties that the airborne self separation support systems must deal with, and the steps we will take on the iFly program to determine the potential safety risks and hazards that must be mitigated in order to ensure safe, airborne self-separation operations in enroute airspace amidst high traffic demand.

Introduction

The European Union and the United States are developing advanced concepts of operations in support of safe air traffic management (ATM) for tomorrow's high density airspace. These developments are enabled by advances in communication, navigation and surveillance (CNS) technologies. The European SESAR [1] and the US NextGen [2] concept of operations define the ground and airborne technologies that are needed to ensure safe (i.e., equal or better than today's safety levels) air traffic management at traffic densities up to three times the level observed in 2005. Both SESAR and NextGen envision trajectory-based ATM for the 2020+ timeframe and a shift in separation management responsibilities from the air traffic controller to the flight crew. Trajectory-based operations will enable the management of flights via the 4 dimensional specification (latitude, longitude, altitude and time) of an aircraft's current and future position.

Today, one of the major obstacles to managing the anticipated traffic capacity increase is the limitation that the Air Traffic Controller (ATCo) brings to the decision making processes. In order to overcome this limitation, the idea of airborne self separation was proposed more than a decade ago, under the name of "Free Flight" [3]. Essentially, "Free Flight" aimed to transfer all separation tasks to the pilots. Since then, "Free Flight" has received ample attention from the ATM research community, and significant progress has been made. Nevertheless, the ATM research community remains divided into optimistic and cautious schools of thought. The optimistic school believes that airborne self separation can be safe under high enroute traffic demand; the best evidence is that piloted real time simulations have shown that pilots perceive the airborne self separation concept of operation to work well under high traffic demand. The cautious school agrees that airborne self separation can be safe amidst low traffic demand but not amidst high traffic demands in busy enroute airspace. For the cautious school piloted real-time simulations fall short in assessing rare non-nominal conditions under significant traffic demand. In fact the difference between the two schools is not whether or not airborne self separation is feasible, but up to which traffic demand level it is safe. From a research perspective this difference between the two schools asks for a systematic study of the safety risk level of airborne self separation concepts of operation as a function of traffic demand and a comparison of the assessed risk level against proper safety targets. The iFly project aims to systematically investigate this question for en-route airspace by the exploitation and further development of the mathematical techniques that recently emerged through the HYBRIDGE project [4].

In recent years, a trend in ATM community research has been to direct large airborne self separation research projects to situations of less dense airspace. This is remarkable because airborne self separation has been "invented" as a potential solution for high density airspace. If iFly is able to show that airborne self separation is safe at high traffic densities, then this forms great motivation for NEXTGEN and SESAR to establish a step change in this trend.

The aim of this paper is to outline the approach taken on the iFly project. This paper is organized as follows: First, we introduce the issue of maintaining a predefined minimum separation between aircraft, and how this is expected to change in the future. Second, we outline the functionality of advanced airborne self separation and the enabling technical systems. Third, three complementary safety approaches are outlined which will be exploited within the iFly project in support of building safety into the design of the advanced airborne self separation operation, and to assess up to which en route traffic demand airborne self separation may work safely.

Preventing Loss of Separation Minima

Self Separation aircraft will be responsible for separation from other aircraft using Autonomous Flight Rules (AFR), which are expected to mirror current ICAO Annex 2 IFR rules, but take into account the shift in separation responsibilities from ground-based ATC to the airborne side. For example, for conflict avoidance within a mid term time horizon (15-20 minutes), priority rules will determine which aircraft has "the right of way" and which aircraft must manoeuvre to avoid a potential conflict; AFR aircraft can not willingly create a short term conflict or manoeuvre in a way that it causes unacceptable traffic flow complexity.

