Universitat Autònoma de Barcelona

CAUSAL MODELS FOR ANALYSIS OF TCAS-INDUCED COLLISIONS

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CERTIFY:

That the thesis entitled “Causal models for analysis of TCAS-induced collisions” and submitted by Jun Tang partial fulfilment of the requirements for the degree of Doctor, embodies original work done by him under my supervision.

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The journey of a thousand miles begins with one step.

Lao Tzu (604 BC - 531 BC)

EXECUTIVE SUMMARY

A series of mid-air collisions have occurred over a period of 30 years (1956-1986). This spurred the Federal Aviation Administration (FAA) to make a decision to develop and implement an effective collision avoidance system that would act as the last-resort when there is a failure in air traffic controller (ATC)-provided separation services. The resulting Traffic Alert and Collision Avoidance System (TCAS) was developed using comprehensive analysis and abundant flight evaluation. The influence of TCAS on safety flight has been effective, beneficial, and significant in reducing the collision probability.

Work in the Single European Sky ATM Research (SESAR) and the Next Generation Air Transportation System (NextGen) will introduce new technologies and procedures to deal with a more efficient Air Traffic Management (ATM) while remove pre-set latent capacity. Thus, new research considering the impact on safety is required to increase the airspace capacity based on comprehensive analysis and effective flight evaluation. In this thesis, several causal encounter models are proposed to promote the improvement of TCAS ability considering its effect on surrounding traffic which is intended to address the future hectic and congested traffic.

All the causal encounter models are represented in Coloured Petri Net (CPN) which is a Discrete Event System (DES) formalism. Based on the state space analysis of an air space volume with several aircraft, the encounter models provide a downstream trace of the different effects of potential resolution advisories (RAs) issued to avoid a collision. The implemented models have been validated using the Interactive Collision Avoidance Simulator (InCAS) and provide a global perspective on the scenario dynamics and a better understanding of the induced collision occurrence for risk assessment.

As a result, the neighbouring traffic scenarios that could initiate induced collisions have been identified and characterized. The quantitative analysis of the risk ratio of TCAS-induced collisions has been provided to assess the impact of pilot delay to respond TCAS advisories during flight in high-density scenario. Through considering probabilistic pilot response, all the future possible reachable states are generated to provide a cooperative feasible collision resolution. Consequently the TCAS avoidance performance could be innovatively improved without the change of relevant logic.

The proposed causal encounter models would provide auxiliary supports in the analysis of heavy traffic scenarios, and increase the airspace capacity while safely and efficiently manage a higher amount of flights. These contribute to follow-up research for the safety analysis of current and advanced ATM concepts including the developing TCAS.

RESUMEN EJECUTIVO

Una serie de colisiones en el aire que ocurrieron durante un período de unos 30 años (1956-1986) fueron uno de los principales motivos por los que la Administración Federal de Aviación (FAA) tomó la decisión de desarrollar e implementar un sistema de prevención de colisiones eficaz que actuara como último recurso, cuando se produjese un fallo del servicio de separación de aeronaves por parte del controlador de tránsito aéreo (ATC). El Sistema de Alerta de Tráfico y Anticolisión (TCAS) fue desarrollado para este objetivo a partir de un análisis completo de datos de vuelo. Como resultado La influencia de TCAS en la seguridad del vuelo ha sido eficaz, beneficiosa y significativa en la reducción de la probabilidad de colisiones.

Los proyectos Single European Sky ATM Research (SESAR) y Next Generation Air Transportation System (NextGen) pretenden mejorar la eficiencia en la gestión del tráfico aéreo (ATM) al mismo tiempo que se pretende reducir la actual capacidad latente en el lado aire mediante la incorporación de nuevas tecnologías y procedimientos,. En consecuencia, va a ser necesario investigar el impacto en seguridad al aumentar la capacidad del espacio aéreo mediante un análisis exhaustivo y una evaluación efectiva del vuelo. En esta tesis, se proponen varios modelos causales de encuentro entre aeronaves para mejorar el rendimiento del TCAS teniendo en cuenta el potencial efecto sobre el tráfico colindante, considerando escenarios futuros con un número elevado de trayectorias.

Los diferentes modelos han sido especificados como sistemas a eventos discretos mediante el formalismo de Redes de Petri Coloreadas. Mediante el análisis del espacio de estado de un volumen de espacio aéreo con varias aeronaves, los modelos desarrollados evalúan los efectos de los distintos RA's generados por TCAS sobre el tráfico colindante. Los modelos han sido validados utilizando INCAS y ofrecen una perspectiva global de las dinámicas que se generan, y una mejor comprensión de las potenciales colisiones inducidas para una mejor valoración del riesgo de colisión.

Como resultado, los escenarios con tráfico colindante que podrían iniciar colisiones inducidas han sido identificados y caracterizados. El análisis cuantitativo del factor de riesgo de colisiones inducidas por TCAS ha sido realizado para evaluar el impacto de la demora del piloto para responder a los avisos TCAS durante el vuelo en escenarios de alta densidad. Mediante el uso de modelos estocásticos para representar la respuesta del piloto se han analizado los diferentes estados alcanzables con el objetivo de generar resoluciones cooperativas. En consecuencia, el rendimiento de TCAS se podrá mejorar de forma innovadora sin necesidad de introducir cambios relevantes en la lógica.

Los modelos de encuentros causales propuestos pueden ser utilizados como herramientas auxiliares en el análisis de escenarios de tráfico denso, y aumentar la capacidad del espacio aéreo, gestionando de manera eficiente y segura un mayor número de vuelos. El presente trabajo contribuye a continuar las investigaciones en el análisis de la seguridad de los conceptos ATM actuales y avanzados, incluyendo las futuras extensiones de TCAS.

RESUM EXECUTIU

Una sèrie de col•lisions aèries que van succeir durant un període d'uns 30 anys (1956-1986) van ser un dels principals motius pels quals l'Administració Federal d'Aviació (FAA) va prendre la decisió de desenvolupar i implementar un sistema de prevenció de col•lisions eficaç que actués com a últim recurs, quan es produís una fallada del servei de separació d'aeronaus per part del controlador de trànsit aeri (ATC). El Sistema d'Alerta de Trànsit i Anticol•lisió (TCAS) va ser desenvolupat per a aquest objectiu a partir d'una anàlisi completa de dades de vol. Com a resultat, la influència de TCAS en la seguretat del vol ha estat eficaç, beneficiosa i significativa en la reducció de la probabilitat de col•lisions.

Els projectes Single European Sky ATM Research (SESAR) i Next Generation Air Transportation System (NextGen) pretenen millorar l'eficiència en la gestió del tràfic aeri (ATM) al mateix temps que es pretén reduir l'actual capacitat latent en el costat aire mitjançant la incorporació de noves tecnologies i procediments. En conseqüència, serà necessari investigar l'impacte en seguretat en augmentar la capacitat de l'espai aeri mitjançant una anàlisi exhaustiva i una avaluació efectiva del vol. En aquesta tesi, es proposen diversos models causals de colisions entre aeronaus per millorar el rendiment del TCAS tenint en compte el potencial efecte sobre el trànsit colindant, considerant escenaris futurs amb un nombre elevat de trajectòries.

Els diferents models han estat especificats com a sistemes a esdeveniments discrets mitjançant el formalisme de Xarxes de Petri Acolorides. Mitjançant l'anàlisi de l'espai d'estat d'un volum d'espai aeri amb diverses aeronaus, els models desenvolupats avaluen els efectes dels diferents RA's generats pel TCAS sobre el tràfic col•lindant. Els models han estat validats utilitzant InCAS i ofereixen una perspectiva global de les dinàmiques que es generen, i una millor comprensió de les potencials col•lisions induïdes per a una millor valoració del risc de col•lisió.

Com a resultat, els escenaris amb tràfic col•lindant que podrien iniciar col•lisions induïdes han estat identificats i caracteritzats. L'anàlisi quantitativa del factor de risc de col•lisions induïdes per TCAS ha estat realitzat per avaluar l'impacte de la demora del pilot per respondre als avisos TCAS durant el vol en escenaris d'alta densitat. Mitjançant l'ús de models estocàstics per representar la resposta del pilot s'han analitzat els diferents estats assolibles amb l'objectiu de generar resolucions cooperatives. En conseqüència, el rendiment de TCAS es podria millorar de forma innovadora sense necessitat d'introduir canvis rellevants en la lògica.

Els models causals de col•lisions proposats poden ser utilitzats com a eines auxiliars en l'anàlisi d'escenaris de tràfic dens, i augmentar la capacitat de l'espai aeri, gestionant de manera eficient i segura un major nombre de vols. El present treball contribueix a continuar les investigacions en l'anàlisi de la seguretat dels conceptes ATM actuals i avançats, incloent les futures extensions de TCAS.

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1 INTRODUCTION

1.1 Motivation

As stressed in [1], “accidents are dramatic examples, among other less critical events, pointing out how prospective assessment methods often poorly represent human and organizational aspects and hence limit their value for accident prevention”. We must accept that the existent air collision risk needs some feasible policies and methods to deal with the trade-off between flight efficiency and Air Traffic Management (ATM) capacity. Thus the research of air collision risk should consider both level of safety figures and new useful safety metrics to identify “system weaknesses” that need to be resolved or at least mitigated. These new metrics should provide a better understanding of several micro-level dynamics such as the estimation variation of collision risk achieved by new risk mitigation policies considering the analysis of different interdependent scenarios in the same time-period.

1.1.1 ATM and the new operational context

ATM is universally considered to be a “high reliability” service industry in which accidents are infrequent [2]. However, in the beginning of 21st century, several factors have contributed to an incremental focus on measuring and managing the safety flight. The collision of two aircraft in 2002 over Überlingen carried away the lives of 71 passengers and crew [3]. Furthermore, all 114 people on a MD-87 and a Cessna CJ2 were killed in the 2001 Linate Airport disaster, as well as four ground staffs on the ground [4]. These accidents strengthened all services related to air navigation specially Air Traffic Flow Management (ATFM) [5] which supports the use of available airspace effectively, including airport capacity, and therefore its importance has been increased significantly. In the main, the introduction of new technologies and procedures (e.g., high density, remotely piloted aircraft (RPA), flight level capping and free flight among others) would evidently promote the improvement of the air side capacity but further studies on safety are required to understand new scenarios that could emerge in high density traffic areas.

