A Causal Model for Air Traffic Analysis Considering Induced Collision Scenarios

Marko Radanovic and Miquel Angel Piera Eroles
Department of Telecommunications and Systems Engineering,
Autonomous University of Barcelona, Spain,
{marko.radanovic, miquelangel.piera}@uab.cat

Abstract

Present research on the air traffic management systems is trying to improve an airspace capacity, accessibility and cost-efficiency while maintaining the safety performance indicators. The discretization of the aircraft trajectories in a sequence of the 4D points specifying an agreement between the airspace users and the traffic flow management, in which the aircraft are required to arrive at the certain waypoints in the required time instants, opens a huge scope of applications for the decision support tools. This paper presents the causal model of an induced collision scenario, generated by the Traffic alert and Collision Avoidance System logic, tailored by an impropriate pairwise collision resolutions. It elaborates a unit simulation case and introduces a new modeling approach through the Colored Petri Net formalism. The proposed model provides a better insight on the geometry of collision trajectories which is a baseline for the simulation of new conflict-free resolution strategies that could be automated, and integrated in the further research.

Keywords: causal modeling, hotspot, induced collision, pairwise encounter, resolution advisories

1 Introduction

The constant increase in the air transport demand is generating a continuous pressure on the air traffic control (ATC) system. As a result, more efforts in the ATC modernization have been made to satisfy the main ATM criteria: enhanced capacity, cost-efficiency and safety. Based on the Single European Sky ATM Research (SESAR) initiative (Drogoul *et al*, 2009), there would be necessary to shift from the completely centralized tactical ATC interventions to more efficient, decentralized, collision-avoidance operations. This foresees the important changes in the roles and responsibilities of the overall air traffic management (ATM) system.

At present, an upgraded Traffic Alert and Collision Avoidance System (TCAS II v7.1), has been designed for operations in the traffic densities of 0.3 aircraft per squared nautical mile. The system demonstrates an excellent performance in cases of the pairwise encounters (PEs) but, concurrently shows some performance drawbacks in its logic due to the well reported induced collisions in some traffic scenarios (Jun *et al*, 2014, 2015; Ruiz *et al*, 2013). These drawbacks are also a result of frequent changes in the kinematic trajectory elements (the speed and altitude changes), as well as an ambiguity in the horizontal level crossings and level busts. Thus, one of the goals will be to investigate and implement a new operational framework improving the TCAS functionalities to react at both tactical and operational level as a robust collision avoidance system for different complexities of the traffic scenarios, in which ergonomics and automation interdependencies will be fully considered and aligned with the realistic aircraft performances.

This paper analyzes a pairwise collision scenario as a product of the previously resolved conflicts. From a causal point of view, it illustrates the case in which some inappropriate maneuvers, issued by TCAS to solve one-on-one encounters, can induce a new collision. This effect is known as a downstream effect (i.e. emergent dynamics) of the previous TCAS decisions and can be treated as a surrounding traffic effect, separately from a multi-threat encounter approach. The scenario is then simulated using an open-source conflict detection and resolution (CD&R) toolset *Stratway*, and obtained results are presented. Based on the simulated case, a new approach is introduced through development and validation of a Colored Petri Net (CPN) model. The model presents a baseline for further research on a probabilistic, state-based collision prediction.

The remainder of the paper is organized as follows. Section 2 discusses a conceptual analysis of the hotspot scenario describing both the one-on-one encounters and pairwise induced collisions. A simulated scenario with the obtained results is presented in Section 3, while Section 4 describes the causal modeling approach for the collision prediction. Section 5 validates the presented model, and conclusions are given in Section 6.

2 Conceptual Analysis

A reduction of the separation minima might occur due to many circumstances; in a moment when an air traffic controller issues a resolution directive, in which any change in a desired cruising speed, heading or vertical rate is not appropriate, or when a pilot performs a maneuver that a controller had not anticipated. The airspace volume that encompasses a subset of trajectories with tight spatiotemporal interdependencies, which can easily lead to reduction of the separation minima, defines a hotspot. This volume is both space- and time-dependent on the aircraft closure rates, in sense that can occupy a couple of flight levels (several thousands of feet's) and a longer horizontal distance (several tens of nautical miles).

An idea of the PE approach lies in fact that an induced collision with the closest points of approach (CPA) of two aircraft cannot dimension the hotspot area, which is not in the case of the multi-threat encounters. Instead, a surrounding traffic aircraft introduce a certain level of uncertainty in the geometry of a resolution trajectories and, thus, very tight spatiotemporal interdependencies between trajectories that can be involved in collision are essential to define the hotspot itself (Billingsley *et al*, 2013). The CPA is an estimated 4D point on the aircraft trajectory, for which a 3D distance between two conflicting aircraft reaches its minimum value.

