RISK ANALYSIS OF AIRBORNE SPACING IN APPROACH SEQUENCING

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Abstract

The airspace capacity in Terminal Movement Areas (TMAs) may increase considerably with the use of airborne spacing operations. Under this paradigm, the task of maintaining spacing to a leading aircraft in a sequence is delegated to the flight crew, aided by the Airborne Separation Assistance System (ASAS) as an automation tool. The capacity increase is a consequence of the more accurate spacing between aircraft obtained with Time-Based Spacing, shown in many studies, as well as a lower Tactical Air Traffic Controller workload. The adoption of the new automation tools in this scenario, however, might bring unexpected emerging behavior, due to the combination of diverse local subsystems state changes. This study evaluates an estimated collision probability based on the TOPAZ (Traffic Organization and Perturbation AnalyZer) methodology, which includes mathematical techniques such as Dynamical Colored Petri Nets and Monte Carlo Simulation, and compares the results obtained with the ICAO (International Civil Aviation Organization) Target Level of Safety.

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1. INTRODUCTION

Although efficiency and capacity are the main drivers for the Air Traffic Management (ATM) development, safety is perceived as a key element in designing advanced ATM concepts (Blom et al., 2001). ATM design teams try to obtain improvements in capacity and efficiency, through the exploration of new technologies, procedures changes, introduction of new ones, etc. However, the target safety level is intended to be “equal or better” when compared to the current practices, thus leaving a wide range of interpretation of how safety is expressed and measured. Quantitative risk analysis tries to put several ATM applications in a continuous risk scale, enabling objective comparison and definition of minimum acceptable levels. Since the major part of the Air Traffic Control responsibility is maintaining a safety rage around the aircrafts, ICAO establishes Target Levels of Safety (TLS) in order to guide the acceptance of aircraft separation criteria and Air Traffic Control (ATC) practices (ICAO, 1988). The ICAO TLS is expressed in probability of collision, which must be lower than 5×10^{-9} per flight hour for each of the three spatial separation dimensions (longitudinal, lateral and vertical).

The purpose of this study is to present preliminary results of a quantitative risk assessment for Airborne Time-Based Spacing operations in civil aviation. Accordingly to this goal, a mathematical model was developed, based on the TOPAZ (Traffic Organization and Perturbation AnalyZer) methodology (Blom et al., 1998) that includes technical systems to account human performance as risk influencing factors. TOPAZ was used in several other risk assessment studies for advanced ATM concepts (Daams et al., 1998; Daams et al., 1999; Everdij et al., 2002, Blom et al., 2005). The result of this risk assessment is an estimated probability of collision per flight hour in approach procedures under airborne spacing.

2. DESCRIPTION OF AIRBORNE SEPARATION ASSISTANCE SYSTEM (ASAS)

Airborne Separation Assistance System (ASAS) is seen as a promising option in the future ATM concept to provide an increase in capacity and flight efficiency while enhancing flight safety. ASAS aims to exploit advances in flight deck technologies, such as Experimental Flight Management System (EFMS), Automatic Dependent Surveillance Broadcast (ADS-B), data link, etc., to improve the safety, capacity and efficiency of air traffic (CARE/ASAS, 2002). Fig. 1 provides a scope of how ASAS is inserted in the context of Air Traffic Control and flight guidance, see Fig. 1.