A key issue in the design of future ATM will be the concept of preventing the loss of minimum separation between aircraft (or between an aircraft and conflict areas such as convective weather, terrain, or no fly zones). In conventional radar controlled en route air space, the primary responsibility of the air traffic controller is to ensure that flights remain within international standards of safe separation. Current ICAO regulations prescribes that in modern radar controlled en route airspace, aircraft must be separated at least five nautical miles horizontally or 1000 feet vertically from other aircraft. Recently, within the European Commission RESET project, a need has been identified to reduce the horizontal value from 5 to 3 nautical mile in future busy en route airspace [5]. Whether these reduced separation minima are suitable to airborne self separation operations shall be assessed within the iFly project.

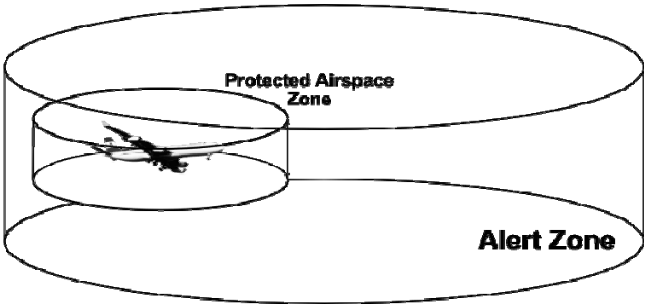

Figure 1 — The Protected Airspace and Alerts Zones surrounding an aircraft

As shown in Figure 1, separation minima can be defined in terms of a Protected Airspace Zone (PAZ) that should not be penetrated, or an Alert Zone (AZ), which, when (potentially) penetrated, may trigger intervention by pilots. The dimensions of the PAZ and Alert Zone may change as the navigation and surveillance capabilities of equipped aircraft improve and the reliance on ATC for separation management is delegated to the onboard automation system.

Airborne Self Separation Decision Support

An advanced airborne self separation concept of operation is expected to be critically dependent on enhanced airborne automation and decision aides to augment the pilot's traffic awareness and conflict avoidance capabilities of the aircraft. AFR pilots, performing autonomous flight operations, will have several support systems that allow them to maintain separation minima and safely resolve any hazards that have the potential to underscore the applicable separation minima. Decision support systems that are designed to provide effective support when an aircraft potentially underscores any separation minima are typically referred to as safety nets. In very specific non-nominal and emergency situations there are special procedures in using these safety nets.

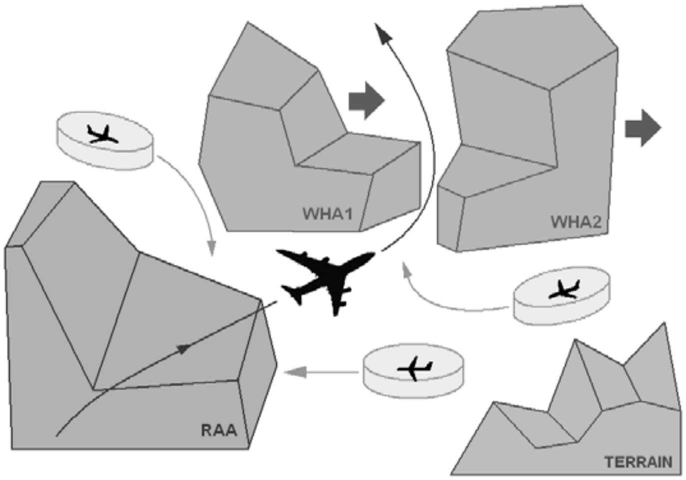

Figure 2 — Types of Conflict Areas

As is shown in Figure 2, on-board equipment must assess, prevent, detect and solve potential conflict situations when an aircraft could enter a Restricted Airspace Area (RAA), a Weather Hazard Area (WHA), a Terrain/Obstacle restriction or the PAZ of another aircraft. This functionality will be provided by a future airborne system called the Airborne Separation Assurance System (ASAS). The conflict detection and resolution (CD&R) tasks within the ASAS will need to be executed in a timeframe that will allow the airborne Flight Management System (FMS), autopilot or flight crew to avoid the conflict in a safe and timely manner. The system requirements for the on-board technical system reliability and performance will be identified within the iFly project.