Even if assumed that integrity levels of the 4D trajectories are fully accomplished (i.e. very small along-track, across-track and vertical path deviations) and the flight parameters (heading, altitude and speed) are progressively maintained, which also imply the constant timestamp changes, it is not possible to predict an induced CPA. Naturally, this question opens many analytical aspects, but the main ones are a limited TCAS logic, based on a certain number of the resolution advisories (RAs), TCAS threshold requirements, and the feasible maneuvering strategies based on the aircraft performance (ICAO, 2006).

Table 1 lists all advisories for TCAS II v 7.1, while Table 2 depicts the TCAS threshold values for different flight levels. The second column in Table 2 refers to the sensitivity level (SL) indexes. This one-digit number features a strength sense of TCAS command.

Table 1. TCAS Advisories.

TCAS II v 7.1			
Type	*Text*	*Meaning*	*Required Action*
TA	Traffic, traffic	Intruder near both horizontally and vertically	Attempt visual contact, and be prepared to maneuver if RA occurs
RA	Climb, climb	Intruder will pass below	Begin climbing at 1500-2000 ft/min
RA	Descend, descend	Intruder will pass above	Begin descending at 1500-2000 ft/min
RA	Increase climb	Intruder will pass just below	Climb at 2500-3000 ft/min
RA	Increase descent	Intruder will pass just above	Descend at 2500-3000 ft/min
RA	Reduce climb	Intruder is probably well below	Climb at slower rate
RA	Reduce descent	Intruder is probably well above	Descend at slower rate
RA	Climb, climb now	Intruder that was passing above, will now pass below	Change from descent to climb[1]
RA	Descend, descend now	Intruder that was passing below, will now pass above	Change from climb to descent[1]
RA	Maintain vertical speed, maintain	Intruder will be avoided if vertical rate is maintained	Maintain current vertical rate
RA	Level off, level off	Intruder considerably away, or weakening of initial RA	Begin to level off
RA	Monitor vertical speed	Intruder ahead in level flight, above or below	Remain in level flight
RA	Crossing	Passing through intruder's level, usually added to any other RA	Proceed according to associated RA
CC	Clear of conflict	Intruder is no longer a threat	Return promptly to previous ATC clearance

[1]This is reversal RA that requires change of 1500 ft/min vertical rate.

Table 2. TCAS Threshold Values.

Own Altitude [ft]	*SL*	*TAU [sec]*		*DMOD [NM]*		*ZTHR [ft]*		*ALIM [ft]*
		TA	*RA*	*TA*	*RA*	*TA*	*RA*	*RA*
1000 - 2350	3	25	15	0.33	0.20	850	600	300
2350 - 5000	4	30	20	0.48	0.35	850	600	300
5000 - 10000	5	40	25	0.75	0.55	850	600	350
10000 - 20000	6	45	30	1.00	0.80	850	600	400
20000 - 42000	7	48	35	1.30	1.10	850	700	600
> 42000	7	48	35	1.30	1.10	1200	800	700

2.1 CD&R for One-On-One Encounters

To explain the concept of induced collision, it is first considered an initial state of a non-vectored traffic scenario in the vertical plane, which presents the SESAR concept for a free routing without a level capping. There are four aircraft A/C01, A/C02, A/C03 and A/C04 flying on the trajectories that form two predicted encounters A/C01-A/C02 and A/C03-A/C04 (Figure 1).

A/C01 is cruising on FL160 while A/C02 starts descending at FL180 in the opposite direction from A/C01, which means a direct approch to A/C01 with a loss of height. On the other side, A/C03 starts climbing at FL130, and, with an increase in height, approaching to A/C04, which is crusing at FL153 in opposite direction from A/C01. The sequences of 4D waypoints (WPs) for all four trajectories are assumed to be charaterized by the same absolute timestamps, which confirms the time-based dimension of potential hotspot. It can be noted that a difference in altitude between A/C01 and A/C04 is only 700 feet, and in this case TCAS vertical threshold is still satisfied since the hotspot area belongs to SL6 with an RA activation at the 600-feet difference. Therefore, by concluded that these two aircraft operationally maintain the required vertical separation.

As known, in the normal flight conditions TCAS is incessantly surveying the surrounding airspace by sending queries (interrogations) and receiving responses from the neighbouring aircraft. Therefore, when A/C02 flies into the range of A/C01, the TCAS on-board both aircraft issues traffic advisory (TA) to warn the crew about a possible conflict. In this scenario, the TCAS advises A/C01 and A/C02 in moments t_{TA}^{01} and t_{TA}^{02}, respectively. Naturally, this warning is activated if and only if all three TCAS thresholds for the particular SL are infringed (Table 2). Based on the current flight configuration of both aircraft and approaching closer to each other, at the instances t_{RA1}^{01} and t_{RA}^{02} TCAS issues the RAs requiring that both aircraft perfom an appropriate maneuver (Table 1). Moreover, the RAs are also a subject to the TCAS threshold infringements (Table 2).