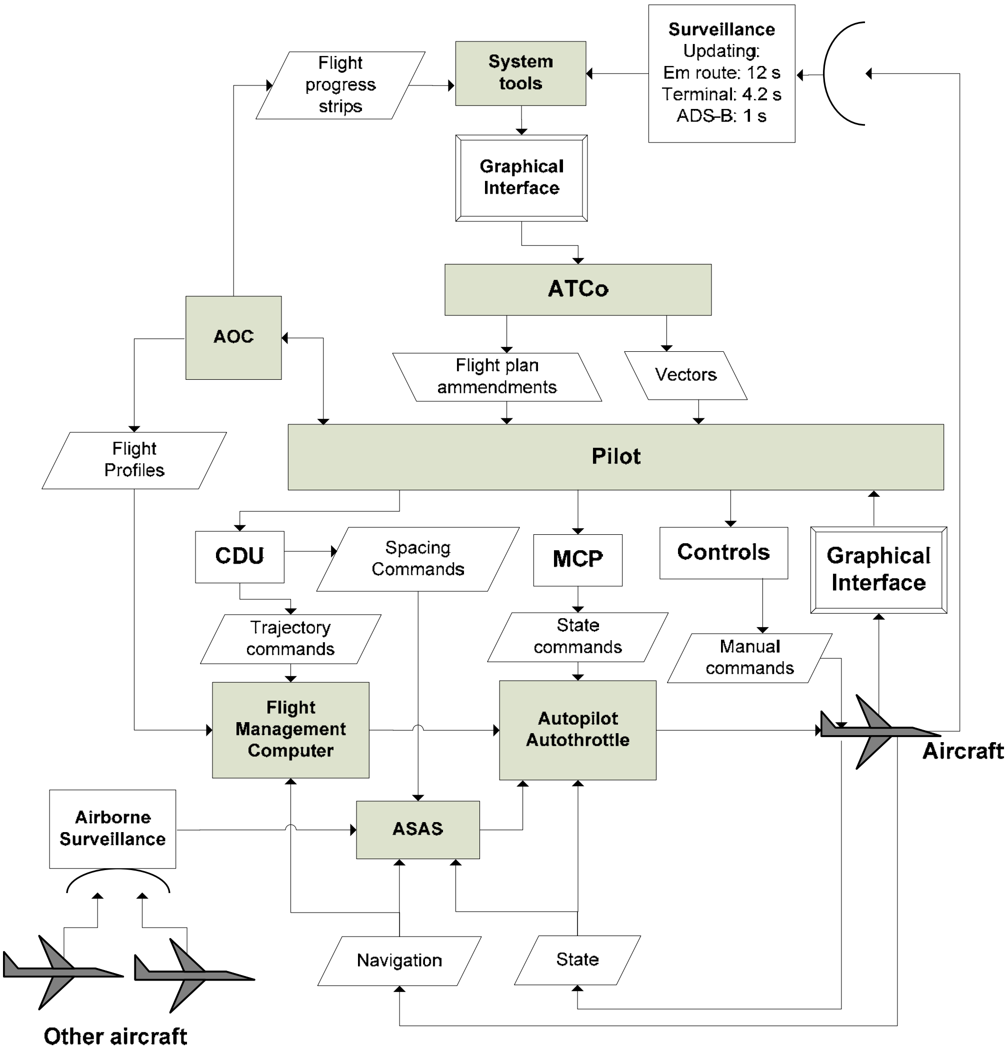

Fig. 1: Air Traffic Control loop with the introduction of ASAS.

Fig. 1 shows both ground and airborne control elements. AOC (Airline Operations Center) creates the flight plans and communicates them to the Air Traffic Control authority, which produces the corresponding flight progress strips. AOC also communicates flight plans to the pilots, also loading pre-settings in the Flight Management Computers, which specify preferred flight profiles. Air Traffic Controllers (ATCo), based on the flight progress strips and on the radar view, issue instructions to aircraft, consisting of vectors (changes in direction, altitude and speed), and flight plan amendments, when necessary. The pilot may control the aircraft at four different command levels. The lowest one is the manual level, using control wheel, sticks, knobs and pedals. The second level uses state commands such as speed hold, altitude hold, etc., specified by the Mode Control Panel (MCP) and uses autopilot and autothrottle electronic systems. The third level is under development and is the focus of this study. It uses Spacing Commands and alters the state of the aircraft based on the states of other aircraft, and uses the ASAS module. The fourth and the most sophisticated level uses trajectory commands and may be programmed once for the whole flight. These sophisticated level of command is operated through the CDU (Cockpit Display Unit), which is a small keyboard connected to a text computer screen.

In the current ATM system, the flight crew is in charge of a safe and efficient control and navigation of their individual aircraft. Unlike air traffic controllers, flight crews are currently not responsible for maintaining separation between aircraft, but only for avoiding collision and wake turbulence (CARE/ASAS, 2002). A new (proposed) allocation of tasks between air traffic controller and flight crew is envisaged as a possible option to improve ATM and in particular the sequencing of arrival flows. It relies on a set of applications enabled by ASAS, such as: Airborne Situational Awareness, Airborne Spacing, Airborne Separation and Airborne Self Separation (ICAO, 2003), which transfers part or most of the responsibility of maintaining separation between aircraft, from the ATCo to the flight crew.

This different task allocation is expected to increase controller availability, which could lead to improved safety, could enable better quality of service and more capacity (depending on airspace constraints). Also, it is expected that flight crews would gain in situational awareness and anticipation by taking an active role in the management of their situation with respect to a designated aircraft (Ivanescu et al., 2005; Grimaud et al., 2005).

One major issue in the establishment of airborne spacing operations is to achieve safe flight practices (CARE/ASAS, 2002), that consider instructions to be used by the air traffic controller, conditions of applicability of airborne spacing, hazardous situations, etc.

3. DESCRIPTION OF TIME-BASED SPACING OPERATION

The present study considered ASAS Time-Based Spacing (TBS) application in TMA. ASAS TBS aims to delegate to the flight crew some tasks necessary to maintain a precise spacing between aircraft that are in convergence or coincident arrival flows. It is expected TBS application to provide more accurate spacing between arriving aircraft, minimize the idle runway time without violating the separation minima and increase the possibility for TMA to handle more aircraft (Ivanescu et al., 2005; Grimaud et al., 2005). The study of Cloarec, Purves and Vergne (2004) shows that there is a potential increase between 12% to 15% in the terminal airspace capacity when using ASAS TBS operations, due to the Air Traffic Controller workload reduction per flight.

3.1. Operational Concept for TBS Operation

The TBS procedure in this report focuses on the airspace before the final approach. It is assumed that TBS procedure may start between the Extended-TMA entry point (after the top-of-descent, assumed here to be 60 nautical miles from the airport) and the Final Approach Fix (FAF), where the procedure should be ended (Grimaud et al., 2005).

In this phase of the flight, as in other phases, the flight crew must be aware of the surrounding traffic through the ASAS traffic synthesis provided in the Cockpit Display of Traffic Information (CDTI). It is also assumed that ASAS system will be working in Airborne Spacing mode (that is one of the available modes), and the conflict detection is a task of the ATCo.

To have a general idea of how it works, the following example of (RFG, 2005) is shown in Fig. 2. In this example, the controller builds the sequence of aircraft earlier in the sector by assigning target aircraft to each aircraft in the sequence (i.e. E is a target for F, D is a target for E etc). Sequencing and merging instructions are then given to ensure that the appropriate spacing is achieved by the merging waypoint (WPT). After the establishment of the sequence and the communication of the instructions to the aircraft to maintain the sequence (by maintaining the spacing), the controller must now monitor the aircraft for compliance, as C spaces itself from its target B, and B spaces itself from its target A.

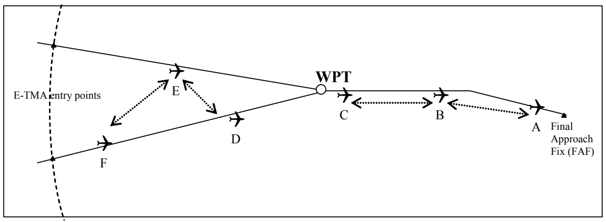

Fig. 2: Airborne Spacing operational example.