Following [6], airborne self separation decision support systems for pilots take all available sources of information about neighboring traffic and environment into account and consider various flight time-to-conflict/hazard horizons, such as:

- **Short-term timeframe** – typically 3-5 minutes, up to which a flight trajectory can be reconstructed from aircraft state data (e.g., speed, heading, altitude).
- **Mid-term timeframe** – typically 10-20 minutes, up to which an accurate flight trajectory can be reconstructed from intent data (data describing the aircraft intended trajectory in 4 dimensions: latitude/longitude, altitude and time).
- **Long term timeframe –** typically more than 30 minutes, used for dynamic onboard trajectory optimization.

As the aircraft calculates potential conflicts within these time horizons, one or more Conflict Detection and Resolution **(**CD&R) applications can be used to ensure a safe flight trajectory. Three levels of traffic/hazards information are processed in parallel by three independent CD&R applications, as shown in Figure 3:

1. **Areas CD&R** combines information about hazardous or restricted areas with state and intent data from its own aircraft to identify possible penetration of undesirable areas within the long-term timeframe (across all three considered timeframes).
2. **Intent CD&R** combines intent information from surrounding aircraft with state and intent data from its own aircraft to perform intent-based CD&R for the Mid-term timeframe (including short-term). The Intent CD&R function may also detect areas of high complexity (assessed by an appropriate complexity metric).
3. **State CD&R** combines state information from surrounding aircraft with state data from its own aircraft to perform CD&R for the Short-term timeframe.