The corresponding maneuver depends on the CPA which is determind by speed, heading and position of the aircraft. It is worth mentioning that, due to high level of range-bearing errors in the horizontal plane (Kochenderfer *et al*, 2013), the RAs consider only maneuvers in vertical plane, possibly combined with some turns or heading changes. However, those cases are a measure of the aircraft performances and the crew experiences, and are out of scope of this study. There are four rules in the TCAS logic for the PEs:

1. Two aircraft are alerted by the RAs when the horizontal and vertical threshold distances, DMOD and ZTHR respectively, are violated, or when the time to the CPA (TAU) falls below a specific threshold, with respect to the current aircraft closure rates and a corresponding SL.

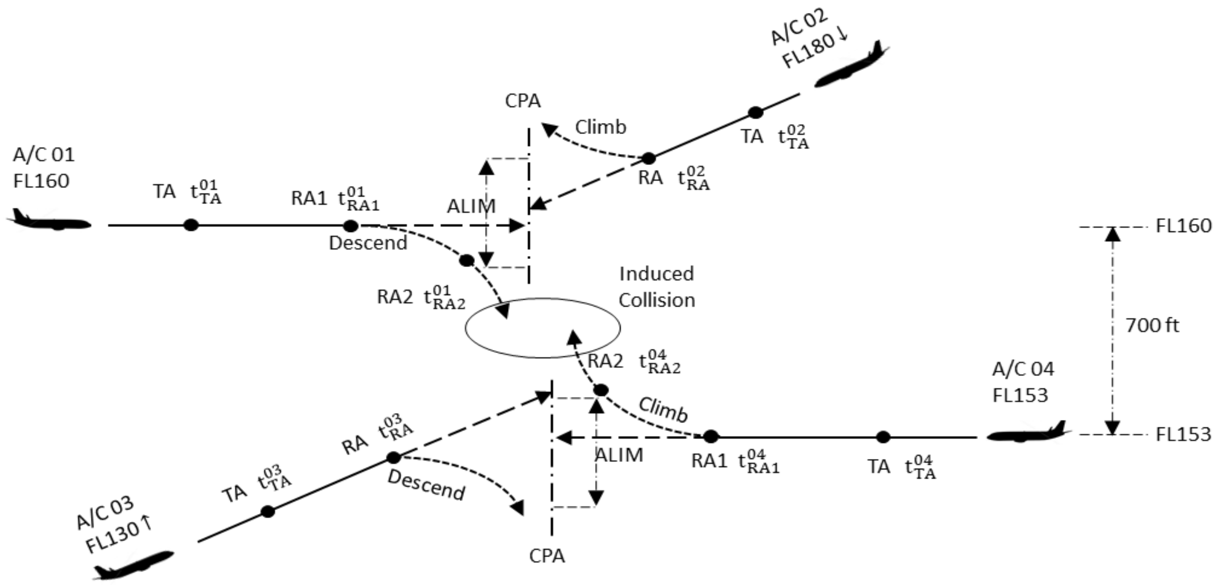

Figure 1. An induced collision scenario.

2. Two RAs are opposite to each other, i.e. they advise an opposite sense for maneuver to the crew (for instance, climb-descend or descend-climb). It is defined as a *reversal* TCAS logic.
3. When the RAs are alerted, an aircraft at a lower altitude performs descending maneuver and the one at a higher altitude complies to a climbing amendment, without consideration of the current flight configuration (cruise, climb or descent); However, the strength sense of the requested manouver will depend on the flight configuration consequently (Table 1).
4. After the RA activation the aircraft following the requested amendments must achieve a vertical separation minima at the CPA, called the altitude limitation (ALIM), as illustrated in Figure 2.

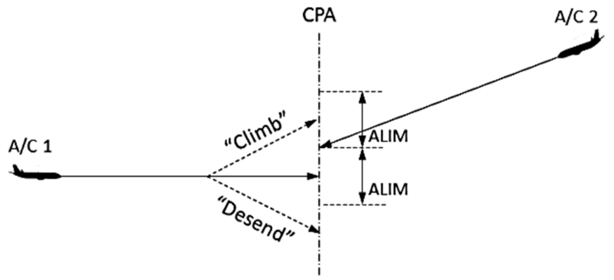

Figure 2. "Descend" RA to achieve ALIM.