The Terminal Manoeuvring Area (TMA) and hot spots are relatively complex types of airspace which need special attention. Congested TMA are being forced to receive more flights each day, and departure pushes to accommodate late arriving flights bringing about further up and down-line disruptions [6]. In [7] it is reported using experimental data how the traffic density can increase considerably in certain reduced areas during short periods, known as hot spots. Several research teams are analysing new concepts, procedures, technologies and tools that can improve airspace efficiency, among them it is mentioned two procedures that could affect the geometries analysed in most TCAS reports:

- Flight level capping is an excellent procedure to reduce air traffic controller (ATC) workload and tackle safety issues [8]. Mainly it is an ATFM procedure whereby a flight has a limit applied to the altitude/flight level at which it will be allowed to operate. This is usually applied to restrict the amount of air traffic entering a particular vertical sector of airspace in order to balance demand and capacity [9]. Besides, further research on maximizing the airspace latent capacity could introduce some changes in present flight level capping, considering also the inclusion of RPA [10] and free routing procedures.

- The basic definition of free flight is that the crews in aircraft possess the freedom to amend their trajectory including the responsibility of resolving threats with other intruders [11,12]. Free flight scenarios can be easily achieved in a low-pressure circumstance while the results would not be conclusively determined when the traffic loads become heavier. In telecommunications and software engineering, scalability is the ability of a system, network, or process, to handle growing amounts of work in a graceful manner or its ability to be enlarged to accommodate that growth [13]. Considering the increasing demand for air travel, the scalability concept requires a particular attention in the developing ATM by applying several effective techniques and systems to ensure the free flight when there are various aircraft coexisting in the same airspace.

In [12] it is described the importance to analyse TCAS in a context in which RPAs are introduced. Note that RPAs offer a unique range of features, most notably ultra long-endurance and high risk mission acceptance, which cannot be reasonably performed by manned aircraft. These features, when coupled with advances in automation and sensor technologies, and the potential for cost saving, make a strong case for the eventual emergence of a robust, civil, government and commercial RPA market. The emergence and consolidation of a commercial RPA market poses a number of challenges to the aviation system. At that operations level, the integration of RPA with (manned) general aviation is one of the most challenging topics to be considered for future ATM. RPAs generally possess so higher flexibility that they have the huge capacity to execute any task among which they could easily change flight level. Thus, the probability of encounters with the conventional aircraft which are cruising in their corresponding level would significantly rise in some future ATM scenarios. At present, despite the increasing demand of RPA for civil applications is placing pressure to ease the integration of these unmanned aircraft with the conventional aviation, the aeronautical authorities will not accept this integration until those unmanned aircraft achieve the "equivalent level of safety" (ELOS) of traditional aviation [10], i.e., with the same level of risk for air traffic and ground assets and persons. Adequate consideration and various efforts have occurred as steps that are required to improve the compatibility of Traffic Alert and Collision Avoidance System (TCAS) on RPAs; this concern once served as a main topic of discussion at the ICAO Surveillance and Conflict Resolution Systems Panel (SCRSP) meetings [14].

The safety in conventional aviation resides in the own aircraft equipment, the operating crew and the ground navigation aids, together with the air traffic management and control systems (ATM/ATC) in charge of the surveillance and separation assurance during all phases of flight, from the beginning of each trajectory (take-off and climb), during cruise (en-route) and up to the end (approach, descent and landing). Therefore, RPAs are expected to operate (if integrated) in a non-segregated airspace whose structure, management and control have been designed for manned aircraft, whose required high safety standards must be accomplished by all the airspace users. The integration of RPAs in the current ATM, though is a complex and combined process of technology development and legal framework improvement (not only national but also international), must be fully compatible with the rules issued by the same competent aeronautical authorities that currently affect traditional aviation [12]. It means two basic requirements:

- Equivalent level of safety to the applicable to conventional aviation.
- Transparency towards the ATM/ATC systems.

It is widely accepted the importance of research in future ATM scenarios that could be characterized by high density areas with some flights under free routing procedures coexisting with RPAs [10]. Present technology allows own aircraft to broadcast its state information such as the position and velocity to neighbouring traffic, and also to receive similar state information from intruder aircraft. Because of the increasing air traffic density and technological development, the fundamental concept of ATM has been greatly rethought [15]: transfer the control from centralise to distribution, transfer responsibility for conflict avoidance from ground to air, and introduce new technologies to replace the fixed air traffic routes.

In the high-density scenarios, the unpredictable behaviour that emerges in a system-wide range suddenly arises based on the integrated result of successive dynamical operations and pilots' possible reactions which would make an important effect on the surrounding traffic (i.e., safety issues). As it is quite unpredictable, several novel complementary techniques and systems are needed to estimate the rigorous safety of new ATM in the congested traffic situations. Thus, despite all the procedures are properly analysed in the new paradigm shift, it is very important to enhance the last-resort of safety (i.e., TCAS) in case an error could be produced and propagated from the different hierarchical safety procedure levels.

1.1.2 Decision support tools

The current ATM system is in the fleetly extensive development from the relatively structured airspace and mainly human-operated system framework [13]. In line with the requirements of the future ATM concepts proposed by The Single European Sky ATM Research (SESAR) [16] (launched by the European Community) and the Next Generation Air Transportation System (NextGen) [17] (launched by US government), the air-traffic flow needs to be more predictable to offer the possibility of more effective use of airspace and airport capacity. Furthermore, to provide ATC and aircrew with more valuable information about the traffic flow, especially the accurate states of the nearby aircraft, various decision support tools (DSTs) in different levels are being developed. It is indispensable to propose and design new DSTs to increase the airspace capacity while safely and efficiently manage a higher amount of flights.

Guaranteeing safety in air traffic is still the primary factor to be considered in the future ATM. The separation assurance between the involved aircraft's trajectories acts as the main research direction. Whenever a specified minimum separation between two approaching aircraft is violated, an encounter emerges and several effective measures should be taken in time to resolve it.

With the growth of airspace congestion, there is an extensive need to implement DSTs to assist the human operators in handling with any emergency to improve flow efficiency. The fundamental functions of the DSTs system are conflict detection (CD) which is to predict a threat that would occur in the future, communicating with human operators to inform the detected threats, and conflict resolution (CR) which is to provide assistance in the process of resolving threat. The complete survey of models and approaches to the conflict detection and resolution (CDR) problem is presented in [18]. On account of the prediction horizon, generally, most CDR techniques and methods can be classified into three major categories.

-Long term CDR, is useful for airspace planning at strategic level and roughly handles the horizons above 30 minutes. Their main concern is typically management problem of air traffic flow, including the planning of all aircraft trajectories within a relatively longer look-ahead time. Predictions are made from several days up to a few (>30) minutes before the flights execution phase. Their main goal is to maximize the network route efficiency while minimize the global operational costs, taking into account the airspace restrictions such as the available capacity at the airports and sectors [19,20]. The EuroControl long-term forecast (LTF) [21] is developed by growing baseline traffic using a model of economic and industry developments, taking into account factors related to economic growth, passenger demand, prices, air network structure and fleet composition. Constrained by annual airport capacities, specific models are utilized to address cargo, passenger, business aviation and military general air traffic (GAT). Besides, the research project of Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM) innovatively adopts the usage of Spatial Data Structures (SDS) for conflict detection and resolution at strategic level (long term) with a seamless coordination with the tactical level (medium term) [22].

-Medium term CDR, works at tactical level and possesses prediction horizons up to 30 minutes. These planning systems make impossible to improve and perfect the proposed flight plans of Long term CDR during the execution phase, generally thinking about prediction look-ahead time of several minutes. These systems are often used by ATCs due to the presence of disturbances caused by unforeseen events that cannot be predicted beforehand with enough accuracy (i.e., during the flight planning of strategic level) and that usually make impossible to accomplish with the long term CDR's proposed flight plans during the execution phase [23,24]. The look-ahead time is large enough to allow a tactical control for the flight safety and there is no risk of any imminent collision between aircraft. Our research group has developed an efficient Medium Term CDR approach based on four-dimensional (4D) trajectories (trajectories defined in the three spatial dimensions together with a time-stamp) to solve conflicts in a Terminal Manoeuvring Area (TMA) [25]. The CD subsystem uses SDS to avoid non-efficient pairwise trajectory comparisons and a simplified wake vortex modelling through 4D tubes to detect time-based separation infringements between aircraft. The CR subsystem solves the detected conflicts with an efficient and dynamic three-dimensional (3D) allocation of the arrival routes that takes into consideration the execution of Continuous Descent Approaches (CDAs). The resulting conflict-free trajectories of several stressing traffic scenarios have been validated for flyability conformance both with a certified B738 Full Flight Simulator.

-Short term CDR, works at operational level to avoid the upcoming conflicts, and takes effect horizons up to 10 minutes. Since they are not planning systems which are different from Long term and Medium Term CDR, there is no need to consider the fuel and flight optimization. Normally it mainly includes two kinds of systems: one is the ground-based safety net intended to assist the controller in preventing collision between aircraft by generating, in a timely manner, an alert of a potential or actual infringement of separation minima [26,27] (e.g., Short Term Conflict Alert (STCA) [28]); the other one is a family of airborne devices that function independently of the ground-based ATC system [29] (e.g., Airborne Collision Avoidance System (ACAS)).

The STCA system comprises alert mechanisms for ATCs which provide warns of airspace infractions between aircraft. It monitors aircraft locations from ground radar, raising a warning to remain a short time to redirect the aircraft when there is a developing threat between dangerously approaching aircraft. Because of the input of STCA systems is from ground radar, they cannot be aware of the intentions of the pilots or ATCs, who may know a potential encounter and already taking measures to resolve it. Thus the alerts issued maybe are not always necessary and the predictions of STCA usually are considered conservatives.

In reality, the current ATM system heavily relies on the skills of ATCs and traffic flow managers. Most of the short term and medium term predictions in particular are made by controllers and flow managers looking at air traffic displays and mentally extrapolating the situation, using partial automation aid during the decision-making processes [27].

Short term CDR requires particular attention, because it works at the operational level to avoid imminent crashes by the implementation of alert mechanisms for controllers (e.g., STCA), and alert mechanisms for pilots, such as the ACAS, which provides some degree of collision threat alerting.