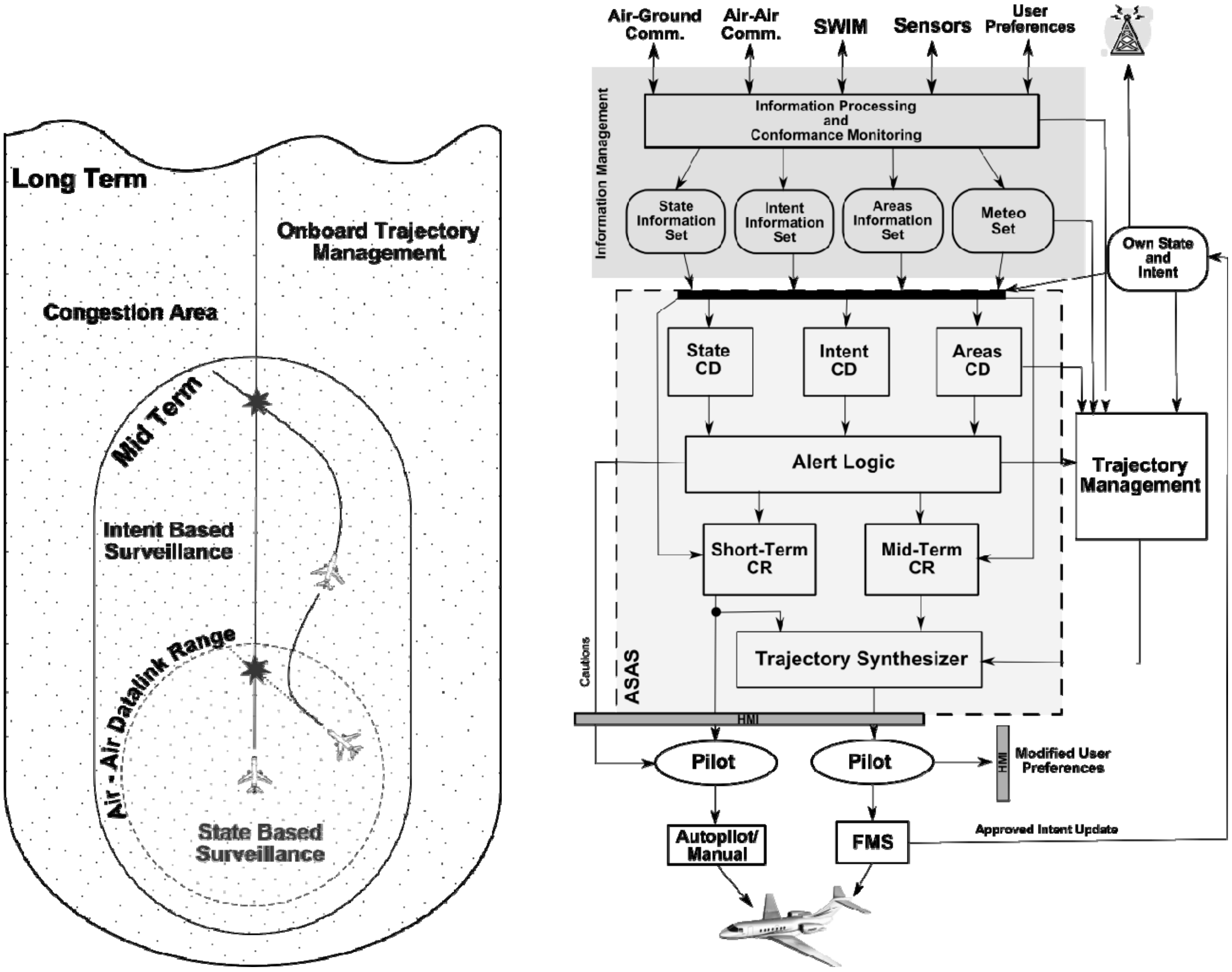

Figure 3 — CD&R applications and their applicable time horizons.

This hierarchical scheme aims to ensure that situations within shorter time-to-conflict horizons are processed through complementary CD&R approaches. Long term trajectory management and medium and short term CD&R outputs are collected and analyzed in an integration module that determines and prioritizes the appropriate options for the pilots. Ideally, all potential conflicts are identified and resolved within the mid term time frame using intent data about other aircraft. The state CD&R functionality is aimed to work for conflicts that are, for any reasons, not resolved in the mid term timeframe. Long term surveillance functions as a strategic preventive system and increases the effectiveness of the flight.

Aircraft position uncertainty impacts the effectiveness of the CD&R algorithms, which rely on the accurate prediction of the trajectory flown by the aircraft within the 10 to 20 minute time horizon. The performance of separation and trajectory management tools is directly dependent on the accuracy of the predicted trajectory, as uncertainty drives the size of the Alert Zones used to detect and avoid conflicts and reduces the usability of the predicted information. Studies conducted within the ERASMUS project [7] point out that inaccurate or missing wind forecast and temperature data used by the FMS are the primary sources of errors in airborne trajectory predictions. The on-board CD&R algorithms will utilizes the trajectory predicted by the ownship and the trajectories broadcasted by surrounding traffic to identify potential infractions into the aircraft alert or protected area zones and will compute a conflict resolution maneuver for the ownship that will optimally route the ownship away from the conflict. Inaccuracies in atmospheric data surrounding the projected path of the aircraft may impact the trajectory along-track error, especially during flight level changes. Thus CD&R algorithms in particular should be able to cope with uncertainty due to wind. Uncertainty modeling and evaluation is an explicit part of the CD&R

algorithm development and evaluation studies on the iFly project. To a significant extend these studies build on the stochastic hybrid systems basis developed within the HYBRIDGE project [4], together with the novel insights resulting from ERASMUS [8].

In addition to the airborne self separation CD&R systems, there is a safety net in the form of an Airborne Collision Avoidance System (ACAS) system, either the currently mandatory system, or an advanced future version which receives neighbouring aircraft position information from an independent surveillance source. This ensures that ACAS is an independent safety net for collision avoidance that will overrule any separation assurance resolution provided by the airborne separation assurance system from the time-to-collision threshold where it becomes operative.