TCAS computes TAU as a ratio between the range (an interdistance among the aircraft) and closure rate (or, range rate). Both range and range rate in horizontal plane are obtained from the TCAS interrogations, usually with one-second update, and they apply to aircraft in crusing configuration. In vertical plane, the time to co-altitude (vertical TAU) is computed as a vertical separation divided by a vertical closure rate (Jun *et al*, 2015).

It can be observed from Figure 1 that A/C01 at moment t_{RA1}^{01}, from the crusing phase, starts descending while A/C02 changes from descending to climbing manouver at t_{RA}^{02}, both achieving required separation minima at the CPA. Another PE, A/C03-A/C04, results in a similar way. The TAs in the moments t_{TA}^{03} and t_{TA}^{04} warn A/C03 and A/C04 about a potential conflict. At t_{RA}^{03} and t_{RA1}^{04}, the RAs are activated and both aircraft start performing the advised maneuvers. A/C03 is passing to the descending and A/C04 to the climbing amendment. In practice, it could happen that any of the Ras is not properly applied due to some unpredictable factor(s) (a meteo situation – a wind component, lack of the requested aircraft performance, or any technical error on-board the aircraft). In this case, the ALIM might be infringed and the conflict evolves into a collision.

2.2 Induced collision scenario

The previous subsection has led to the conflict resolutions of two neighbouring encounters. However, the main question is whether these amending trajectories could possibly generate a new conflict. This induced conflict can be elaborated though the emergent dynamics concept. Based on the dimensioned hotspot, it can be observed that A/C02 and A/C03 leave the area on their new conflict-free paths. In other words, they achieve their clear of conflict (CC) points (Table 1).

Concurrently, by following the previous RAs A/C01 and A/C04 induce a conflict. This state could be ambiguous. If the hotspot encompasses several flight levels and a larger horizon this encounter would become an induced conflict and might remain a conflict-based with enough time for the new RAs activation. However, if there is no sufficient time, the induced collision occurs. The analyzed scenario points out to that state. As a collision avoidance layer activates in less than 60 seconds and the RAs are issued in less than 35 seconds before the CPA reachability, once resolved conflicts produce very high uncertainty in guidance over the resolution amendments. Since the original trajectories of A/C01 and A/C04 have been vertically separated only by 700 ft and, by performing their resolution manouvers, the aircraft triggered the new TCAS alerts, the vertical thershold has been considerably violated. A/C01 and A/C04 were automatically alerted by the succeeding RAs, at the timestamps t_{RA2}^{01} and t_{RA2}^{04}, respectively. Due to insufficient time for the appropriate maneuvers, the aircraft came to the induced collision.

TCAS is operating in vertical plane which comprises a set of the vertical RAs only. Therefore, a collision event is predominantly affected by the upstream and downstream traffic flows.

3 Scenario Simulation – Unit Case

This section describes the simulation platform for CD&R algorithm and provides the scenario results for unit case. Results are presented both graphically (within integrated Graphical User Interface – GUI) and textually (in form of the log messages).

3.1 Simulation Platform for CD&R algorithm

For simulation of our scenario we have used the Stratway tool. It is the algorithm for a strategic, intent-based, CD&R, developed by the NASA Langley Research Center. Stratway is an open source software tool, implemented both in Java and C++ environment, and can be called from other programs through an Application Program Interface (API) and also excuted from a command line. The main features are as follows:

- work with the complete 4D flight plans as inputs (three spatial geographic coordiantes + time);

- generation of the conflict resolution in the form of conflict-free paths for the ownship aircraft (a reference trajectory) in presence of the multiple traffic aircarft (intruders), if feasible;
- use of a set of the heuristic search strategies for the conflict resolution;
- output of the message errors and warnings, as well as the textually-based solutions;
- considerably based on the real aircraft performances and use of a large set of the navigation parameters, that are user-configurable;
- implementation of a set of maneuvering strategies (*vertical*, *track*, *speed*, or *side-step*) which are 3D-oriented (Figures 3, 4 and 5);
- iterative tests of all involved trajectories, and output of all possible combinations for the trajectory resolutions;
- no current support to testing the induced collision scenarios; however, there are possibilities for making the upgrades with the new functionalities and strategies.

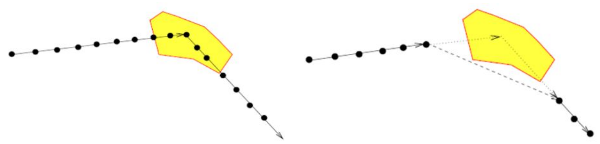

Figure 3. Track search strategy.

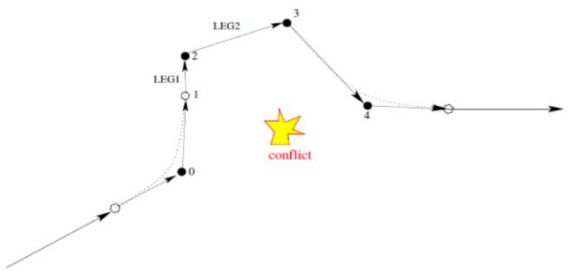

Figure 4. Vertical search strategy.