ACAS is designed to be the last resort airborne system. A weakness in the long term CDR is usually solved by medium term CDR, and a medium term CDR failure scenario can be dealt with by ACAS. The main topic of this research focuses on the final phases of an encounter (in ACAS course) that may deteriorate into a collision. Thus, by improving the performance of ACAS it could be possible to avoid failures hidden at long term and medium term CDR that could deal with a collision when applied to future ATM scenarios.

To prevent mid-air collisions (MACs) and significantly reduce near mid-air collisions (NMACs) between aircraft, the ACAS has been developed to serve as the last-resort safety net [30]. MAC [31] is an accident where two aircraft come into contact with each other while both are in flight, and NMAC [32] is an incident associated with the operation of an aircraft in which the possibility of collision occurs as a result of proximity of less than 500 feet to another aircraft, or a report is received from a pilot or flight crewmember stating that a collision hazard existed between two or more aircraft.

To ensure the flight safety, ACAS as an automated sense and avoid system is mandatory (according to ICAO rules) in certain airspace regions. In essence it is an on-board CDR system giving Traffic Advisories (TAs) and Resolution Advisories (RAs). TCAS [29] is a specific implementation of the ACAS concept and currently TCAS II is the only commercially available implementation of ICAO standard for ACAS II. Until now, TCAS I and its improved version, TCAS II, have been defined and approved by the ICAO, and they differ primarily in their alerting capability. TCAS I provides TAs to assist the pilot in the visual acquisition of intruder aircraft, whereas TCAS II provides both TAs and RAs, in other words, recommended escape manoeuvers [33]. Various literatures have been published to represent the operating mechanism of TCAS and increase its capability [34-37].

The main functions of TCAS are to communicate the detected threat to the pilot and to assist in resolving the threat by recommending an avoidance manoeuver. Normally, TCAS, as an alert system operates quietly in the background most of the time. When the TCAS logic determines that an action is needed, TCAS interrupts the flight crew to bring the threat to their attention. The conceptual process of the TCAS logic functions is described as follows:

1. First, TCAS broadcasts inquiries and receives answers from neighbouring aircraft, to monitor the surrounding airspace constantly.
2. Then, TCAS generates a TA when an intruder comes within the range of the own aircraft and a collision is predicted to occur within 20-48s (depending on the altitude). It aims to draw the flight crew's attention to the risk situation and provides a visual state.
3. If the situation deteriorates, and a collision is predicted to occur within 15-35s (depending on the altitude), TCAS issues an RA, which is always in the vertical plane. With the communication between TCAS to ensure complementary manoeuvers, the RA could be passive (don't climb, don't descend) or active (climb, descend) depending on the situation. If an RA occurs, the pilot should respond immediately to achieve a safe separation.
4. When the threat has passed, TCAS advises "Clear of Conflict" (CoC).

In the encounter shown in Figure 1-1, a downward sense for *Aircraft i* would be advised by TCAS at the same time of an upward sense for *Aircraft j* since these non-crossing senses provide greater vertical separation. Then it is to determine the RA strength, which is the least disruptive to the existing flight paths while still providing at least Altitude Limit (ALIM) feet of vertical separation between the two involved aircraft at closest point of approach (CPA) [29]. This means that the amendment of the vertical speed should be minimal.

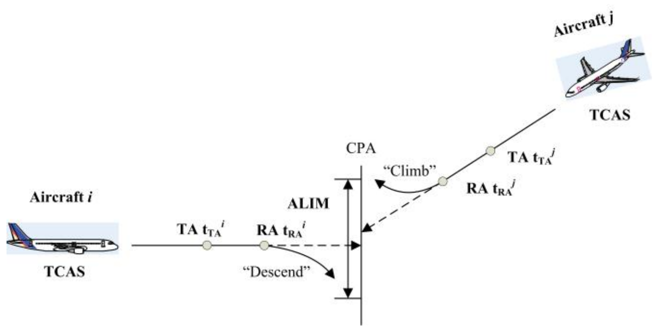

Figure 1-1: TCAS conceptual model

Range and altitude tests are implemented on each neighbouring intruder. If the time to the CPA in both the horizontal and vertical planes meet the time threshold and/or the spatial for protected airspace (distance modification (DMOD) and altitude threshold (ZTHR)) in slow-closure-rate encounters (time criteria values are not appropriate), the intruder is declared to be a threat [1]. These time and spatial values vary with different sensitivity levels (SLs). The values used to issue TAs and RAs are shown in [29]. In addition, ALIM provides the desired vertical minimum separation at the CPA. However, actually the pilots in the involved aircraft may not always follow the TCAS advisories that would initiate different states of the RA results. There is a lack of tools to analyse the effects of the different combinations of potential RAs issued by TCAS and the potential pilot reactions. A deep analysis of the state space solutions that could be originated from a RA issued by TCAS would contribute to better knowledge of TCAS impact on surrounding traffic and more rigorous safety studies.

TCAS II was designed to operate in traffic densities of up to 0.3 aircraft per square nautical mile (NM), i.e., 24 aircraft within a 5 NM radius, which was the highest traffic density envisioned over the next 20 years [29]. The influence of TCAS on safety flight has been effective, beneficial, and significant in reducing the collision probability [29]. However, the increased airspace usage can induce a secondary threat as a result of an RA issued by a TCAS, which may issue an inappropriate suggested resolution that resolves a one-on-one encounter with the first threat. This secondary threat may deteriorate to be an induced collision. Induced risk is the potential for TCAS to cause a collision that did not exist in its absence [38].

The case scenario shown in Figure 1-2 illustrates the process of an induced collision occurrence between four aircraft where TCAS would fail. In this scenario, four TCAS-equipped aircraft are considered with two predicted encounters (*threat 1* between *Aircraft 1* and *Aircraft 2*, and the other one is *threat 2* between *Aircraft 3* and *Aircraft 4*). Variable $t_{TA}^{i}(i = 1,2,3,4)$ is used for the TA emergence time, and variable $t_{RA}^{i}(i = 1,2,3,4)$ indicates the RA. In normal flight, *Aircraft 1* is cruising at FL160 and *Aircraft 2* is cruising at FL180 on an opposing route. When *Aircraft 2* starts a descending operation and flies into the range of *Aircraft 1*, a TA is issued by TCAS to warn the crew of *Aircraft 1* that a collision is predicted to occur within t_{TA}^{1}. An RA is issued at t_{RA}^{1} to ask the crew to take the responsibility of achieving a safe separation. Once the threat is detected, *Aircraft 1* performs a descend operation while *Aircraft 2* climbs to provide the greatest vertical separation at CPA. Normally, the RA strength selects the ALIM as the smallest safe separation that requires a minimal speed change. Meanwhile, a similar TA and RA process is initiated between *Aircraft 3* and *Aircraft 4*. When *Aircraft 4* comes within the range of *Aircraft 3* and a collision is predicted to occur, a TA is issued at t_{TA}^{3} and an RA is issued at t_{RA}^{3}. The crew in *Aircraft 3* responds to the RA by attempting to descend, while *Aircraft 4* climbs with the strength of ALIM. Unfortunately, despite the RA's resolution of both encounters, a new secondary threat is initiated between *Aircraft 4* and *Aircraft 1* as a consequence of previous decisions. This is detected by the TCAS and the crew has to address the emergent encounter. However, there is not enough time left for the pilot reaction, and an induced collision would occur.

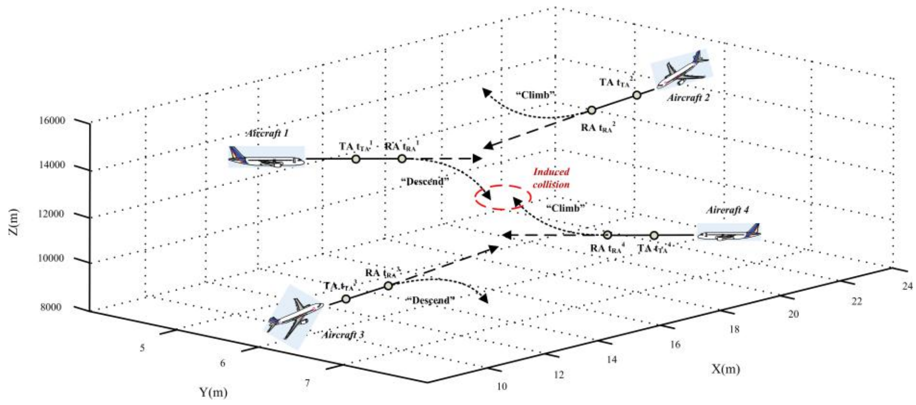

Figure 1-2: Four-aircraft induced collision scenario

Therefore, research that explores such potential induced collision scenarios is needed to enable ATM to avoid such accidents [39]. There is no rigorous tool to analyse the induced collision avoidance process, to test the TCAS multi-threat logic, and to identify all of the failure scenarios that should be avoided in advance. Taking the future unsegregated airspace as an example, it would be possible to have a situation in which improper manoeuvers that were issued by TCAS to resolve one-on-one encounters between manned aircraft induce a collision with a secondary threat that appears to be a domino effect (i.e., emergent dynamics) to the neighbouring RPA of previous decisions.

To achieve maximum ATM capacity, efficiency and safety, not only the mere transparent ATM/ATC integration of RPAs should be contemplated, but also the new technologies should be studied to ensure the flight safety of RPAs inside the non-segregated airspace.

Several efforts [40-44] such as to examine the components, aural and visual annunciation, advisory, modes, functions, and interfaces, have been made to apply the TCAS II that is used for conventional aviation to be a collision avoidance device for RPAs. TCAS has been proposed and proved as a potential collision avoidance system for RPAs though there are also several technical problems to work out [41].

The available development of various encounter models that support the quantitative analysis of TCAS and innovative improvement of TCAS avoidance performance in high-density traffic is the focus of this doctoral dissertation research.

1.1.3 Collision risk models: state of the art

The estimation of MAC/NMAC risk in airspace and its mathematical modelling for processes leading to possible collisions have been in progress for more than 40 years [45]. The study of aircraft collision risk was primitively initiated in the early 1960s by B. L. Marks [46] and P.G. Reich [47]. In particular, the Reich model mainly estimates the collision risk for an airway structure including more than one parallel trajectory. In this approach to the problems of estimating safe separation standards and specifying the quality of navigation needed, emphasis is laid on the observations of flying errors which occur in operational conditions [48]. With several minor improvements of Reich model, ICAO employed it in the North

Atlantic Organised Track System (NAOTS) to assess the minimum safe separations between parallel routes [48]. In [49], the collision risk model realizes the assessment of collision risk including two independent components: one is to represent the influence of the route network on the collision risk, i.e., how often a pair of aircraft is likely to fall into a given scenario of accident; the other one depends on the performance capability (e.g., the surveillance performance, the ground and airborne communication performance, and the aircraft navigation performance) of the environment, corresponding to the probability of collision associated to the pair of aircraft.