Technical Systems that enable airborne self separation operation

A key enabler of this advanced airborne self separation concept of operation is a reliable communication network and information sharing system (System-Wide Information Management – SWIM). AFR aircraft need to receive all relevant information about surrounding traffic and obstacles. To this aim aircraft will be equipped with ADS-B OUT technology to periodically broadcast their position, velocity and intent information to surrounding traffic and down to SWIM. SWIM provides up-to-date "on request" (automated) surveillance information regarding neighbouring aircraft, current weather, forecasts, special use airspace and other areas to avoid.

For advanced airborne self separation, an additional ADS-B IN capability is also required for aircraft to continuously receive position, velocity and intent information from surrounding aircraft within ADS-B range. Air to air exchanges of aircraft trajectories, locally sensed weather and wake vortices data will enable aircraft to increase the separation precision and safety of their flights.

A high level airborne functional architecture is shown in Figure 4. It depicts the information flow between the on-board systems involved in ensuring safe, self-separating airborne operations. The airborne separation assurance system needs to be integrated with other on-board equipment such as a 4D capable FMS, long term trajectory management, ACAS, Cockpit Display of Traffic Information (CDTI), and a Communications Management Unit (CMU) able to communicate with the SWIM system and other aircraft via datalink (ADS-B In/Out).

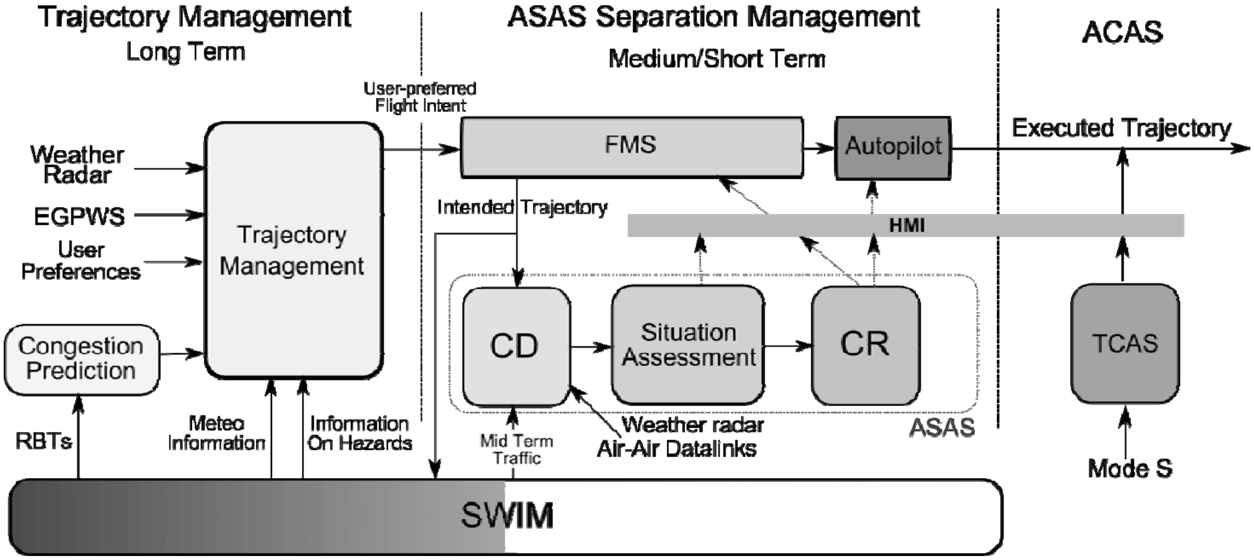

Figure 4 — On-board equipment in support of airborne self separation

The airborne equipment gives advice to the flight crew regarding potential maneuvers; the pilots-in-command decide and actually execute these maneuvers (manually, via the autopilot or via the FMS). The feasibility of this new aircrew task requires a very efficient and easily understandable Human Machine Interface (HMI) design. Whereas today the pilot builds a mental picture of surrounding traffic from monitoring pilot-ATC communications on VHF radio, the crew will use the Cockpit Display of Traffic Information (CDTI) to monitor the traffic situation during AFR operations. To guide the pilot, the CDTI can display information such as traffic, weather, the contracted trajectory and its containment limits, an airport map, or proposed conflict resolution maneuvers. Ultimately, the task of the CDTI is to inform the crew of the situation around the aircraft and help them in the handling potential conflicts.