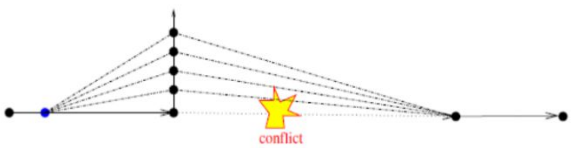

Figure 5. Side-step search strategy.

Figures above illustrate three types of maneuvering strategies. The first type is a *track* strategy (Figure 3) which is based on a heading change. The goal is to avoid a hotspot by isolating the WPs, positioned inside the hotspot, and to directly re-route to the first available WP outside the hotspot. Nevertheless, this strategy can be treated as a *fly-by-waypoint* procedure, where this WP is an imaginary center of the hotspot area. The second type is a *vertical* strategy (Figure 4). It seeks to resolve the conflict through a sequence of climbs or descents without changing the current heading of the trajectory. The strategy starts from the WP in vicinity of the hotspot using the same isolation method as the track strategy. From this WP, an aircraft increases the climb amendment (or descent, in the opposite case) in order to overtop a potential intruder. The amending trajectory leg is usually shaped as a polygon consisting of the shorter segments. A *side-step* strategy (Figure 5) is the third type, and is not considered so flight-efficient as the track strategy, but sometimes can provide the comparable solutions. It resolves a conflict by only removing a WP right before the conflict. The strategy is very effective for the trajectories containing longer segments. It inserts a *lead-in* WP (blue-colored point) in advance of the current aircraft position, from which the aircraft starts with an amending leg, and then continues with a resuming leg to the original trajectory. A deviation from the original trajectory, or the point at which amending leg terminates and the resuming leg starts, depends on the geometries of the conflicting trajectories and the closure rates.

3.2 Unit Case Simulation and Results Validation

For simulation of two PEs, it has been implemented a unit case scenario within the Dortmund enroute airspace (51°30′53″ N, 7°27′57″ E), between 13000 and 18000 ft (FL130 – FL180). Each of four trajectories has been generated in a sequence of 10 WPs with the constant time-based segments (15 seconds of the time interval) in order to facilitate the encounters prediction. Closure rates, i.e. the true airspeed (TAS) in cruising and vertical speed - rate of climb/descent (ROC/D) - are assumed to be constant as well, and by default set to TAS = 330 knot and ROC/D = 1500 ft/min. Nevertheless, these values can be changed as per user preferences, or adopted to a specific SL. Table 3 illustrates a sample of the sequences of the 4D WPs for all four trajectories used as an input. *OWN* in the table denotes the ownship aircraft, while *TRAF* with the given index corresponds the traffic aircraft.

Table 3. Input Data.

Name	*Latitude [deg]*	*Longitude [deg]*	*Altitude [deg]*	*Time [sec]*
OWN	51.51389	7.53075	16000	2400
OWN	51.51389	7.55370	16000	2415
TRAF1	51.51649	7.61961	18000	2400
TRAF1	51.51604	7.61894	17625	2415
TRAF2	51.48779	7.68225	13000	2400
TRAF2	51.48824	7.68292	13375	2415
TRAF3	51.49155	7.80565	15000	2400
TRAF3	51.49155	7.78405	15000	2415

In order to graphically present the simulated results, a graphical user interface (GUI) has been developed as a part of the Stratway algorithm. The Stratway GUI is composed of 6 views illustrating the interdependencies between 4D coordinates:

- latitude-longitude,
- altitude-longitude,
- altitude-latitude,
- altitude-time,
- latitude-time,
- longitude-time.

By default, latitude and longitude are expressed in degrees [deg], altitude in feets [ft] and time in seconds [sec]. The simulation of the Dortmund scenario in Stratway has validated that the present resolution algorithm cannot find a conflict-free path within an induced collision (Figure 6). None of four aircraft, set iteratively as the ownship, could avoid induced collision as it has occurred on the central segments of their trajectories. The Stratway also generates also the graphical output of the pairwise conflicts without a possibility for any aircraft approaching to the induced collision state to perform an appropriate RA maneuver (Figure 7).

[All strategies failed at time 2400.00''
----- Time 2442.00 -----------------------------
SideStep did not find a solution
TrackEarly did not find a solution
Vertical did not find a solution
Speed did not find a solution
Track did not find a solution
All strategies failed to resolve the conflict]
Resolution status Unresolved

Figure 6. Log message output.