The example shows that the TBS operation involves two steps. In the first step, an ATCo instructs the flight crew to select a neighboring aircraft as a target on the CDTI (Ivanescu et al., 2005), which will present a screen similar to Fig. 3. Aware of the required target, the flight crew must identify and select it in the ASAS system, and report the target identification to the ATCo. In case the flight crew finds that the target is not in a convenient position, or that the selection of the target might lead to an inconsistent flight execution, or even that they cannot find the target in the CDTI, then they ask the ATCo for clarification. In these cases, the procedure would be either delayed or aborted.

Fig. 3: CDTI screen for Airborne Spacing application.

In the second step, after the target identification read-back with the target identification instruction, ATCo instructs one of the following options, depending on the trajectories of the flights involved:

(a) - Merge behind - the flight crew is instructed to merge the own flight trajectory behind the trajectory of the target aircraft, in a chosen waypoint, maintaining at a given time spacing to the target aircraft. This is the case when the aircraft involved are executing converging approach routes. In Fig. 4, AFR123 is the target and DLH456 is instructed to merge behind, maintaining the spacing D.

(b) - Direct-to then merge behind- the merge operation described above is executed, but preceded by an horizontal-path change, which consists in turning the aircraft to the direction of the merging waypoint when the aircraft reaches the required spacing (this position is called *resume point*). This instruction is used when the follower aircraft has to achieve the desired spacing, then it follows a divergent path of the target aircraft, and when the separation is achieved, the pilot must turn to the cleared merge waypoint. In Fig. 5, AFR123 is the target and DLH456 is instructed to go directly to the merge waypoint, merging behind AFR123 with spacing D.

(c) - Remain behind – the flight crew is instructed to achieve and maintain a given time spacing behind the target trajectory, in a chosen waypoint, maintaining at this point a given time spacing to the target aircraft. This third option is applied when the specific aircraft is already flying on the same trajectory of the target aircraft, as in Fig. 6.

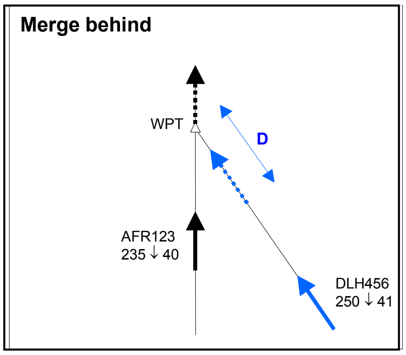

Fig. 4: "Merge behind" (a) schema.

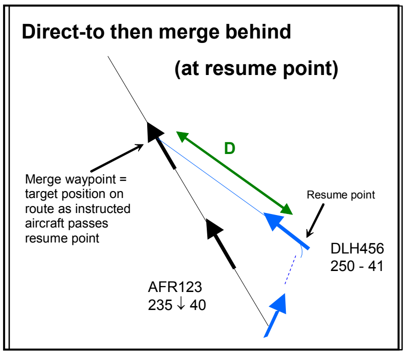

Fig. 5: "Direct-to then merge" (b) schema.

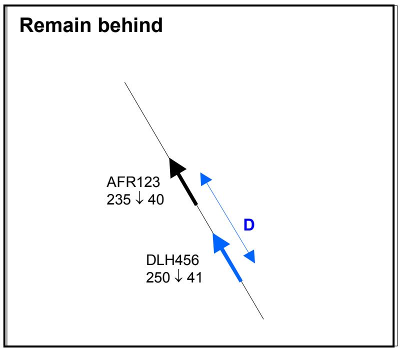

Fig. 6: "Remain behind" (c) schema.

After selecting one of the options (a), (b) or (c), the flight crew of the follower aircraft may have to apply speed adjustments suggested by the ASAS system, in the Autopilot System, and to monitor the evolution of the spacing to check if it tends to the desired spacing. It is also possible that the flight crew has then only the task of monitoring the evolution of the spacing, when the follower aircraft is equipped with ASAS director that automatically inputs its suggested speed in the Autopilot System.

The aircraft which is applying TBS is denominated the "follower" aircraft, in order to distinguish from the "target aircraft", which is supposed to land in the same airport as the "follower aircraft", but earlier. While monitoring the TBS procedure, flight crew will monitor the execution of the flight plan, and this execution must have RNP-1 (Required Navigation Performance Level 1) property.

The Air Traffic Controller will have graphical system tools to support the task of mounting and monitoring chains of airborne spacing aircraft. The interface developed in the COSPACE project (COSPACE, 2006) is shown in Fig. 7. In this figure, the aircraft selected as target by someone else is indicated by the small circumference, and the aircraft performing airborne spacing is indicated by a greater circumference. The links between aircraft indicate the target of one to another.

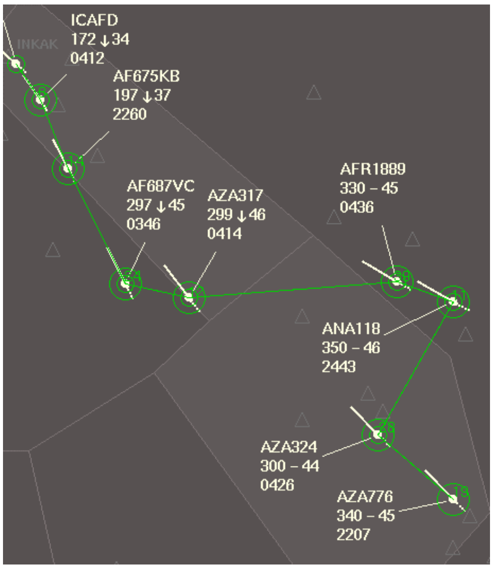

Fig. 7: ATCo graphical interface for airborne spacing.

The TBS procedure may normally finish at the Final Approach Fix, or eventually finishes abnormally, due to some failure in the ASAS system, or to some hazard detected by the flight crew or the ATCo. In cases of abnormal termination, the ATCo will execute conventional procedures for separating and sequencing aircraft. In this paper, only one single flow of arriving aircrafts will be considered, with no other surrounding traffic, which is one of the assumptions of the study.

