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Review: Analysis and Improvement of Traffic Alert and Collision Avoidance System

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ABSTRACT Several well-known international cooperation programs in the research field of air traffic management, e.g., SESAR and NextGen, aim to overcome the deficiencies of airspace capacity, while ensuring safety level and efficient operations. The increasing airspace traffic density would cause congested traffic scenarios, which require the developed safety procedures to resolve multithreat conflicts. In this paper, we provide a complete survey on the conflict detection and resolution approaches (CDR), mainly including long term CDR, medium term CDR, and short term CDR on three different levels classified based on the acting period. In order to achieve absolute security, it is very important to conduct a summarization of previous and present study on the traffic alert and collision avoidance system (TCAS), utilized as the final means in the security technology system. This review not only offers an intuitionistic and in-depth comprehension of the potential collision emergence for risk assessment, but also summarizes the various encounter models for the TCAS analysis and different strategies for the TCAS improvement, making an overall perspective of the research progresses and trends to facilitate the development.

INDEX TERMS TCAS, conflict detection, conflict resolution, collision risk, encounter model.

I. INTRODUCTION

As emphasized in [1], accidents are emblematical cases, among other inconsequential incidents, representing how prospective assessment approaches frequently poorly express human and organizational elements, and therefore restrict their capacity for accident prevention. Apparently the potential risk of aircraft collision requires specific, feasible policies and techniques to handle the balance between air traffic management (ATM) ability and flight efficiency. Therefore the research which is associated with the air collision risk should take the safety level and new safety metrics into account to explore "system weaknesses" which should be dealt with or at least reduced. The new valuable safety metrics are supposed to supply a deep comprehension of some proprietary dynamics, e.g., the assessment alteration of potential collision risk generated based on novel risk mitigation methods thinking over the neighbouring interactional scenarios within a definite period.

ATM is widely deemed to be a typical "high reliability" service occupations in which accident probability is very low [2]. However, since entering the 21st century, some particular factors, especially the accidents, have caused great concern on managing and measuring the flight safety. Over the Überlingen that locates in the southern German, a Tu-154 passenger aircraft and a Boeing 757 cargo aircraft collided in midair on 1 July 2002, the lives of 71 passengers and crew were lost [3]. Besides, in the 2001 Linate Airport disaster, all 114 people on both aircraft, a McDonnell Douglas 87 airliner and a Cessna Citation business jet, were injured to death by accident, as well as four staffs on the airport runway [4]. These sudden air disasters strengthened the relevant air navigation services, particularly air traffic flow management (ATFM) [5] that optimizes the utilization of practicable airspace, containing the local key airport airspace, and thus the significance of ATFM has been evidently promoted. The emergence of novel techniques, standards, and situations, e.g., free flight, high-density airspace, remotely piloted aircraft (RPA) and so on, would remarkably heighten the improvement of the airspace capacity, while further researches of aviation safety are required to comprehend new situations which would be induced in hectic airspace.

These congested regional airspace, e.g., hot spots and terminal manoeuvring area (TMA), contains relatively complex scenarios that require special and technical attention. In the congested TMA, it has to receive a number of flights each hour, and departure forces to accept several late arrivals producing a series of delays [6]. Based on experimental data, it is reported in [7] that the process of the air traffic density would raise fairly in the particular regional area during a short time, which could be called as a hot spot. Some scientific groups proposed novel concepts, techniques, procedures, methods and tools [8]–[10], which would improve the efficiency of airspace, among them the free flight is emphasized and it can affect the scenario geometries represented in a majority of traffic alert and collision avoidance system (TCAS) literatures. Free flight is basically defined that the pilots in their own vehicle have the right to change the flight route, having the freedoms and responsibilities to resolve encounters with other aircraft regarded as intruders [11]. For free flight in different scenarios, it could be simply realized in the low-density environment, and the expectation would not be completely achieved when the number of flights becomes greater. In the field of software engineering and telecommunication systems, scalability is defined as the capability of a tool, platform, network, system or procedure, to manage the increasing number of workload in a perfect and feasible manner, or the capacity to be advanced to reply this rise [12]. Taking the incremental requirement for air traffic into account, the scalability issue needs a special attention on the developing ATM by utilizing various effective professional modules and tools to guarantee the free flight when plenty of aviation vehicles exist in the unsegregated airspace.