In the TCAS arena, there are also several collision risk models based on different methods and techniques which have been developed over the years to support the certification and performance analysis of TCAS [50-56]. These models are used to generate encounter situations for use in estimating the rate of NMAC and MAC events where aircraft are treated as point masses.

In [39], Kochenderfer et al. describe a methodology for an encounter model construction based on a Bayesian statistical framework, and they used it to evaluate the safety of collision avoidance systems for manned and unmanned aircraft. Kuchar et al. [50] try to use a fault tree to model the outer-loop system failures or events that in turn define the environment for a fast-time Monte Carlo inner-loop simulation of a close encounter. Zeitlin et al. [51] outline the steps of a safety analysis process to assess the performance of TCAS on conventional and unconventional aircraft. Netjasov et al. [52] propose an encounter model that contains the technical, human and procedural elements of TCAS operations. The model was demonstrated to work well for a historical en-route mid-air collision event [53], and it was very powerful in determining the most critical elements that contribute to non-zero collision probability in TCAS operations. Some other researchers focused on pilot behaviour that could influence the safety risk. Lee and Wolpert [54] combine Bayes nets and game theory to predict the behaviour of hybrid systems involving both humans and automated components, thereby predicting aircraft pilot behaviour in potential mid-air collision situations. Chryssanthacopoulos and Kochenderfer [55] extend the pilot response model in which the pilot responded deterministically to all alerts to include probabilistic pilot response models that capture the variability of pilot reaction time to enhance robustness. Garcia-Chico and Corker [56] provide a detailed analysis of the human operational errors that would increase the probability of a collision.

In addition, note that the Lincoln Laboratory of Massachusetts Institute of Technology (MIT) has carried on the long-term research on TCAS performance to estimate collision risk and the development of collision avoidance techniques [57]. Their involvement in TCAS dates back to 1974, when the FAA tasked them to participate in the development of an on-board collision avoidance system, and in the mid-1970s this laboratory began TCAS-related monitoring of aircraft in the Boston airspace, using their own prototype Mode S sensor. In the mid-1990s, Lincoln was tasked with analysing the performance of the TCAS threat logic of that time. Note that since the early 2000’s, Lincoln Laboratory has supported safety assessment and evaluation of proposed changes to the TCAS algorithms. [58] outlines the redesign issues when several extensions of the previous TCAS studies are required to estimate the relative safety of a RPA equipped with TCAS. In [59], a new cooperative aircraft encounter model is proposed to generate random close encounters between transponder-equipped (cooperative) aircraft in fast-time Monte Carlo simulations to evaluate collision avoidance system concepts. Furthermore, [60] constructs the U.S. correlated encounter model utilizing important sampling techniques to increase the precision of the results and to evaluate the safety impact of the latest TCAS (version 7.1). In [61], Lincoln Laboratory has been pioneering the development of next-generation airborne collision avoidance system that completely rethinks how such systems are engineered, allowing the system to provide a higher degree of safety without interfering with normal, safe operations. [62] focuses on recent research on coordination, interoperability, and multiple-threat encounters. The proposed methodology that optimizes airborne collision avoidance in mixed equipage environments performs better than legacy TCAS.

Of special relevance is the Interactive Collision Avoidance Simulator (InCAS, developed by EuroControl) [63]. This is a software tool that is TCAS logic-based, and it is designed for the replay of a real or a synthetic event. InCAS is an interactive system for the evaluation, study, demonstration and training on TCAS, and it is designed to simulate incidents that provide a relatively exact reconstruction of reality. Although it is not a standard encounter model that is to support the safety assessment of TCAS operations [63], InCAS provides valuable information and data for operational understanding and also for pilot TCAS training. Besides, Lincoln Laboratory use Matlab analysis code to generate random trajectories [59], to simplify the process of TCAS logic [38], or to simulate several integrated sub-models including an aircraft dynamic model, TCAS, and a pilot response model [64].

The input data of the existing models to test the TCAS performance in different circumstances are known information of several trajectories. Therefore, the models could be used to check whether a multi-aircraft scenario contains a potential collision or not. However, there is a lack of rigorous models to identify and generate all of the potential induced collision scenarios for a certain amount of aircraft in a particular dense airspace, which could be processed to provide valuable information at operational level for future ATM.

1.2 Objective

The PhD dissertation implements a set of encounter models using a Discrete Event System (DES) approach as a DST to promote the improvement of TCAS ability considering its impact on surrounding traffic which is intended to address the future hectic traffic. The main sub-objectives for this dissertation are summarized as follows.

- Develop various encounter models that support the quantitative analysis of TCAS induced collisions. Causal analysis of these induced collisions could provide a baseline for designing new TCAS logic rules to mitigate any undesirable effects.

- Based on the encounter models whose inputs are the state information of involved aircraft, they could be used to check the current traffic in a high-density area whether a potential induced collision could emerge. Therefore it could be used as a collision avoidance surveillance system.

- Provide quantitative analysis of the risk ratio of induced TCAS collisions for assessing the impact of pilot delay to respond TCAS advisories during flight in high-density scenario.

- Apply the encounter models to characterize the surrounding traffic scenarios that could initiate induced collisions. The generated TCAS state space of all possible induced collision scenarios could be stored in a database and a TA warning would be automatically displayed when the traffic in a particular airspace volume matches one of the scenarios identified by the model.

- Considering uncertain pilot reactions, all the future possible downstream reachable states can be generated to enhance the follow-up decision making of pilots via synthesising relevant information related to collision states, thus it could contribute to the innovative improvement of TCAS avoidance performance.

1.3 Document structure and context

This doctoral dissertation aims to explore and characterize the surrounding traffic scenarios that could initiate induced collisions, and improve the TCAS avoidance performance without greatly changing the original TCAS logic. For this purposes it is necessary to develop a series of gradual encounter models, and the methodological process is depicted in Figure 1-3.

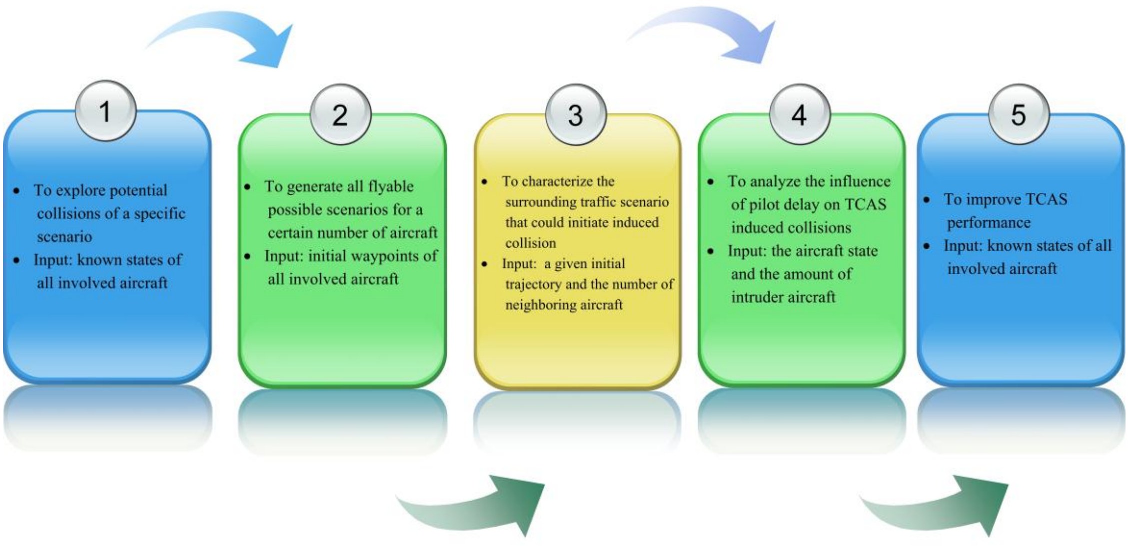

Figure 1-3: Conceptual depiction of the research structure

1. Causal encounter model I (chapter 3): First research step begins with the known initial states (e.g., trajectories) of all involved aircraft for the analysis of particular traffic geometries. Results are validated with InCAS.
2. Causal encounter model II (chapter 4): The second step aims at ensuring the flight safety within a short foreseen time when free route airspace is considered, and the only known information are the current coordinates of involved aircraft.
3. Causal encounter model III (chapter 5): Then, altering the perspective to the own aircraft, a new model has been developed to characterize the surrounding traffic scenarios that could initiate induced collisions. The term “own aircraft” is relative to the “intruder aircraft” which act as the surrounding traffic. Therefore the inputs of this encounter model are the own aircraft’s state and the number of intruder aircraft.
4. Causal encounter model IV (chapter 6): This research is deepened to explore quantitatively the influence between the pilot response time and the probability of potential induced collision initiated by the deterministic TCAS logic.

5. Causal encounter model V (chapter 7): Lastly, a novel approach is proposed to enhance the TCAS performance for the future hectic and congested traffic to assure the flight safety.

Chapter 2 introduces the basic notions of DES and a general perspective on the modelling methodologies. Particular description has been placed in the Coloured Petri Net (CPN) used in this research, presenting the main features of this formalism.

Chapter 3 presents the paper named “A causal model to explore the ACAS induced collisions”, which has been published in the Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering (2014, 228(10): 1735-1748). This paper considers some of the difficulties in establishing validation of the ACAS, which constitutes the last-resort for reducing the risk of near mid-air collision between approaching aircraft. A causal model that is specified in CPN formalism provides a novel tool to explore TCAS logic’s failure in high-density traffic scenarios. It is presented as a key approach to analyze the state space of a known congested traffic scenario in which the events that could transform a conflict into a collision are identified, providing a challenging tool not only for validation but also for the implementation of a new ACAS logic.