As part of the evaluation of the expected number of aircraft accidents per flight hour in airborne spacing operation, a stochastic model is built to describe this accident probability under the influence of human behavior, technical systems behavior, communications environment, flight procedures, etc. In the context of the TOPAZ methodology, such a model has the format of a Stochastically and Dynamically Colored Petri Net (SDCPN) (Everdij and Blom, 2005).

4. SUMMARY OF STOCHASTICALLY AND DYNAMICALLY COLOURED PETRI NET MODEL FOR ASAS TBS OPERATION

Stochastically and Dynamically Colored Petri Net for Time Based Spacing (TBS) operation is developed and presented in detail in (De Oliveira et al., 2006) study. The SDCPN model is presented in two hierarchical levels. The first level distinguishes the agents and the operation, where an agent is an entity that has situational awareness components (Blom and Stroeve, 2004). At the second level, the Local Petri Nets (LPN's) of each agent is described in (De Oliveira et al., 2006), where each LPN is a Petri net describing a specific process of an agent. There may be connections between LPNs within the same agent or between different agents. In this Section, the main characteristics of the SDCPN model for ASAS TBS operation will be summarized.

4.1 General Definition of SDCPN

A Stochastically and Dynamically Coloured Petri Net is, according to (Everdij and Blom, 2003) given by the following tuple:

SDCPN = $(P, T, A, N, S, C, V, G, D, F, I)$

where:

- P - is a set of places;
- T - is a set of transitions, which consists of a set of guard transitions (T_G), a set of delay transitions (T_D) and a set of immediate transitions (T_I);
- A - is a set of arcs, which consists of a set of ordinary arcs (A_O), a set of enabling arcs (A_E) and a set of inhibitor arcs (A_I);
- N - is a node function, which maps each arc to an ordered pair of one transition and one place (multiple arcs

between the same place and transition are allowed);

- S - is a set of colour types for the tokens occurring in the net;
- C - is a colour function, which maps each place to a colour type in S;
- V - is a set of place-specific colour functions, which describe what happens to the colour of a token while it resides in its place;
- G - is a set of Boolean-valued transition guards associating each transition in T_G with a guard function;
- D - is a set of transition delays associating each transition in T_D with a delay function;
- F - is a set of probabilistic firing functions, which for each transition describes the quantity and colours of the tokens produced by the transition at its firing;
- I - is an initial marking, which defines the set of tokens initially present, i.e. it specifies in which places they initially reside, and the colours they initially have.

Some of these elements are graphically represented, as shown in Fig. 8.

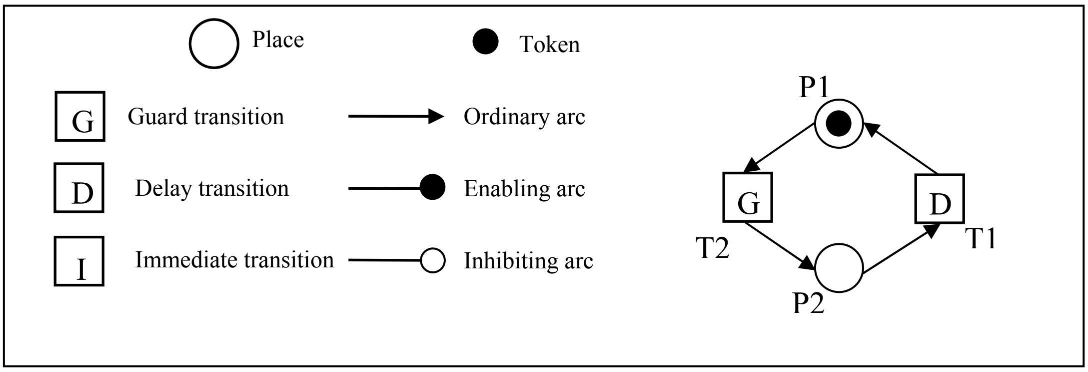

Fig. 8: Graphical representation of the SDCPN elements.

SDCPN are very adequate to mathematically model ATM applications. However, because of the complexity of the model, the formalism of SDCPN is extended to allow hierarchical grouping of its basic elements in agents and LPNs.

4.2 Agents

Agents are defined as entities that have some kind of situational awareness and a certain level of complexity. For this particular application, in order to assess the accident risk, the following agents are assumed to exist in a SDCPN model of TBS operation:

- Aircraft;
- Aircraft Guidance, Navigation and Control Systems (GNC), including Guidance Systems, Own Positioning System, and Communication Systems;
- ASAS System;
- Pilot Flying (PF);
- Pilot Not Flying (PNF);
- Air Traffic Services (ATS) System, including Ground Radio Telecommunication, Navigation Systems Global / GNSS (Global Navigation Satellite System), and ATS Surveillance System;
- Tactical Air Traffic Controller (ATCo).

A high level representation of the relations among agents is shown for two aircraft in Fig.9.

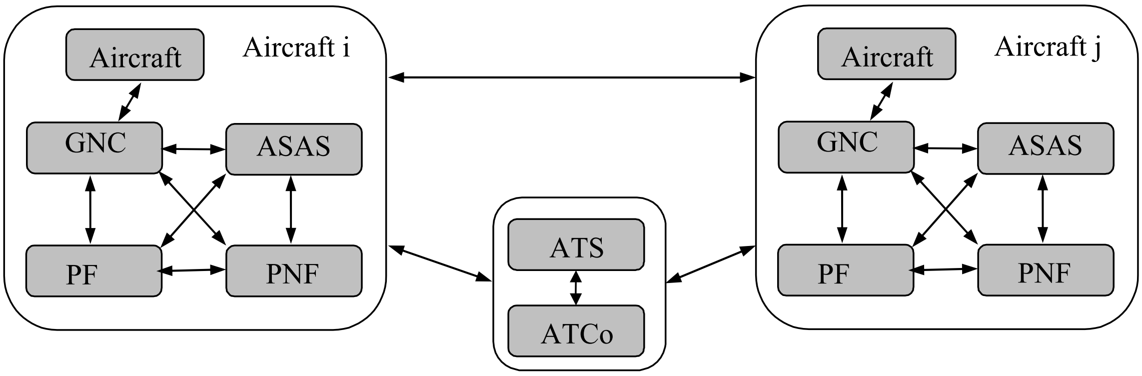

Fig. 9: Relations between Petri Nets at Agent Level.