Building safety into the advanced airborne self separation design

Inherent to the novelty of the advanced airborne self separation design, the analysis and mitigation of safety risks forms a key element in the iFly project. Examples of safety risks that need to be properly addressed are airborne automation equipment, aircraft position uncertainty, degraded airborne system performance and reliability, pilot loss of traffic situation awareness, unmanageable traffic complexity, and failure and/or degradation of the communication, navigation and surveillance systems. In order to get a handle on this multitude of potential safety hazards, three complementary safety based design approaches are followed within the iFly project:

1. Overall hazard analysis and accident risk assessment, using TOPAZ methodology [9];
2. System Safety Engineering according to ED78A methodology [10];
3. Formal verification using critical observability analysis of hybrid automaton [11].

The purpose of these accident risk assessment and system safety engineering and verification methods is to identify the required technical system capabilities and the traffic demand that can safely be accommodated by the advanced airborne self separation concept of operation. In the remainder of this paper we will first outline the TOPAZ accident risk methodology and how its use is foreseen within the iFly project. Next, we will describe how the other two risk mitigation approaches will be used within iFly.

TOPAZ based accident risk assessment

The scope of the accident risk assessments within iFly is detailed in [12], and covers various aspects such as:

- Technical equipment (hardware and software for e.g. air-ground communication, alerting tools);
- Procedures (e.g. crossing and passing procedures, alerting procedures);
- Pilot roles and responsibilities, taking into account that in the advanced airborne self separation concept, pilots remain the most flexible and creative element in maintaining a rich situation awareness, and to direct the performance of the operation, including management of threats, errors and unpredictable events.
- Interactions with the environment, e.g., weather situations or traffic demands, are included in the assessment since they can have significant influence on the level of safety. Interactions between the original and the new elements are also important to consider as automation of services might lead to changes in human roles and responsibilities, and therefore also to new unforeseen hazards.
- The focus of the iFly risk assessment is on mid-air and near mid-air collisions between two or more aircraft. As such, wake vortex and security induced risks fall out of the iFly scope. This remains to be investigated in a follow up study.

In [12], the TOPAZ accident risk assessment methodology has been identified as the logical choice for use within iFly. The general aim of the TOPAZ accident risk assessment is to model the accident risks of an advanced ATM design in order to provide effective feedback to the designers of the advanced operation regarding the main sources of unsafety as a function of traffic and environment characteristics, including quantification. This produces unique insights into which safety/capacity aspects of the design can best be addressed to realize improved capacity without sacrificing safety. The following include the objectives of the TOPAZ based accident risk assessment within iFly:

A. To identify the large variety of potential safety hazards that come with, or are emergent from, the advanced airborne self separation design; and
B. To assess the total accident risk, as a function of traffic demand, that these hazards (separately or in combination) pose to the safety of flights;

C. To compare the assessed overall risk level against the accident risk level that is maximally acceptable in future air traffic, and hence identify up to which traffic demand levels the advanced airborne self separation concept is expected to be safe;
D. To identify which hazards, or combination of hazards, constitute the largest safety risk, and therefore are the key candidates for the development of safety risk mitigation approaches.