Chapter 4 corresponds to the article “Analysis of induced Traffic Alert and Collision Avoidance System collisions in unsegregated airspace using a Colored Petri Net model” published in the Simulation: Transactions of the Society for Modeling and Simulation International (2015, 91(3): 233-248). In this research, a quantitative approach that is based on state space analysis has been developed to identify TCAS weaknesses by generating all of the flyable possible scenarios for a certain number of involved aircraft over a period of time. This causal model assumes unrestrained initial positions and TCAS II-equipped aircraft; it is demonstrated to be extremely effective for generating all possible future TCAS failure end-states from the current locations. The complete CPN model is proposed in such a way that it is absolutely based on the TCAS II version 7.1, which potentially enabling a centralized and unabridged view of the current state space of the TCAS and its evolution along time. This approach is a key contribution of this research because it provides a global perspective on the scenario dynamics and a better understanding of the collision occurrence. This approach can be used to assess the impact and effectiveness of the local decisions.

Chapter 5 illustrates the manuscript “Coloured Petri Net-based TCAS encounter model for analysis of potential induced collisions” which has been in the second review process of the Transportation Research Part C: Emerging Technologies. The existing encounter models focus on checking and validating the potential collisions between trajectories of a specific scenario. Note that there is absence of methods and techniques in the public domain to characterize the surrounding traffic scenarios that could initiate an induced collision, and these could be used for the comparison of those actual traffic scenarios to reduce induced collision probabilities. In contrast, the innovative approach described in this paper concentrates on quantitative analysis of the different induced collision scenarios that could be reached for a given initial trajectory and a rough specification of the surrounding traffic. The generated state space of all possible induced collision scenarios could be stored in a database and an advanced warning could be automatically displayed when the traffic in a particular airspace volume matches one of the scenarios identified by this model.

Chapter 6 introduces the work “A discrete-event modeling approach for the analysis of TCAS-induced collisions with different pilot response times” in the Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering (in press). Prior work has designed different encounter models to identify all the induced potential collision scenarios that are representative of possible hazardous situations which may occur with a fixed configuration of aircraft in the surrounding airspace. However, there is a lack of causal model to explore the influence between the pilot response time and the probability of potential induced collision initiated by the deterministic TCAS logic. This paper extends the encounter model using an agent-based modelling approach developed via the CPN formalism to include the agent pilot response time that captures the variability delay in pilot behaviour in order to analyse its influence on TCAS induced collisions. The results demonstrate that the risk rate of TCAS induced collision increases as the pilot delay increases.

Chapter 7 represents the article “Extended traffic alert information to improve TCAS performance by means of causal models” that is under review in the Mathematical Problems in Engineering. This paper aims to improve the TCAS collision avoidance performance by enriching traffic alert information, which strictly fits with present TCAS technological requirements and extends the threat detection considering induced collisions and probabilistic pilot response. The proposed model generates by simulation all the future possible downstream reachable states to enhance the follow-up decision making of pilots via synthesising relevant information related to collision states. Besides, several techniques (e.g., eliminating the situations that the aircraft are separate from each other because no new threat will occur) are utilized to improve the computational efficiency, effectively resolved the well-known expansive state exploration problem. It can enhance the TCAS performance at the operational level in high-density traffic scenarios (without the need to heighten or change the relevant logic) to enable precise monitoring of all of the traffic to assure safe and efficient operations. The causal model can play a major role for resolving TCAS-TCAS encounters in the aircraft flocks, and support follow-up research for the safety analysis of current and advanced ATM concepts including newly TCAS version.

Finally, Chapter 8 contains the overall conclusions, future work, summary of contributions.

2 DISCRETE EVENT SYSTEMS

Most systems can be roughly classified considering the time evolution of the properties of interest as continuous or discrete [65]. In a continuous system the state variables evolve continuously over time. These are called “continuous variables” in the sense that they can take on any real value as time itself “continuously” evolves. In a discrete system, the state variables change only at a certain instant or sequence of instants (discrete set of points in time) known as the events, and remain constant between events [6].

It is well accepted that a continuous system can be described using a discrete representation, while a discrete system can be described by a continuous model. The choice of employing a continuous or a discrete representation depends on the purpose of investigation (particular objectives) of each study rather than the characteristics of the system. In this research, to explicitly sense the effect of each action, the dynamics of equipped aircraft encounters are modelled as a series of discrete events from which the different states of the system can be evaluated.

2.1 Modelling methodologies

DES is a unified modelling framework which recently emerged integrating traditionally separate disciplines such as queuing theory, supervisory control, and automata theory [66]. A Discrete Event System is defined as “a discrete-state, event-driven system, that is, its state evolution depends on the occurrence of asynchronous discrete events over time” [67]. In many situations, the system under consideration can be modelled as a DES and the problems can be translated into state estimation problems in a DES framework [68]. The distinction between DES and the more familiar time-driven dynamical systems studied under Control Theory for example is subtle but important: the state-transition mechanism in the latter is driven by time alone or is synchronized by “clock ticks”, whereas state transitions in DES are driven by “discrete events” (e.g., press of a button, arrival of a shipment) which can happen asynchronously (at various time instants not necessarily known in advance or coinciding with clock ticks) [66].

In the discrete event-based models, events (i.e., the state changes) can be depicted by a graph-based notation with several nodes and the relations between those events are represented using links [69]. Thus, a series of discrete events that form the model record the dynamics of a system to perform the state changes, and the links define the relations between events. These DES representations aim to describe the occurrence of finite number events in a discrete time base, (i.e., events happen in a continuous time base, but during a bounded time-span, only a finite number of relevant events occur) [70].

Typical DES include queuing systems, communication systems and telephony, databases, manufacturing and traffic systems to mention a few [71]. Discrete-event formalisms help to develop a high level of abstraction appropriate for realistic representation of a system's behaviour [6]. According to [67], there are different methodologies for modelling and analysing DES, among them it is worthy to mention:

- An automaton
- Timed automata
- Finite state machines (FSMs)
- A Markov chain
- Generalized Semi-Markovian process
- Petri nets
- Coloured Petri nets

2.2 Coloured Petri Nets

In this research, the TCAS logic has been modelled to analyse the cause-and-effect relationships between the actors that could potentially interact leading to different behaviours. The established causal models formalizes a number of causal relationships between successive events (causes, occurrence, or states) that produces a phenomenon (behaviour, effect or consequence) by which an event is interpreted as a consequence of the previous one [72], which corresponds to the main analysis characteristic of Petri Nets (PN), and the enhanced version, CPN formalism [73].

Despite the fact that there are several formalisms to explore the system dynamics, such as an automaton, Markov chain, Timed automata, PN, CPN, min-max algebra, etc. (summarized in [74]), the PN and CPN formalisms are versatile and well-founded modelling languages that can be used in practice for systems of the size and complexity found in industry [75]. CPN is a graphical and discrete-event modelling language that combines the capabilities of PN with the capabilities of a high-level programming language. Petri nets provides the foundation of the graphical notation and the basic primitives for modelling concurrency, communication, and synchronization toward a very broad class of systems, but it is intended to be a general modelling language, i.e., it is not aiming to model a specific class of systems. Both PN and CPN have been employed to describe the synchronization of concurrent processes, but in particular, CPN provides the strength that is required to define data types and manipulate data values [76].

CPN is a high-level modelling formalism suitable to complex systems and it has been widely used to model and verify systems, allowing the representation of not only the system dynamics and static behaviour but also the information flow [65]. A CPN model can be defined as the following nine-tuple [65]:

$$CPN = (\Sigma, P, T, A, N, C, G, E, I)$$

Where

- $\sum$ = { C1, C2, … , C_{nc}} represents the finite and not-empty set of colors. They allow the attribute specification of each modelled entity.
- P = { P1, P2, … , P_{np}} represent the finite set of place nodes.
- T = { T1, T2, … , T_{nt}} represents the set of transition nodes such that $P \cap T = \varnothing$ which normally are associated to activities in the real system.
- A = { A1, A2, … , A_{na}} represents the directed arc set, which relate transition and place nodes such as $A \subseteq P \times T \cup T \times P$
- N = It is the node function $N(A_i)$, which is associated to the input and output arcs. If one is a place node then the other must be a transition node and vice versa.
- C = It is the color set functions, $C(P_i)$, which specify for the combination of colors for each place node such as C: $P \rightarrow \sum$.

$$C(P_i) = C_j \qquad\qquad P_i \in P, C_j \in \Sigma$$

- G = Guard function, it is associated to transition nodes, $G(T_i)$, G: $T \rightarrow EXPR$. It is normally used to inhibit the event associated with the transition upon the attribute values of the processed entities. If the processed entities satisfy the arc expression but not the guard, the transition will not be enabled.
- E = These are the arc expressions $E(A_i)$ such as E: $A \rightarrow EXPR$. For the input arcs they specify the quantity and type of entities that can be selected among the ones present in the place node in order to enable the transition. When it is dealing with an output place, they specify the values of the output tokens for the state generated when transition fires.
- I = Initialization function I (P_i), it allows the value specification for the initial entities in the place nodes at the beginning of the simulation. It is the initial state for a particular scenario.
- EXPR denotes logic expressions provided by any inscription language (logic, functional, etc.).
- The state of a CPN model is also called the marking which is composed by the expressions associated to each place p in which tokens are properly specified.

CPN have been used to verify and validate systems through property analysis and more recently, the state space analysis tool has been used to explore the dynamic evolution of a system and to determine all of the possible future states that are reachable as initiated from a given current state vector (initial trajectories in this research).

The formalism can be graphically represented by circles, called place nodes; rectangles or solid lines, called transition nodes; and directed arrows, called the arcs, that connect one transition with one place node or a place node with one transition. To model the occurrences of activities, the input place nodes connected to a transition node must have at least the same number of entities (called tokens) as the correspondent arc weight, and the colours of the potential tokens must satisfy the expressions associated with the colours in the arc expressions which connect the input place node with the transition. The Boolean condition attached to the transition (guard) is the final restriction that must be fulfilled for the transition to occur. When all of the latter conditions are satisfied, then the transition can be "fired," which means that the entities that satisfy the mentioned conditions are removed from the original input place nodes and that new entities (i.e., tokens) are created in the output place nodes of the transition. The new tokens are created with the characteristics and quantities stated in the colours and output arc weights, respectively. A CPN model can be graphically represented by a set of place (circles) and transition nodes (rectangles or solid lines) connected with directed arcs (see Figure 2-1).