Each of the agents present in Fig. 9 is internally composed by LPNs.

4.2.1. Local Petri Nets Introduction

Each agent is modeled with multiple Local Petri Nets (LPN), which are mutually connected forming the SDCPN. It is not possible in this article to give an extensive description of the 43 Local Petri nets used, so only a few of them will be presented, aiming to provide an idea of how they work.

The first LPN is shown in Fig. 10. It is one of the simplest LPNs, and represents the aircraft radio telecommunication (R/T) system availability. At any moment, the Aircraft R/T system may be either in the state Working, i.e., working normally, or in the state Not working, i.e., in failure, with no possibility of performing communication.

The LPN status is determined by the positioning of the token. In this LPN, the token switches between places through the delay transitions, non-deterministically, at exponentially distributed times. Some other LPNs are shown in Fig. 11, representing other aircraft communication components. For the sake of simplicity, it was chosen in this project to allow only one token per LPN.

The use of continuous variables called colors, in the LPNs, enables the use of differential equations, as for example the aircraft physical behavior and control law presented in the following subsection.

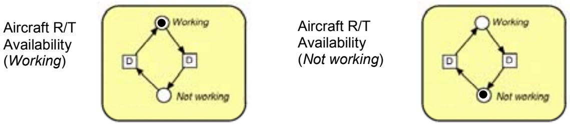

Fig. 10: Different places for a token in a LPN.

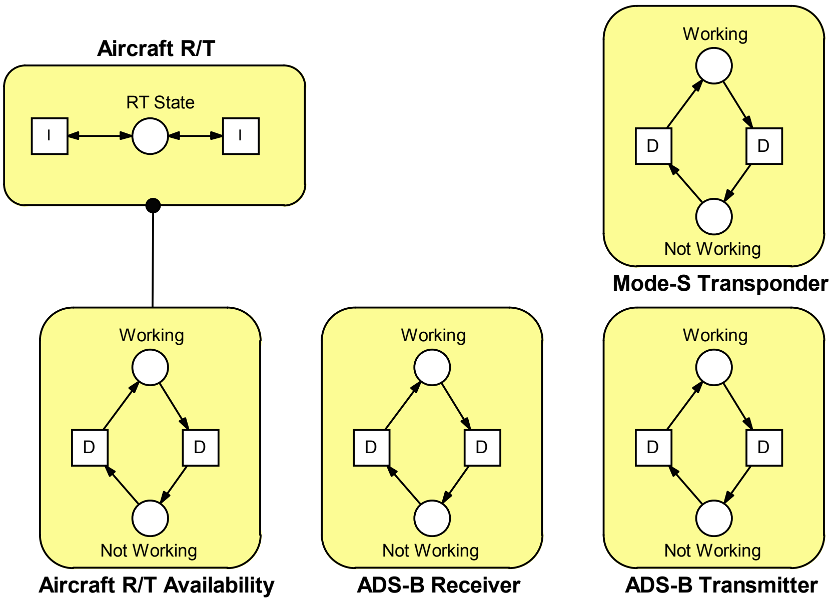

Fig. 11: Aircraft Communication LPNs.

4.3. Aircraft Guidance Behavior LPN

The LPN that describes the aircraft physical dynamics is shown in Fig. 12.

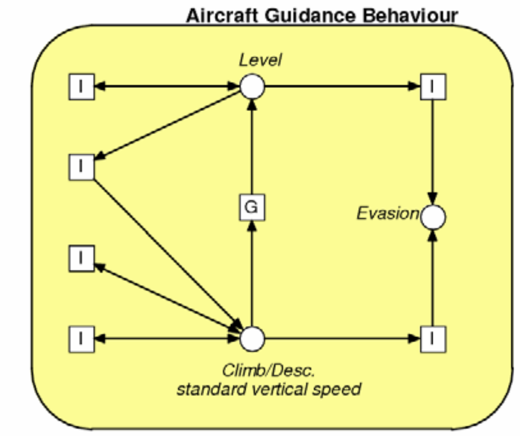

Fig. 12: Aircraft Guidance Behavior LPN.

The possible places for the aircraft state are either *Level*, when the aircraft is trying to keep a constant altitude, *Climb/Desc. standard vertical speed*, when the aircraft is changing the altitude, or *Evasion*, when the aircraft is leaving the approach route. The immediate transitions (indicated by I in Fig. 12) are triggered by tokens in other places (not shown in the figure) that represent command inputs by the pilot in the aircraft guidance system. The aircraft equations in all the places of this LPN follow the model described by Geest (2002). In this model, the basic aircraft dynamics is described by the following differential equation system:

$$\dot{y} = \begin{bmatrix} y_4 \cos(y_5)\cos(y_6) + w_1 \\ y_4 \sin(y_5)\cos(y_6) + w_2 \\ y_4 \sin(y_6) + w_3 \\ \dfrac{u_1 \cos(u_2) - D(u_2, y_4, y_3)}{m} - g\sin(y_6) \\ \dfrac{g}{y_4}\tan(u_3) \\ \dfrac{L(u_2, y_4, y_3) + u_1 \sin(u_2)}{m y_4}\cos(u_3) - \dfrac{g}{y_4}\cos(y_6) \end{bmatrix}$$

where:

- $y \in \Re^6$ and $[y_1, y_2, y_3]^T$ is the aircraft 3-D position, y_4 is the aircraft true airspeed, y_5 is the heading angle and y_6 is the vertical path angle;
- $u \in \Re^3$ is the control input vector, with u_1 being the engine thrust, u_2 the angle of attack and u_3 the bank angle; these variables are evaluated using the control laws described by Geest (2002);
- $w \in \Re^3$ is the wind vector;
- m is the aircraft mass, g is the gravity acceleration;
- $D : \Re^3 \mapsto \Re$ is the aircraft drag function;
- $L : \Re^3 \mapsto \Re$ is the aircraft lift function.