4 Causal Model for Collision Prediction

4.1 CPN Formalism

The main CPN characteristics that present very applicable formalism for a description of the discrete event-oriented simulation models are:

- all events that could appear according to a certain system state can be easily determined by a reachability graph;
- all events that can set off the *firing* of a specific event can be detected visually. CPNs are considered as a graphical modeling tool with a few syntactic rules.

The main CPN components that meet the modeling requirements are: the *places*, represented by the circles, and specifying the system states; the *transitions*, depicted by the rectangles and expressing the system events; the *input arc expressions* and *guards*, indicating the types of tokens used to fire a transition; the *output arc expressions* indicating the system state change that appears as a result of firing the transition; the *color sets*, the entity attributes which determine types, operations and functions that can be used by the elements of the CPN model; a *state vector,* the smallest piece of information for prediction of the events that could appear. This vector denotes the number of tokens in each place and the colors in each token. The color sets allow specification of the entity attributes, and the output arc expressions define what actions should be coded in the event routines linked to each event.

4.2 CPN Modeling Approach for Pairwise Collision Prediction

This subsection proposes a new causal modeling approach for the right discretization of conflict/collision

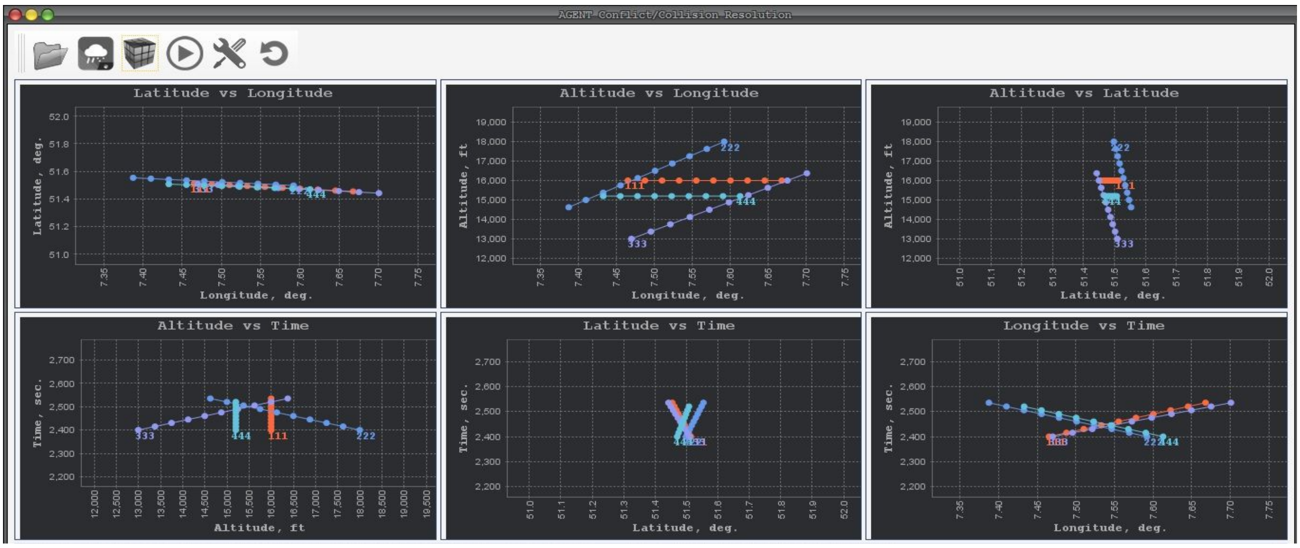

Figure 7. Stratway GUI Output.

events (Munoz *et al*, 2013) considering a larger time horizon in form of a *look-ahead* time (LAT), which is decomposed into a sequence of shorter time intervals for the control actions. For the simulated induced collision scenario, it is proposed the LAT of 300 seconds. Since, the simulation case assumes the ideal case – the constant closure rates and timestamps - the CPA will occur after 150 seconds. In real cases, i.e. the flown trajectories that include the trajectory prediction states, the CPA presents a fluctuating point, so it may occur in less or more than 150 seconds. The LAT could be sequenced in different time intervals. In this scenario, an update rate of 30 seconds has been used, meaning that the system has been considered in the discrete moments: 120, 90 and 60 seconds before the CPA. The elapsed time in less than 60 seconds denotes the TCAS convergence area based on the TAU thresholds (the TA and RA activations). The model is based on the following pre-conditions:

- The LAT provides a prediction of collision event and a way on how to avoid the hotspot at all.
- A pre-decision process (a multi-trajectory selection) is given advantage over a decision process (RA maneuver) with respect to the aircraft performance (feasibility criteria);
- With a continuous decrease in distance to the CPA less number of the potential conflict-free trajectories is achievable.