In [13] it depicts the significance of analysis and improvement in TCAS in the circumstance when RPA is existent. Especially, RPA provides a unique range of features, i.e., high-risk mission acceptance and quite ultra long-endurance, which could not be feasibly executed by conventional aviation vehicles. Their characteristics, along with the developments in electronic and telecommunication techniques, and the necessity for energy conservation, initiate the probability of the potential rise of a commercial and broad RPA market. However, the rise and prolongation of RPA market pose massive difficulties in the current traffic management. Actually, the combination of RPA with conventional vehicles is a challenging problem for next-generation ATM. The RPA ordinarily are so flexible that their flight level would be continually amended when execute different tasks. Therefore the probability of threats to the general (manned) aircraft cruising in the differential flight level, will greatly increase in the prospective situations. Currently, in spite of the increasing application requirements of the RPA with the coordination of the manned aircraft, the aeronautical authorities must not admit the coordination until these unmanned vehicles reach the "equivalent level of safety" (ELOS) of general aviation [10]. Comprehensive consideration and substantial amendments have been required to promote the TCAS compatibility for RPA; this topic once regarded as one of the primary discussion subjects in the Surveillance and Conflict Resolution Systems Panel (SCRSP) conference organized by the International Civil Aviation Organization (ICAO) [14].

The safety in traditional aviation relies on the relevant equipments installed in own aircraft, the ground navigation assists and the operating pilots' responses, in connection with the ATM and air traffic control (ATC) systems which are responsible for the surrounding surveillance in the whole-process flight, starting from the take-off, the cruise to the landing. Thus, RPA is supposed to fly (if cooperated) in the unsegregated airspace in which the control structure and standards are currently designed for traditional aircraft. The requisite high-safety regulations should be abided by every airspace subscriber.

That RPA integrates successfully into the actual ATM is quite complex, and it is a combination procedure of technology improvement and legal framework evolution in international society. It must be completely compatible with the standards and specifications constituted by the same aeronautical authorities which is competent in charge of the current conventional aviation [13]. This delegates two elementary requirements:

- Equivalent level of safety insurance to be applied in traditional aviation.
- Transparency and compatibility to the current ATC/ATM systems in use. Obviously it is very important for the future ATM situations which can be represented by hectic and dense airspaces with several flights under free flight integrated with various RPA [10]. Note that the current technique supports the own vehicle to transmit the state data (i.e., the position and velocity values) to nearby aircraft, and also to receipt the analogous state data from them. Due to the increasing density of air traffic and the development of technologies, the fundamental trend of ATM is improved by several authoritative ATM stakeholders [15]: the control is changed from centralise to distribution, the responsibility of collision avoidance will be transferred from ground to air, and new techniques and skills are introduced to substitute for the fixed air traffic trajectories.

In the congested scenarios, the unexpectedly operations which appear in a system-wide range increases on account of the comprehensive results of sequent dynamical behaviours and crew's possible responses, which could play an evident influence on the neighbouring aircraft, especially the safety issues. The new synergic systems and modules are requisite to assess the strict aviation safety of future hectic ATM scenarios. Therefore, although all the processes are timely discussed in the innovative paradigm pattern, it is of great significance to strengthen the final safety net (i.e., TCAS), in case a fault may be caused from the previous levels of the hierarchical safety system.

This review summarizes various conflict detection and resolution (CDR) approaches which aim to ensure the flight safety by different means, and makes the main classification of them. As the last safeguarding measure, the operations process of TCAS is described in detailed and its weakness in multi-aircraft scenarios is represented. Then the survey on TCAS analysis and improvement are respectively exhibited. These methods and techniques are the attempts to improve and perfect the TCAS performance, which would improve the airspace capacity while efficiently manage and control more aircraft involved in the same scenario. Sufficient effort has been made as much as possible to explore contributions which are primarily related to the pivotal techniques and logics of TCAS. Because of the limited capacity, it is regrettable that many conference reports and papers could not be cited and covered in spite of the endeavour, the author of this review sincerely apologizes this deficiency in advance.

It is shown the brief outline of this paper, Section 2 summarizes the CDR approaches in different levels and mainly introduces the TCAS operations; Section 3 displays the discovered weakness of TCAS logic required to be analysed and improved; Section 4 provides the description of TCAS analysis in detail; Section 5 states the art of TCAS improvement; finally, the overall conclusions are represented in Section 6.

II. CONFLICT DETECTION AND RESOLUTION APPROACHES

The existing ATM systems are fleetly improved in view of the comparatively fixed airspace framework and primarily human-operated system architecture [1]. In conformity with the demands of the next-generation ATM hierarchy (system) developed by SESAR [16] (Single European Sky ATM Research, founded by the European Community) and NextGen [17] (Next Generation Air Transportation System, founded by the American government), the air-traffic flow requires to supply more feasible utilization of airspace levels and capacities. In addition, to offer air traffic controller (ATCo) and pilots much more valuable and referential state data, the exact information of the neighbouring vehicles in especial, different decision support tools (DSTs) of various activity levels are in the development. In the future air traffic, ensuring safety is still the principal factor to be taken into consideration. The guarantee of reasonable separation between the neighbouring vehicle routes is regarded as the core study goal. Whenever a prescriptive separation (safe time and distance intervals) between two approaching aircraft is transgressed, a threat emerges and some efficacious measures should be adopted in time to avoid it.