4.4. ASAS Agent LPNs

The LPNs composing the ASAS Agents are shown in Fig. 13.

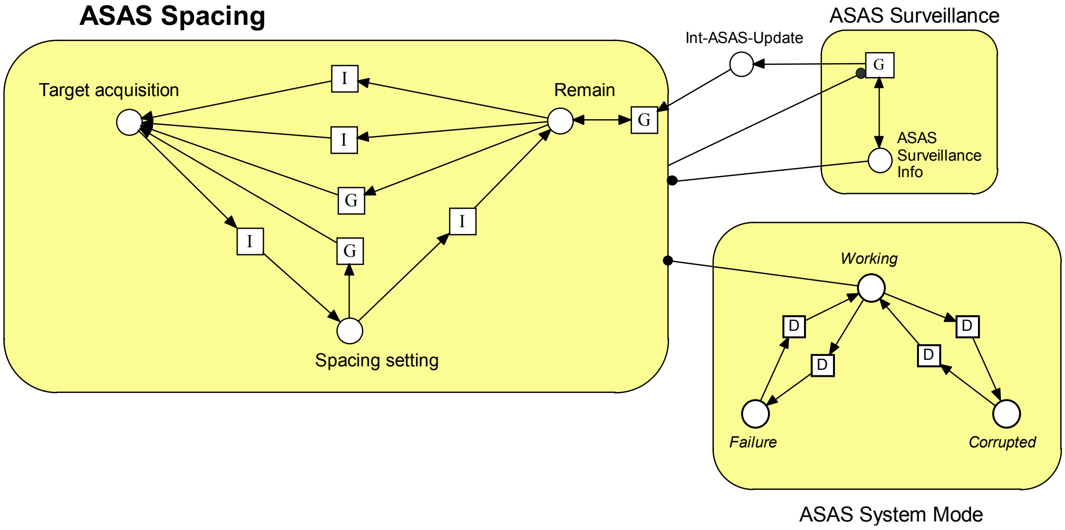

Fig. 13: ASAS Agent LPNs.

The ASAS Surveillance LPN has a token whose color contains information on the status of all aircraft inside the range of the ADS-B receiver, plus the own aircraft state information. The ASAS System Mode LPN has the places *Working*, which represents the nominal ASAS working state, *Failure*, where ASAS is not executing its functions, and

Corrupted, where ASAS is working with some non-detectable fault. As can be observed by the enabling arc between the places *Working* and the ASAS Spacing LPN, the transitions between the places of ASAS Spacing occur only if there is a token in the *Working* place, i.e., if ASAS is correctly working.

The ASAS Spacing LPN determines the phase of execution of the ASAS spacing function. *Target Acquisition* is the initial phase, where the Not-Flying Pilot can select an aircraft as target through the CDTI. After this selection, the token moves to the *Spacing Setting* place, where the Pilot Not-Flying can input a spacing value. Finishing this phase, the token moves to the *Remain* place, where ASAS constantly calculates a required speed to maintain the required spacing. The calculation of this speed depends on the information in the ASAS Surveillance LPN, and is done in accordance with the algorithm of Geest (2002).

4.5. LPNs of the Human Operators

The Flying Pilot, the Not-Flying Pilot and the ATCo are the most complex agents in the model. Following the analysis described in (De Oliveira et al., 2006), the LPNs of the Pilot Flying Agent are jointly presented in Fig. 14. The Task Performance PF LPN presents a pattern of stages for the task execution, which is also present in other human operators, and originated in other projects with the TOPAZ methodology. The task performance stages are represented by the places of this LPN, described as:

(T1) *Monitoring*: stage where the pilot gathers and integrates information about the current goal.

(T2) *Monitoring and Decision*: in this stage, using information provided by the instrumentation systems and, possibly, by other human operators, and based in his situational awareness, the pilot takes decisions about:

- If he needs to query some other human operator and, if he does, what is the query to be made;
- If a particular action is required and, in case it is, what are the parameters for its concrete application.

(T3) *Coordination*: stage in which the pilot coordinates with other human operators, communicating, questioning and answering, and checking the consistence of his decisions.

(T4) *Execution*: stage where the pilot is effectively operating the aircraft control, activating functions by means of the aircraft control devices.

(T5) *Execution Monitoring*: stage on which the pilot observes the results of the executed action.

(T6) *Monitoring and Goal Prioritization*: stage in which the pilot gathers information and prioritizes his goals.

In this model, it is assumed that the pilot performs exclusively one of the stages T1-T6 per time. This is a simplification of the reality, because it is known that the human being is able to perform many mechanical or repetitive tasks per time. However, the current design tries to keep the model simple.