The proposed model relies on one basic concept – protected volumes. They take a shape of the imaginary cones, ground-in horizontally, with the peaks presenting the starting points of the 300-seconds time horizon. The shortest distance within these cones is the LAT distance along x-axis. These protected volumes have been considered to denote the aircraft capability to fly in a limited airspace. The limitation reflects both laterally and vertically, in the following way:

- The maximum heading change in the horizontal plane is 30 degrees. For an easier model representation, it is used the term *gradient*, presenting a coefficient of a gradual increase of the horizontal divergence measured from the x-axis, with the beginning at an identified LAT WP;
- The maximum vertical gradients from the LAT WP, i.e. ROC/D are ±5000 ft/min.

With the shortest distance and specified gradients, it is possible to define a base of the cone computing the LAT distance. After this distance, both gradients form a base with two radiuses. This imaginary base takes a shape of an ellipse. The simulation model computes all the aircraft cones together with its proximity and/or intersections defining the hotspot volumes. The intersection volumes are defined by the aircraft cones that mutually intersect in some segments of their trajectories. The shape of these volumes depends on the trajectories geometry, and considerably on the four-time colors: an entrance time of first aircraft (*time-in*, t_{1i}) and its exit time (*time-out*, t_{1o}), as well as an entrance time of second aircraft (t_{2i}) and its exit time (t_{2o}).

Once a hotspot volume has been computed and projected, the simulation model searches for the collision states by applying the TCAS RA thresholds within the intersection volumes. Therefore, any aircraft flying within its cone, but outside the intersection area, is supposed to be in a CC state. This search also includes the neighboring aircraft trajectories for the induced collision cases. If a collision state is identified/predicted the proper RAs are issued, and the aircraft perform requested maneuvers inside their imaginary cones. The model records the pairwise collisions only. It is graphically described in Figure 8.

The elements of the model are structured as follows:

- **T1** – the first transition denoting the protected volumes construction with its guard function **GU1**; **T2** - second transition defining the intersection volumes with the guard function **GU2**; **T3** – third transition that checks out the number of collision events controlled by the guard function **GU3**;
- **P1** – the place expressing the vertical gradients; **P2** – the place expressing the lateral gradient (the heading change); **P3** – the place containing 300-seconds time window; **P4** – the place that stores the along-track distances; **P5** – the control place 1 assuring that input values are satisfied; **P6** – the place linking the transitions T1 and T2, and marking the protected volumes state; **P7** – place denoting the time matrix values; **P8** – the control place 2 checking that extracted time values are satisfied; **P9** – the place that depicts the intersection volumes; **P10** – the place containing the 4D trajectory data; **P11** – the place containing the RA thresholds; **P12** – the place that stores the pairwise checks within a set of aircraft; **P13** – the place storing the pairwise induced collisions.

5 Validation and Evaluation

Presented CPN model is deployed as an essential approach to the quantitative state space analysis of the events in which the potential conflicts can likely result in collisions. At present, the causal model has been validated with some stakeholders by means of:

- *Model Purposiveness*: the conceptual model has been validated by means of a unit test (mainly though the extreme scenarios), and all detected bugs have been removed. As a result of the meeting with the experts, some modifications to the conceptual model has been added to extend the simulation/tests targets.
- *Model Plausibility*: the level of plausibility, or the expert opinion, basically referes to two features of the model. The first considers a question of whether the model *looks logical*. This answer on this question