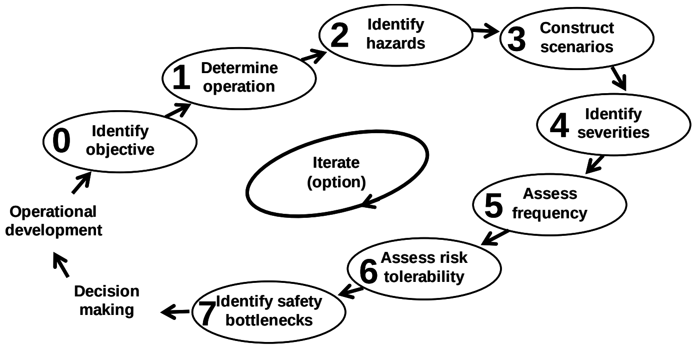

Figure 5 — TOPAZ accident risk assessment high level steps

Within iFly this fourfold objective will be realized through conducting a systematic sequence of the TOPAZ high level steps as pictured in Figure 5. Steps 0 through 4 are of a qualitative nature [13] and address objective A. Steps 5 through 7 are of a quantitative nature and address objectives B-D. For a demanding design, such as airborne self separation, TOPAZ step 5-7 are performed by using Monte Carlo simulation-based accident risk assessment of the air traffic operations. This is accomplished through conducting the following sequence of sub-steps:

- Conduct task and situation awareness analysis for each agent (human or system) that is active in the loop of the operation considered [14];
- Develop a Stochastic Hybrid System model specification of the airborne self separation concept of operation, using a dedicated Petri Net compositional specification formalism [15];
- Apply stochastic analysis to the developed rare event estimation and Monte Carlo speed up methods for the Petri net model and its Monte Carlo simulator [16, 17];
- Generate Monte Carlo simulation code that is one to one with the Petri net specified model, then identify best estimates for the parameter values in the Petri net model, (i.e. in the Monte Carlo simulator) and perform Monte Carlo simulations to produce point estimates of the total accident risk, including identification of the main contributing event sequences;
- Perform parameter sensitivity analysis and a subsequent bias and uncertainty assessment. The aimed result is an estimate of the 95% uncertainty area of the total accident risk [18].

During the Stochastic Hybrid Model development sub-step, all types of safety issues should be addressed, including organizational, environmental, human-related and other hazards, in any combination. Advanced air traffic management is recognized as one of the most complex distributed safety critical systems. In order to conduct TOPAZ steps 5-7 for such a complex operation, there is a need for further developments of dedicated techniques on rare event estimation [19].

Most of these quantitative TOPAZ steps already have successfully been applied to the airborne self separation concept of operation developed for low demand en route traffic over the Mediterranean. This concept made use of state-based CD&R only. For this concept we estimated the collision risk by counting the number of collisions, divided by the number of simulated flight hours. This accident risk assessment showed that this design was behaving in line with the expectations of the designers for two aircraft encounters. However, the results obtained also made it clear that under high en route traffic demands the behavior of this state-based CD&R design was less effective than the designers had expected [20]. For this initial application of TOPAZ to airborne self separation, the Monte Carlo speed up fell short to perform parameter sensitivity analysis and bias and uncertainty assessment. Hence an important side objective of the iFly project is to develop significant improvements in the Monte Carlo speed up methods.

The ICAO TLS for en-route fatal accidents states “Where ‘fatal accidents per flight hour’ is considered to be an appropriate metric, a target level of safety (TLS) of 5×10-9 fatal accidents per flight hour per dimension should be applied for determining the acceptability of future en-route systems that will be implemented after the year 2000.” [21]. This TLS however, does not include the airborne safety net that ACAS provides. Following [12], iFly adopts a TLS of $3 \times 5 \times 10^{-9}/X$ fatal accidents per flight hour (when ACAS is not taken into account), where X is the factor of en route traffic increase relative to the year 2000. Moreover, ACAS should at least yield a factor of 3.5 extra reductions in fatal accident risk. However, even though ACAS/TCAS (Traffic Collision Avoidance System) are typically not included in collision risk studies, the iFly safety assessment will explicitly incorporate ACAS/TCAS in order to gain valuable insight into potential ACAS/TCAS interactions with the ASAS.