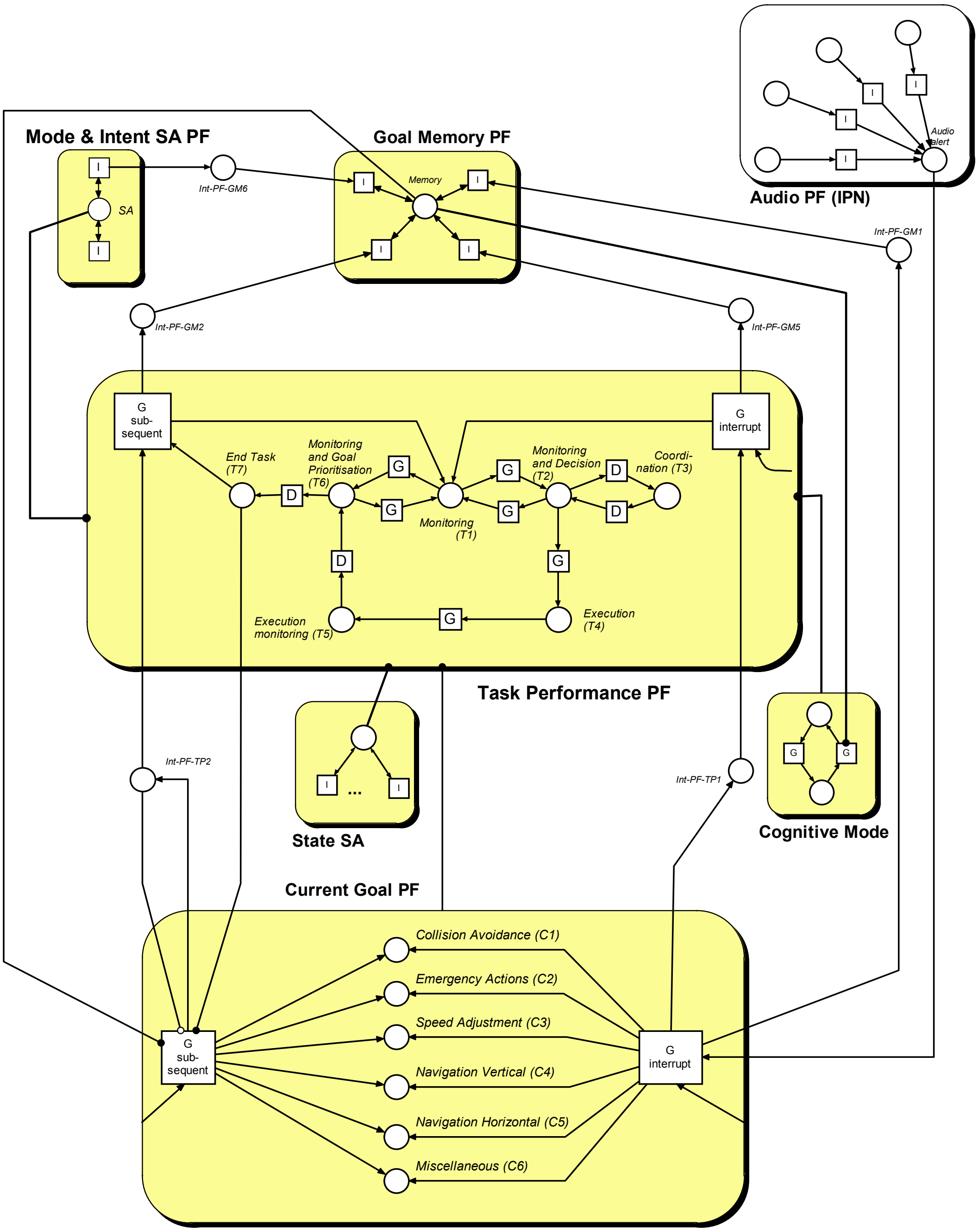

Fig. 14: Pilot Flying Task Performance LPN.

Another LPN of the Pilot Flying Agent is Current Goal PF, which determines the goal assumed by the PF in a given instant. The Current Goal token may be moved in two different ways. On the one hand, through the *interrupt* transition, the token id moved by audio alerts coming from the interaction place *Audio alert*. In this case, the next goal is decided based on the audio message received. On the other hand, the Current Goal token may move through the transition *subsequent*, which is enabled at the end of a task performance cycle, allowing the pilot to decide about the next goal. Goals stored in the Goal Memory PF LPN are then taken into consideration. The PF task performance is still influenced by other three LPNs in Fig. 14.

The Mode & Intent SA PF LPN represents the PF's aircraft desired status at a given moment (such as altitude and speed). The State SA LPN processes the knowledge of the currently active failure indicators in the aircraft, and Cognitive Mode is a simpler version of the Hollnagel's model (1993). When the pilot has few tasks to perform, the token stays in the place *Tactical*, and this means that the pilot has a small probability of error or omission. Likewise, when the pilot has too many tasks, the token goes to the *Opportunistic* status, raising his probability of error or omission.

The Not-Flying Pilot LPNs and ATCo agents are in a great extent similar to the PF agents LPNs, but with different status in the Current Goal LPN. More details about these LPNs can be found in (De Oliveira et al., 2006).

4.5. Other LPNs Hazardous States

The set of LPNs in the model also includes several possible failure components in the system state, such as engine failure, noise in the aircraft instrumentation, failure in the ATC systems, etc. With the entire Petri Net model, it is possible to simulate the execution of an ASAS TBS operation and check the likelihood of a collision. Since the ASAS TBS operation is designed to be as safe as possible, a low probability of collision is expected, i.e., one single collision occurs amongst a great number of safe executions. In this case, the Monte Carlo method is recommended to estimate this rare event.

5. EVALUATION OF COLLISION PROBABILITY

The probability of collision between two aircraft subject to airborne spacing operation is estimated over the SDCPN model, using the Monte Carlo method. This section explains the principles of this method and how it was optimized to allow its use at a reasonable computing time.

5.1. Monte Carlo Method

The basic idea of the Monte Carlo Method is quite straightforward. It consists in randomly drawing a great number of samples from a sampling space and counting how many of them fall into a particular set. The rate of the number of samples falling into the set over the total number of samples gives the estimated quantity. In the particular case of estimating the collision probability per a single ASAS TBS operation, define N_s as the number of sample simulated operations, and c_i the collision indicator for the sample i, i.e.:

$$c_i = \begin{cases} 0 & \text{if sample } i \text{ does not collide} \\ 1 & \text{if sample } i \text{ collides} \end{cases}$$

Then the estimated probability of collision p is

$$p = \frac{1}{N_s}\sum_{i=1}^{N_s} c_i$$

Following this idea, if p is expected to be as low as 10^{-9}, for example, then the number of simulated samples necessary for the Monte Carlo to return to a valid result, i.e., a non-zero result, would be expected to be around 10^9. Assuming that each simulation sample takes one second to be executed, due to the large state space (several LPNs, hundreds of variables), the number of hours necessary to calculate p would be in the order of 2.8×10^5, or equivalently 31 years. Therefore, optimization techniques were used to speed up Monte Carlo Simulations.