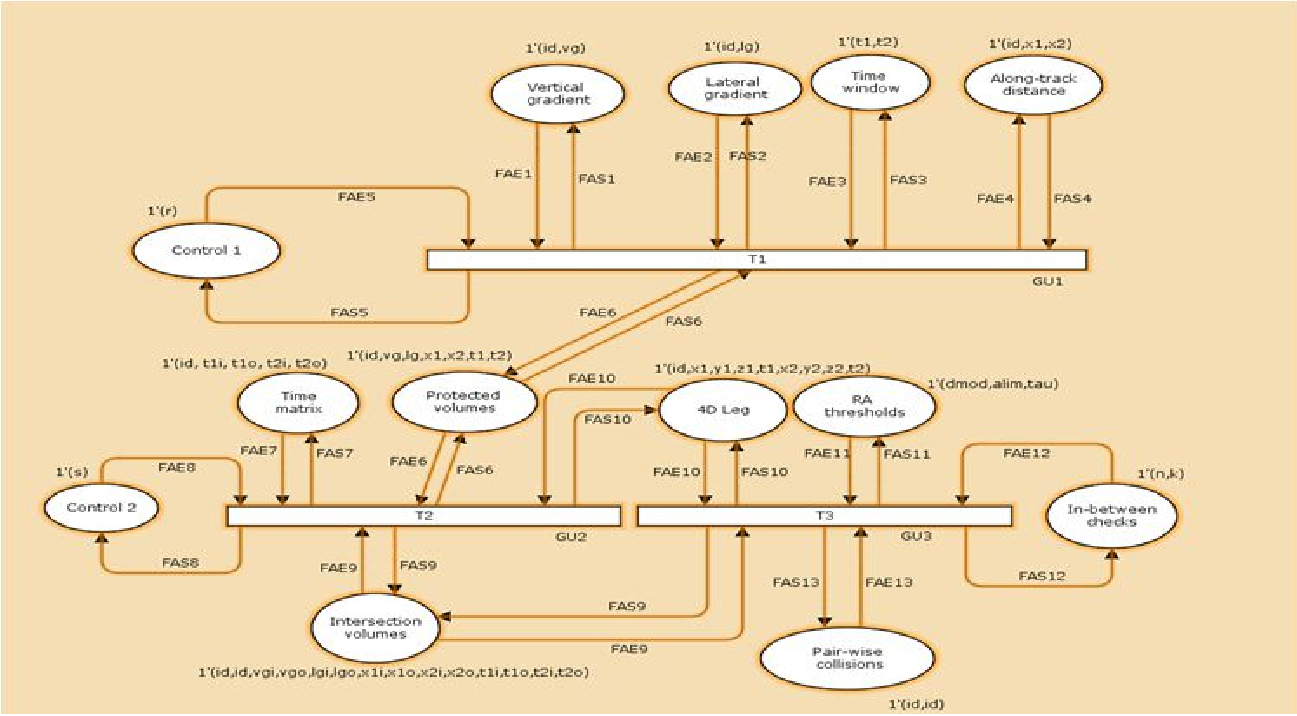

Figure 8. CPN model for pairwise collision prediction.

gives the characteristics of the model structure (the rules and hypothesis) and its parameters. The second is related to the question of whether the model *behaves logically*. This part provides an assessment of the reaction of the model outputs to the typical events (scenarios) on the inputs.

The aircraft state information, such as position and velocity, coming from the analyzed non-vectored scenario have been fed the Stratway simulation tool, and the obtained outputs – conflict segments in a form of the 4D points – have been used as an intial marking, or zero conditions, for generaion and execution of the CPN model. In addition, defined metrics, such as vertical and lateral gradients, conflict time intervals and constants (RA values) had provided a better insight of the spatiotemporal interdeoendencies in the potential collsion scenario, and creation of the intersection volumes as a qualitative solution. Finally, several simulation runs, performed in Stratway, had provided different initial markings, that are further used for computation of the final solution state in the CPN model. The intial markings pointed out to the different geometries of the conflict segments.

The follow-up validation steps will consider the state space analysis of a conflict scenario for detection of the sequence of maneuvres, that could lead to an induced collision. The generated data will be fed to InCAS (the simulation tool developed by EUROCONTROL) to validate the trajectories computed by the causal model. It will be also used *TimSpat* (Baruwa *et al*, 2015) to perform the computation of all states that can be reached from initial configuration, as illustrated in Figure 9.

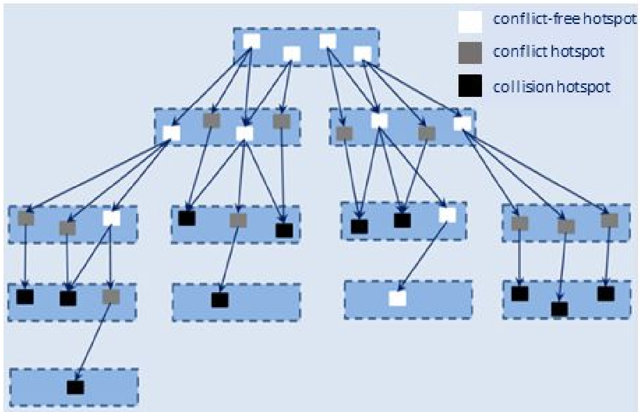

Figure 9. Reachability graph for collision events.

Each node in the graph represents a feasible marking and each arc the transition or event which allows the system evolution from the initial state to a new one. The reachability graph is structured in four levels and composed of nodes of the hotspot areas that are classified in three categories: conflict-free (white-coloured), conflict (grey-coloured) and collision (black-coloured) hotspots. There is only one node in the final level obtaining one collision hotspot. Still, the third level reaches also a node with a conflict-free hotspot.

6 Conclusions

This paper analyses the induced collision scenario in the en-route airspace as a product of the previously resolved pairwise conflicts. Based on the TCAS shortages, it tries to identify the dynamic structures of the 4D trajectories involved in collision through simulation of their tracks and implementation of the appropriate feasible strategies. The paper further focuses on causal modeling trying to generate a new approach that will provide a higher awareness of the collision hotspot and a better decision-making process.

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