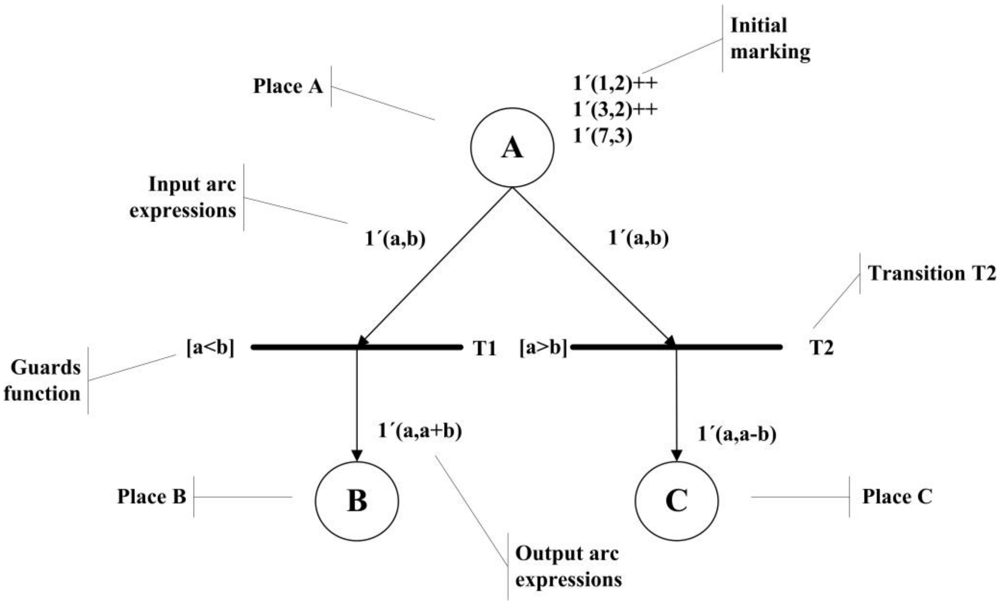

Figure 2-1: A simple example used to depict a CPN

2.3 State Space

The CPN mathematical formalism enhances a quantitative approach relying on computational tools to evaluate the different states that a system could reach considering a particular initial state. The system state is described by the different tokens (i.e., entities with its attributes) distributed in the different place nodes [65]. The state space is computed quantitatively by firing all the enabled transitions at any system state, computing the new states.

The state space in CPN is also called reachability tree or occurrence graph [6]. The basic idea of state space analysis is to calculate all reachable states (markings) and state changes (occurring binding elements) of the CPN model and to represent these in a directed graph where the nodes correspond to the set of reachable states and the arcs correspond to events. Hence, the state space contains all the possible occurrence sequences and reachable states that can be achieved from an initial (known) state. Figure 2.2 illustrates the reachability tree (first level) of the simple case model shown in Figure 2-2, and the state vector of the CPN model with 3 Places is represented. In each position of the vector, the tokens and its colours that are stored in each place node are represented. Given this initial marking, the only enabled events are those that are indicated by transition T1 and transition T2. It should be noted that transition T2 could be fired by using two different combinations of tokens (i.e., different entities). Once a transition has been fired, a new state vector is generated (e.g., a new traffic scenario). Thus, a proper implementation of a CPN model in a simulation environment should allow automatic analysis of the whole search space of the system by firing the different sequences of events without requiring any changes in the simulation model [65]. The reachability tree of system operations applied to a certain scenario provides a deeper understanding of the cause-effect relationship of each action and how the effects of an action are propagated upstream and downstream through the different actions.

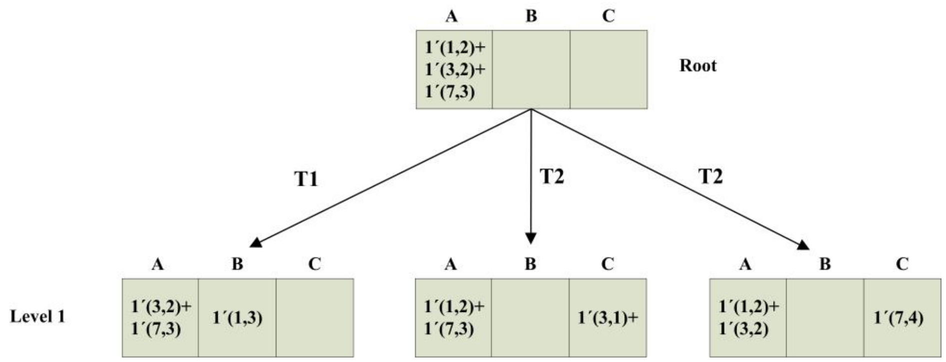

Figure 2-2: An example of reachability tree

The operations of TCAS can be modelled as a discrete sequence of events in time; each event occurs at a particular instant in time and can cause a change of system state [77]. In addition, although the widespread TCAS system has been in application with new developments for more than 30 years, essential parts of its causal analysis, especially those for potential induced collision scenarios that could be considered to be TCAS weakness, seem to have not yet been performed. Thus a CPN model can be developed as a key approach to analyse the state space of a congested traffic scenario in which the events that could drive an encounter into a collision are explored, or the surrounding traffic which is characterized by the simulation results to provide all the possible collision scenarios. The CPN encounter models can act as useful tools for better understanding the aircraft interdependence between the own aircraft and its surrounding traffic conditions (both at macro and micro levels) that could assist the ATCs and pilots, and also to check for future TCAS logic updates.

In this context, the proposed discrete event-based models have the following important features:

- dynamic, each event can determine the results of corresponding action. Its dynamics could form complex patterns of behaviour to represent the unknown effects especially unreasonable decision which may initiate undesirable consequences.

- complex, the decisions and actions may be various in each step. The complex models have many interrelated causal relationships that interact between sub-modules, and these relationships could cause different results of the system.

- conditional, the manoeuvers operates at the corresponding moment or with relevant conditions to achieve its goal. When several certain conditions are satisfied the specific action can be activated, while it would be invalid if the conditions are not met or changed.

3 A CAUSAL MODEL TO EXPLORE THE ACAS INDUCED COLLISIONS

Tang J, Piera M A, Ruiz S. A causal model to explore the ACAS induced collisions. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2014, 228(10): 1735-1748.

4 ANALYSIS OF INDUCED TCAS COLLISIONS IN UNSEGREGATED AIRSPACE USING A COLORED PETRI NET MODEL

Tang J, Piera M A, Nosedal J. Analysis of induced Traffic Alert and Collision Avoidance System collisions in unsegregated airspace using a Colored Petri Net model. Simulation, 2015, 91(3): 233-248.

5 COLOURED PETRI NET -BASED TCAS ENCOUNTER MODEL FOR ANALYSIS OF POTENTIAL INDUCED COLLISIONS

Tang J, Piera M A. Coloured Petri Net -based TCAS encounter model for analysis of potential induced collisions. Transportation Research Part C: Emerging Technologies (under review)

6 A DISCRETE-EVENT MODELING APPROACH TO THE ANALYSIS OF TCAS INDUCED COLLISIONS WITH DIFFERENT PILOT RESPONSE TIMES

Tang J, Piera M A, Baruwa O T. A discrete-event modeling approach for the analysis of TCAS-induced collisions with different pilot response times. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2015,pp:1-13. DOI: 10.1177/0954410015577147 (in press)

7 EXTENDED TRAFFIC ALERT INFORMATION TO IMPROVE TCAS PERFORMANCE BY MEANS OF CAUSAL MODELS

Tang J, Piera M A, Ling Y X, Fan L J. Extended traffic alert information to improve TCAS performance by means of causal models. Mathematical Problems in Engineering (under review)

8 OVERALL CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

TCAS constitute a last-resort means, which is accepted worldwide, of effective and significant reducing the collision probability between aircraft. It executes independently of ground-based systems and relies fully on relevant surveillance equipment on-board the aircraft. TCAS equipped in aircraft does not control the vehicle directly; it just issue advisories to pilots on how to manoeuver vertically to prevent collision. However, the increased airspace usage can induce a secondary threat (negative domino effect) as a result of manoeuvre advisory issued by TCAS, which may initiate an improper manoeuvre that would induce a collision.

This thesis contributes to the study for a better understanding of the induced effects of resolution advisories aroused by TCAS in an overextending airspace. The proposed causal encounter models are represented in CPN formalism. Based on the state space analysis of a sector with several aircraft, the encounter models provides a downstream trace of the different effects of potential RAs issued to avoid a collision. The implemented models provide a global perspective on the scenario dynamics and a better understanding of the induced collision occurrence for risk assessment.

The main contributions to the state-of-art on TCAS-induced collisions are listed below:

- Several causal encounter models have been developed to support the quantitative analysis of TCAS induced collisions. Based on the surrounding traffic specification, the models analyse whether a potential induced collision would emerge.
- The surrounding traffic scenarios that could initiate induced collisions have been characterized. Concentrating the perspective to the own aircraft, all the potential induced collision scenarios that could be reached for a given initial trajectory and a rough specification of the neighbouring traffic are identified to enable precise monitoring of all the flights.
- The influence of different pilot delays for the TCAS-induced collisions has been quantitatively analysed. The simulation results demonstrate that the risk ratio of TCAS-induced collision increases as the pilot delay increases, and it categorically indicates the human factors on the TCAS.
- Considering a probabilistic pilot response, a novel technique based on the proposed mathematical model for TCAS operations has been introduced to innovatively

improve the avoidance performance. Through generating all the future possible downstream reachable states, it aids the crews in the involved aircraft to make a cooperative and feasible option.

The causal encounter models could be deployed to be compatible with the current surveillance and management of threats as well as with the on-board TCAS. They would provide auxiliary supports in the analysis of hectic traffic scenarios (e.g., TMA and hot spots), and increase the airspace capacity while safely and efficiently manage a higher amount of flights.

8.2 Future work

Present work could be extended with further research on the following areas:

(1) State space analysis of the horizontal RA capability

The “next generation” of collision avoidance technology, TCAS III is widely envisioned as an expansion of the TCAS II concept to incorporate the horizontal manoeuvring of aircraft to increase the CA capability. Evidently, the CA performance would be greatly improved if the TCAS can provide not only vertical but also horizontal advisories to pilots on how to manoeuver to avoid collision. Through generating the state space of massive scenarios, the positive effects of importing the horizontal RA capability can be quantitatively analysed in order to synthetically apply both the vertical and horizontal manoeuvers more profitably.