5.2. Monte Carlo Speed Up

There are several optimization techniques to speed up the Monte Carlo method. The one used in this work is generically denominated Interacting Particle System (IPS), inspired in the genetic algorithm of Cérou et al. (2002), and adapted for hybrid systems by Krystul and Blom (2004a). The IPS can be applied in this study because each sample is a SDCPN equivalent to a hybrid state Markov Process. The IPS denominates a sample as a particle, and takes benefit of a certain predictability in the state of each particle, i.e., the probability of an aircraft collision in the interval $[t, T_{\max}]$ is higher for aircraft with smaller separation distance on time t. A filter selects only the aircraft with smaller distances and stops their particles. In the next prediction level, all particles are replications of the selected particles. Then a smaller separation distance is used to select particles and the process is repeated, until the aircraft is reached, meaning a collision event. This filtering process of IPS is depicted in Fig. 15. The final collision probability is the product of all the intermediate conditional evaluated probabilities.

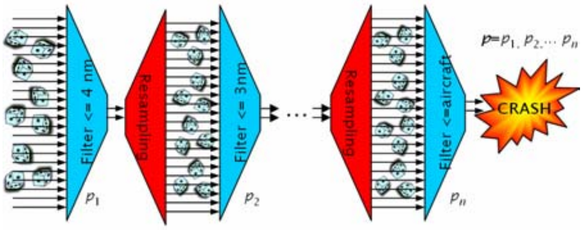

Fig. 15: Schematic of Interacting Particle System algorithm.

The use of IPS and its advanced versions designed by Krystul and Blom (2004b) allows a significant reduction in the computing time. In the implementation of this study, a single Advanced IPS run took about four hours. In order to guarantee a greater numerical precision, ten Advanced IPS runs were performed for each desired combination of parameter values.

5.3. Collision Probability Results

The set of Monte Carlo/IPS executions produced the results shown in Fig. 16. The reference TLS is considered only for the longitudinal direction, as in (ICAO, 1988), because only this type of separation is applicable to this operational concept. As each dimension is required to have a 5×10^{-9} collision probability, this is why the TLS is used. The horizontal axis shows the values of the required time-spacing between aircraft.

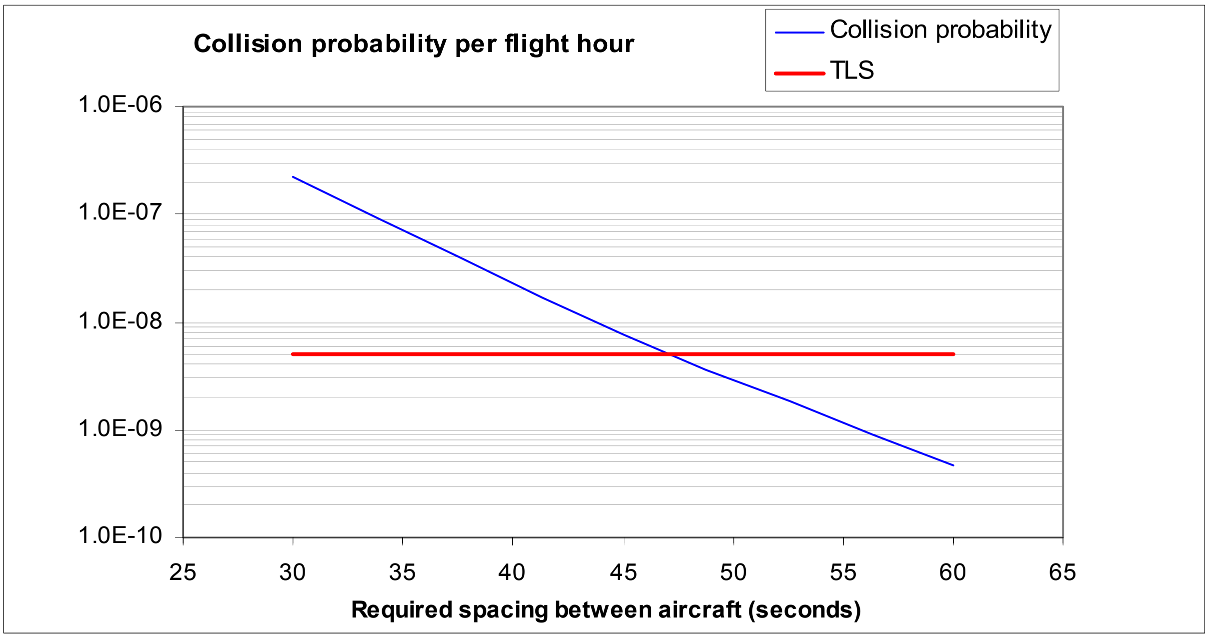

Fig. 16: Probabilities of collision.

6. CONCLUSION

The results shown in Fig. 16 allow the conclusion that the operation of airborne spacing in the ASAS TBS paradigm is compliant with the ICAO target level of safety for required spacing times greater than 47s. Smaller values would be considered unsafe relatively to the TLS.

However, as the model is a simplification of the reality, it causes bias and uncertainty in the result. Bias is a systematic deviation of the results estimated through the Monte Carlo method from the real collision probabilities; uncertainty is a spread around each estimated result that has to be assumed. Both bias and uncertainties exist due to structural and parameter value assumptions in the model, and also because of numerical assumptions. The results of Fig. 16 may be overestimated or underestimated due to the specific assumptions in this model. The estimation of bias and uncertainty will be performed based on the proper steps of the TOPAZ methodology.

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