Mitigation of safety hazards

Within iFly, a preliminary cycle through the RTCA/Eurocae ED78a methodology [10] will be conducted in order to derive preliminary safety and performance requirements for the functional elements of the advanced Airborne Self Separation concept of operation. This methodology supports a systematic system safety engineering process, which allows us to identify the reliability and detailed safety design requirements for the technical systems that form the key enablers of the advanced concept under development. In particular, this addresses safety hazards such as degraded airborne system performance and the reliability of non-airborne equipment, e.g. satellite induced problems may cause navigation and/or surveillance performance degradations that are common for multiple aircraft. Understanding the interactions of the operational services, procedures, and airspace characteristics will assist in the identification of failures, errors, and/or combinations thereof that contribute significantly to safety risk.

Through an Operational Hazard Assessment (OHA) the hazards identified within the qualitative TOPAZ steps will be represented by operational hazards that are functionally uniquely related to the advanced airborne self separation concept. This includes functions related to operational services and pilot responsibilities. Subsequently these operational hazards will be assessed (qualitative only) to establish the safety objectives and candidate safety requirements related to each identified operational hazard. Based on the results of the OHA, we will allocate safety objectives to functional systems, in particular those systems where the responsibilities have different owners. We will develop risk mitigation strategies that are shared by these different owners, and allocate safety requirements to those different owners. Requirements will be allocated to the CNS/ATM system elements that provide the functional capability to perform the service and the stakeholders in control of, or responsible for, each of the elements. A subsequent Operational Performance Assessment (OPA) will provide airborne performance requirements for airborne self separation operations. Performance requirements are the minimum operational requirements that will ensure that end users can expect the same quality of services for the advanced airborne self separation concept in any airspace where the various elements of the CNS/ATM system meet these requirements.

In contrast with TOPAZ based accident risk assessment, the ED78a approach does not systematically consider the effects of hazard combinations. The Monte Carlo simulation approach of TOPAZ ensures that all relevant hazard combinations are being covered. However, TOPAZ does not develop mitigating measures for these hazard combinations. In order to fill this gap, a recently developed complementary method of critical observability analysis of hybrid automata [11] will be applied within iFly. This approach allows us to identify combinations of hazards that form a latent condition of severe safety risk, and develop mitigating measures for making these latent conditions critically observable.

A difference in situation awareness (SA) between pilots and/or systems is an important example of a case where combinations of hazards play a major role. Such a type of SA difference may easily slip in the total system due to a relative innocent local hazard (e.g. a delay between updating the SA of the pilot and the decision support system). When a support system provides advice where the meaning depends of the situation awareness context, then the human-directed responses or actions may very well change due to some difference in SA. Hence any difference in SA within a multi agent system easily propagates through the total system, long before its latent hazardous effect becomes manifest. For this reason, even a small initial SA difference forms a latent condition for severe safety risk, and the potential for SA differences increases faster than linear with the number of agents (human or decision support system) in the total system. The aim of critical observability analysis is to identify and understand the existence of such latent conditions, and subsequently propose a design extension which recognizes such latent condition shortly after it slips in. Recently, [22] has shown how this approach works for an In Trail Procedure in oceanic airspace.

Conclusion

Safety analysis of complex distributed safety critical systems such as advanced air traffic management is essential in order to make airborne self separation a feasible solution in busy en-route airspace. Advanced Monte-Carlo-based safety analysis can provide valuable insights into safety related behavior of autonomous aircraft operations in this complex ATM system. Through complementary system safety engineering approaches, appropriate mitigating measures for the main safety hazards can be identified and developed. With our focus on non-nominal events, human factors and the impact of advanced technical system capabilities on the safety of airborne self separation flight operations, we aim to demonstrate up to which en route traffic demand level airborne self separation, with the required technical systems and contingency procedures in place, will be safely accommodated.

The iFly project, focused on advanced airborne self separation for en route air traffic, began its work in May 2007, and will run through 2010. The project results will be made publicly available through the web site http://iFly.nlr.nl. In total some 40 research reports will be produced which include human factors studies, airborne self separation concept studies, CD&R algorithm development studies and various safety studies. The iFly program results will lay the foundation for the development of a ground based ATM concept that is fully compatible with the advanced airborne self separation capability.

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Biography

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