(2) Robustness improvement with more realistic uncertainty characteristics

Several typical disturbances should be introduced in simulations to test the robustness of the amended trajectories suggested by TCAS advisories under conditions of operational level uncertainties. For example, the speed variation owing to wind instability is identified as the most common factor affecting the en-route trajectory predictions. The causal encounter models could also add a module to store different weather parameters, thus being able to generate more complete information which can be used by the crews to make better decisions with regards to the efficiency of the flights and the robustness of the scenarios.

(3) Extension of the ACAS protection volume

The generated data results of the proposed causal encounter models could be processed to provide valuable information at operational level for future ATM scenarios. During the flight execution phase, the database of all potential induced collision scenarios can be directly related to the pattern recognition. Proper automation contrast can be used to evaluate situations in which multiple aircraft are involved. The recognized pattern (a potential induced collision scenario) that fits the current situation can provide relevant information to pilots.. This enhances the ACAS (without the need to heighten or change the relevant logic) in heavy traffic scenarios to assure safe and efficient operations.

(4) Redesign of the TCAS logic to mitigate any undesirable effects

TCAS represents a clear success story in aviation safety, and its design is a fine balance that provides sufficient time to take action and that minimizes alert rates. RPA introduces a novel element into an already complex environment while brings greater pressure to the current ATM. At the same time, the accuracy of the TCAS basic components (e.g., antenna, display, control panel, transponder and so on) promises to improve the ease with which collisions can be detected and avoided. Thus, the corresponding TCAS logic should be redesigned to fit the new techniques and cope with the changing environment considering off-line information generated by the encounter models.

(5) Development of a stand-alone tool to analyse the complex scenarios

The proposed encounter models could provide a baseline to design a software tool with similar InCAS interface but extending its functionality to induced collision analysis. It could be designed for the replay of a real or a synthetic event in which multiple aircraft are involved. It would be mainly used as an interactive system for the evaluation, study, demonstration the potential TCAS-induced collisions, and to simulate incidents that provide a relatively exact reconstruction of reality to support the safety assessment of TCAS operations.

(6) Identification the clusters of a scenario in which a potential induced collision exists

Based on the proposed scenario generation process, the causal encounter models can be extended to determine all of the collision scenarios for a given aircraft trajectory and a particular amount of aircraft as surrounding traffic. The initial states of the multiple aircraft that are involved in the scenarios are generated one by one. For a scenario which could initiate a potential induced collision, the state value of each aircraft should be an interval, not deterministic and unique, to form a risky cluster that needs to be clearly identified. This functionality would allow an on-line application of the encounter model in a future TCAS extension.

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APPENDIXES

A Net specification of causal encounter model I

The colours used to describe all of the information in places are summarized in Table A-1.

Table A-1: Colour specification

Colours	Description	
	Definition	Meaning
aid	Int 1…N	Aircraft id
cid	Int 1…N	Conflict id
sq	Int 1…N	Sequence number
x	R	*x* axis coordinate for 3D position
y	R	*y* axis coordinate for 3D position
z	R	*z* axis coordinate for 3D position
ao	Int 1…N	ALIM values for different flight levels
alim	Int 1…N	Current ALIM
s	Int 0,1,2	Sense selection (0, unchanged; 1, climb; 2, descend)

The specifications of all places are shown in Table A-2.

Table A-2: Place specification

Num.	Places	Description	
		Definition	Explanation
P1	Conflicts	*cid*aid*aid*	Related colour attributes for the current conflict
P2	Conflict segments	*cid*aid*x*y*z*x*y*z*	Segment information of an aircraft trajectory
P3	Sequence	*sq*	Number of the conflict to be resolved
P4	Turning	*cid*aid*x*y*z*x*y*z*	Related segment that would

	segments		change to resolve a conflict
P5	Climb/Descend	*s*	Selection sense for the two turning segments
P6	ALIM options	*ao*	Least separation at different altitudes
P7	Strength	*st*	Value of the right strength
P8	Amended segments	*cid*aid*x*y*z*x*y*z*s*	New segments with the applied maneuver
P9	Free segments	*cid*aid*x*y*z*x*y*z*s*	Original and amended segments between which there is no conflict
P10	All segments	*cid*aid*x*y*z*x*y*z*s*	All segments from P8 and P9 to detect new conflicts
P11	Encounter segments	*cid*aid*x*y*z*x*y*z*s*	Segments which would have a merging point
P12	Collision segments	*cid*aid*x*y*z*x*y*z*s*	Segments which would have a potential collision

The explanations of transitions are represented in Table A-3.

Table A-3: Transition specification

Transitions	**Explanation**
T1	Select the two involved segments of a conflict to be resolved
T2	Determine the aircraft altitude to obtain the least separation
T3	Amend the two segments in the opposite flight level change to avoid collision considering current states
T4	Generate a sequence number and direction options for resolving the next conflict
T5	Transmit the free segments to “All segments”
T6	Deliver the amended segments to “All segments”
T7	Make a copy of all segments used for CD
T8	Detect new conflicts between the segments which can be classified into “Free segments” and “Encounter segments”
T9	Deduce whether the new conflicts can be resolved
T10	Renovate the recycle information

B Net specification of causal encounter model II

The colours used to describe all of the information in places are summarized in Table B-1.

Table B-1: Colour specification

Colours	Description	
	Definition	Meaning
aid	Int 1…N	Aircraft id
ns	Int 1…N	Sequence number
x	R	*x* axis coordinate for 3D position
y	R	*y* axis coordinate for 3D position
z	R	*z* axis coordinate for 3D position
d	R+	Distance between aircraft
vx	R	Velocity component in *x* axis
vy	R	Velocity component in *y* axis
vz	R	Velocity component in *z* axis
c	Int 1…N	Control
Δz	R	Amendment of vertical velocity

The specifications of all places are shown in Table B-2.

Table B-2: Place specification

Num.	Places	Description	
		Definition	Explanation
P1	Initial waypoint	*aid*x*y*z*ns*	Original position information of an aircraft
P2	Vx	*vx*	Options of initial velocity in x bearing
P3	Vy	*vy*	Options of initial velocity in y bearing
P4	Vz	*vz*	Options of initial velocity in z bearing
P5	Control1	*c*	Subsidiary control condition for T2
P6	Second waypoint	*aid*x*y*z*vx*vy*vz*ns*	the state information of the second waypoint
P7	Control0	*c*	Subsidiary control condition for T1 and T2
P8	Initial distance	*aid*aid*d*	Calculated distance between each pair of aircraft
P9	Next waypoint	*aid*x*y*z*vx*vy*vz*ns*	Serious waypoints in the normal flight without conflict

P10	Involved waypoint1	*aid*x*y*z*vx*vy*vz*Δz*ns*	Waypoint information of the involved aircraft having the primary conflict
P11	Other waypoint1	*aid*x*y*z*vx*vy*vz*ns*	Remaining aircraft that are irrelevant to this conflict
P12	Control2	*c*	Subsidiary control condition for T6
P13	Involved waypoint2	*aid*x*y*z*vx*vy*vz*Δz*ns*	States of the involved aircraft that have a domino conflict initiated by the first conflict
P14	Other waypoint2	*aid*x*y*z*vx*vy*vz*ns*	Remaining aircraft that are irrelevant to this domino conflict
P15	Control3	*c*	Subsidiary control condition for T8
P16	Control4	*c*	Subsidiary control condition for T9
P17	Involved waypoint3	*aid*x*y*z*vx*vy*vz*Δz*ns*	States of the involved aircraft that have subsequent domino conflicts
P18	Collision	*aid*x*y*z*vx*vy*vz*ns*	States of the involved aircraft that have potential collisions

The explanations of transitions are represented in Table B-3.

Table B-3: Transition specification

Transitions	**Explanation**
T1	Calculate the distance
T2	Generate the motion state
T3	Screen out the approaching aircraft
T4	Compute the next waypoints
T5	Detect the first threat
T6	Resolve the primary conflict
T7	Detect the domino effect
T8	Amend the waypoints for secondary threat
T9	Amend the waypoints for secondary threat (alternative aircraft)
T10	Consider the subsequent domino effect
T11	Keep the negative domino effect
T12	Resolve the subsequent encounter
T13	Store the potential collision state

C Net specification of causal encounter model III

The colours used to describe all of the information in places are summarized in Table C-1.

Table C-1: Colour specification

Colours	Description	
	Definition	**Meaning**
aid	Int 1…N	Aircraft identity
x	R	*x* axis coordinate for 3D position
y	R	*y* axis coordinate for 3D position
z	R	*z* axis coordinate for 3D position
vx	R	Speed component in *x* axis
vy	R	Speed component in *y* axis
vz	R	Speed component in *z* axis
d	R+	Vertical distance between aircraft at CPA
alim	R	Desired vertical minimum separation at CPA
t	Int 1…N	Current time
Δt	Int 1…N	Time interval
s	Int 1…N	Optional situations

The specifications of all places are shown in Table C-2.

Table C-2: Place specification

Num.	Places	Description	
		Definition	**Explanation**
P1	Aircraft State	*aid*x*y*z*vx*vy*vz*t*	Initial state of an aircraft
P2	Variable1	*d*	Range of distance between each pair of aircraft
P3	Aircraft 1 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 1 at CPA
P4	Situation1	*s*	Identifier of possible threat situations
P5	Vx1	*vx*	Constant options of the initial speed in x bearing
P6	Vy1	*vy*	Constant options of the initial speed in y bearing
P7	Vz1	*vz*	Constant options of the initial speed in z bearing
P8	Aircraft 2 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 2 at CPA
P9	Aircraft 1 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 1 at CPA
P10	Variable2	*d*	Range of distance between each pair of aircraft

P11	Δt1	*Δt*	Time interval
P12	Start-point for Collision	*aid*x*y*z*vx*vy*vz*t*	Start-point state of the involved aircraft which would have an induced collision
P13	Start-point for Threat	*aid*x*y*z*vx*vy*vz*t*	Start-point state of the involved aircraft which would have a threat
P14	Variable3	*d*	Range of distance between each pair of aircraft
P15	Situation2	*s*	Identifier of possible threat situations
P16	Aircraft 3 Start-end-point	*aid*x*y*z*vx*vy*vz*t*	Calculated start and end points of Aircraft 3
P17	3-Aircraft Collision	*aid*x*y*z*vx*vy*vz*t*	States of the 3 aircraft between which there would be a collision
P18	Vx2	*vx*	Constant options of the initial speed in x bearing
P19	Vy2	*vy*	Constant options of the initial speed in y bearing
P20	Vz2	*vz*	Constant options of the initial speed in z bearing
P21	Aircraft 3 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 3 at CPA

The explanations of transitions are represented in Table C-3.

Table C-3: Transition specification

Transitions	Explanation
T1	Calculate the future CPA of Aircraft 1 based on the TA/RA time criteria
T2	Compute the CPA of *Aircraft 2* that is in the minimum threat separation of *Aircraft 1* at t_{CPA}
T3	Assign the optional speeds in 3D for Aircraft 2
T4	Copy the inputs of the initial states of Aircraft 1 and Aircraft 2 (one set of data for a potential collision and the other set for a possible threat)
T5	Obtain the start point of Aircraft 3
T6	Calculate the speed of Aircraft 3 based on the known start and end points
T7	Compute the CPA of Aircraft 3 that is within the minimum threat separation of Aircraft 1
T8	Assign the optional speeds in 3D for Aircraft 3

D Net specification of causal encounter model IV

The colours used to describe all of the information in places are summarized in Table D-1.

Table D-1: Colour specification

Colours	Description	
	Definition	**Meaning**
aid	Int 1…N	Aircraft identity
x	R	*x* axis coordinate for 3D position
y	R	*y* axis coordinate for 3D position
z	R	*z* axis coordinate for 3D position
vx	R	Speed component in *x* axis
vy	R	Speed component in *y* axis
vz	R	Speed component in *z* axis
d	R+	Vertical distance between aircraft at CPA
alim	R	Desired vertical minimum separation at CPA
t	Int 1…N	Current time
Δt	Int 1…N	Time interval
dt	Int 1…N	Response time
s	Int 1…N	Optional situations

The specifications of all places are shown in Table D-2.

Table D-2: Place specification

Num.	Places	Description	
		Definition	**Explanation**
P1	Aircraft State	*aid*x*y*z*vx*vy*vz*t*	Initial state of an aircraft
P2	Variable1	*d*	Range of distance between each pair of aircraft
P3	Aircraft 1 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 1 at CPA
P4	Situation1	*s*	Identifier of possible threat situations
P5	Vx1	*vx*	Constant options of the initial speed in x bearing
P6	Vy1	*vy*	Constant options of the initial speed in y bearing
P7	Vz1	*vz*	Constant options of the initial speed in z bearing
P8	Aircraft 2 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 2 at CPA
P9	Aircraft 1 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 1 at CPA

P10	Variable2	*d*	Range of distance between each pair of aircraft
P11	Δt2	*Δt*	Time interval
P12	Collision Start-point	*aid*x*y*z*vx*vy*vz*t*	Start-point state of the involved aircraft which would have an induced collision
P13	Conflict Start-point	*aid*x*y*z*vx*vy*vz*t*	Start-point state of the involved aircraft which would have a threat
P14	Variable3	*d*	Range of distance between each pair of aircraft
P15	Situation2	*s*	Identifier of possible threat situations
P16	Aircraft 3 Start-end-point	*aid*x*y*z*vx*vy*vz*t*	Calculated start and end points of Aircraft 3
P17	Aircraft collision state	*aid*x*y*z*vx*vy*vz*t*	States of the aircraft between which there would be a collision
P18	Vx2	*vx*	Constant options of the initial speed in x bearing
P19	Vy2	*vy*	Constant options of the initial speed in y bearing
P20	Vz2	*vz*	Constant options of the initial speed in z bearing
P21	Aircraft 3 CPA	*aid*x*y*z*vx*vy*vz*t*	State of Aircraft 3 at CPA
P22	Pilot Response Time	*rt*	Constant options of the pilot response delay

The explanations of transitions are represented in Table D-3.

Table D-3: Transition specification

Transitions	**Explanation**
T1	Calculate the future CPA of Aircraft 1 based on the TA/RA time criteria
T2	Compute the CPA of *Aircraft 2* that is in the minimum threat separation of *Aircraft 1* at t_{CPA}
T3	Assign the optional speeds in 3D for Aircraft 2
T4	Copy the inputs of the initial states of Aircraft 1 and Aircraft 2 (one set of data for a potential collision and the other set for a possible threat)
T5	Obtain the start point of Aircraft 3
T6	Calculate the speed of Aircraft 3 based on the known start and end points
T7	Compute the CPA of Aircraft 3 that is within the minimum threat separation of Aircraft 1
T8	Assign the optional speeds in 3D for Aircraft 3
T9	Provide the possible pilot response delays

E Net specification of causal encounter model V

The colours used to describe all of the information in places are summarized in Table E-1.

Table E-1: Colour specification

Colours	Description	
	Definition	**Meaning**
aid	Int 1…N	Aircraft identity
cid	Int 1…N	Conflict id
x	R	*x* axis coordinate for 3D position
y	R	*y* axis coordinate for 3D position
z	R	*z* axis coordinate for 3D position
vx	R	Speed component in *x* axis
vy	R	Speed component in *y* axis
vz	R	Speed component in *z* axis
t	Int 1…N	Current time
s	Int 1…N	Sensitivity level
sc	Int 1…N	Sequence control
$time_h$	R+	Horizontal time criteria
$time_z$	R+	Vertical time criteria
$ZTHR_{TA}$	R+	Altitude criteria of TA
$ZTHR_{RA}$	R+	Altitude criteria of RA
$DMOD_{TA}$	R+	Range criteria of TA
$DMOD_{RA}$	R+	Range criteria of RA
td	Int 1…N	Pilot response time
r	-1,0,1	Pilot reaction
dc	R+	Distance criteria to select neighbouring threat
tc	Int 1…N	Time criteria to select neighbouring threat
tr1	Int 1…N	Horizontal time at CPA
tr2	Int 1…N	Vertical time at CPA
cod	Int 1…N	Collision id

The specifications of all places are shown in Table E-2.

Table E-2: Place specification

Num.	Places	Description	
		Definition	Explanation
P1	Aircraft state information	*aid*x*y*z*vx*vy*vz*t*	Initial state of involved aircraft
P2	Sensitivity level	*s*	Sensitivity level of involved aircraft
P3	Sequence control	*sc*	Sequence number
P4	Aircraft in SL	*aid*x*y*z*vx*vy*vz*t*s*	Involved aircraft in corresponding SL
P5	$Time_{TA}$-$Distance_{TA}$	$s*time_h*time_z*ZTHR_{TA}*DMOD_{TA}$	Time and Distance criteria of TA
P6	Threat involved aircraft	*aid*cid*x*y*z*vx*vy*vz*t*s*	Aircraft involved in a detected conflict
P7	$Time_{RA}$-$Distance_{RA}$	$s*time_h*time_z*ZTHR_{RA}*DMOD_{RA}$	Time and Distance criteria of RA
P8	Sequence control	*sc*	Sequence number
P9	Clear of conflict	*aid*x*y*z*vx*vy*vz*t*s*	Aircraft between which the conflict has been resolved
P10	Response delay	*td*	Pilot response time
P11	Possible reaction	*r*r*	Pilot reaction
P12	Possible response	*td*r*	Pilot response time and reaction
P13	CPA position-time	*x*y*z*t*	Position and time of CPA
P14	Distance criteria	*dc*	Distance criteria to select neighbouring threat
P15	Time criteria	*tc*	Time criteria to select neighbouring threat
P16	Neighbouring threat	*aid*cid*x*y*z*vx*vy*vz*t*s*	Threats which are near
P17	RA waypoints	*aid*cid*x*y*z*vx*vy*vz*t*	RA waypoints that would be amended to resolve conflict
P18	Amended RA waypoints	*aid*cid*x*y*z*vx*vy*vz*t*	Amended waypoints to resolve conflict
P19	Approaching aircraft	*aid*cid*x*y*z*vx*vy*vz*t*	Aircraft which are approaching
P20	Time control	*t*	Time control
P21	Sequence control	*sc*	Sequence number
P22	Domino threat aircraft	*aid*cid*x*y*z*vx*vy*vz*t*	Aircraft which have a domino conflict
P23	Judgement criteria	*tr1*tr2*	Evaluative criteria to check the domino conflict
P24	Domino state	*aid*cod*x*y*z*vx*vy*vz*t*	Aircraft which would have a collision

The explanations of transitions are represented in Table E-3.

Table E-3: Transition specification

Transitions	Explanation
T1	Evaluate the SL
T2	Detect the threat
T3	Resolute the threat
T4	Provide probabilistic pilot response
T5	Select the neighbouring threat
T6	Summary the resolution waypoints
T7	Screen the approaching aircraft
T8	Indicate that the aircraft fly to the next waypoints
T9	Detection the domino threat
T10	Estimate the Collision/Conflict

LIST OF ACRONYMS

3D	three dimension
4D	four dimension
ACAS	Airborne Collision Avoidance System
ALIM	altitude limit
ASAS	Airborne Separation Assurance System
ATC	air traffic controller
ATFM	Air Traffic Flow Management
ATM	air traffic management
CA	collision avoidance
CD	conflict detection
CDA	continuous descent approaches
CDR	conflict detection and resolution
CNS	communication, navigation, surveillance
COC	clear of conflict
CPA	closest point of approach
CPN	Coloured Petri Net
CR	conflict resolution
DES	discrete event system
DMOD	distance modification
DST	decision support tool
ELOS	equivalent level of safety
FAA	Federal Aviation Administration

FL	flight level
FSM	finite state machine
GAT	general air traffic
ICAO	International Civil Aviation Organization
InCAS	Interactive Collision Avoidance Simulator
LTF	long-term forecast
MAC	mid-air collision
MIT	Massachusetts Institute of Technology
NAOTS	North Atlantic Organised Track System
NextGen	Next Generation Air Transportation System
NM	nautical mile
NMAC	near mid-air collision
OOP	Object Oriented Programming
PN	Petri Net
RAs	Resolution Advisories
RPA	remotely piloted aircraft
RPAS	remotely piloted aircraft system
SCRSP	Surveillance and Conflict Resolution Systems Panel
SDS	Spatial Data Structures
SESAR	Single European Sky ATM Research
SL	sensitivity level
SS	state space
STCA	short term conflict alert
TAs	traffic advisories

TCAS	Traffic Collision Avoidance System
TMA	terminal manoeuvring area
V&V	verification and validation
ZTHR	altitude threshold