A. CATEGORIES OF CDR APPROACHES

With the growth of airspace density, it is extensively required to execute DSTs to help the pilots in resolving threats while promoting flow efficiency. The major functions of these DST systems, includes two procedures: conflict detection (CD), that is to forecast an encounter which may appear in the near future, communicating with crews and alerting them the detected conflicts; conflict resolution (CR), that is to offer aid for the complete course of removing conflicts. The partial review of approaches, algorithms and models to the CDR issue is summarized in [18]. Based on the contributing horizon, normally, most CDR methods and algorithms could be divided into three representative classifications, shown in Fig. 1.

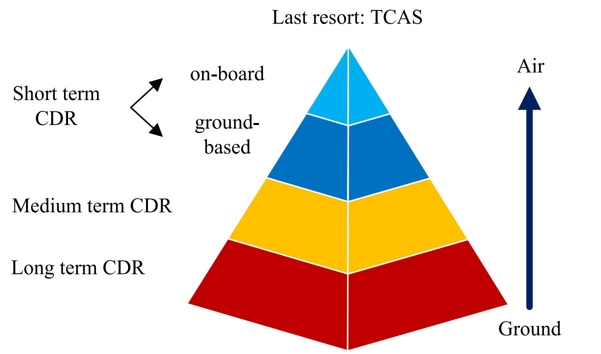

FIGURE 1. Major categories of CDR approaches.

-Long term CDR, take effect on the trajectory programming at the strategic level and manage the function scope more than 30 min. The focal point is a representative management issue of traffic flow, i.e., the trajectory programming and arrangement of all involved routes within a correspondingly longer ahead of time. Calculations in advance are implemented from some months up to several minutes (>30) before the flight process of actual flight. They aim to maximize the efficiency of the route network, and simultaneously to minimize the global flight costs, considering several restrictions, e.g., the practicable capacity at regional airspaces and the airports [19], [20]. Note that the EuroControl long-term forecast (LTF) [21] was proposed considering raising basic traffic based on a collective model of market and manufacture factors, e.g., passenger requirements, ticket prices, airspace network structure, fleet composition, economic growth and so on. Taking the constraint condition of airport capacities into account, appropriate models are used to synthetically manage passengers, trade, cargo, and military aviation traffics. In addition, the novel project "Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)" was led by ALGINDRA, aiming at designing and implementing strategic de-confliction algorithms for a large amount of trajectories along the entire European airspace, to promote some of the decision-making procedures related to ATM [22].

-Medium term CDR, operate at the tactical level and manage the expectation scope up to 30 min. The prediction approaches are applied to improve the planned routes of strategic-level during actual execution, normally considering prediction look-ahead period of time. These are ordinarily employed by ATCo in view of the disturbances created by unforeseen events which could not be forecasted beforehand with adequate accuracy, and generally it is impossible to be accomplished with the systems of flight plans at strategic level [23], [24]. The remaining advance time is adequate to support the tactical calculation for the safety insurance, and to guarantee that no collision risk exists between aircraft at this level. The technical innovation cluster that worked with me has proposed an impactful strategic-level CDR method, on account of four-dimensional (4D) trajectories, i.e., three-dimensional (3D) coordinates with a timestamp, to resolve encounters in the TMA [25]. The CD sub-module applies spatial data structures (SDS) to avoid invalid comparisons of pair-wise trajectories, and a succinct wake vortex modelled based on 4D tubes to explore the infringements of separation (mainly time-based) between vehicles. The CR sub-module resolves the detected encounters using a dynamic, feasible 3D allocation of the arrival paths which consider the utilization of continuous descent approaches (CDAs). The generated conflict-free routes of a large number of hectic traffic scenarios have been validated to be practicable with a full flight simulator of certified B738.

-Short term CDR, execute at operational level to resolve the imminent threats, and they are in charge of the function scope up to 10 min. The fuel cost and flight optimization are not required to be considered, owing to the reason that they are not trajectory programming systems differing from Long/Medium term systems.

Generally, the Short term CDR systems basically contains two classes: the ground-based safeguarding systems used to help the ATCo to resolve conflicts between vehicles, by producing an effective alert for the tendency of minima separation infringement [26], [27] (e.g., the typical STCA, short term conflict alert [28]); a set of equipped airborne devices which are different from the ground-based safeguarding systems [29] (i.e., TCAS).

The STCA system includes alert mechanisms to supply the warning of several infractions in the specific airspace between closer aircraft for ATCo. It is used to monitor aircraft positions from subgrade radar, and provide an alert to keep a short period of time to command the dangerously approaching air vehicles when there is a potential encounter between them. Because its input data are obtained from subgrade radar, they could not perceive the purpose of the crews or ATCo, who would find a detected threat and already take some operations. Therefore the issued alerts may not be necessary in actual situations, and the alarms of STCA sometimes are regarded conservatively.

TCAS is designed as the final safeguard to resolve midair collisions (MACs) and evidently decrease near midair collisions (NMACs) in global airspace [30]–[32]. A defect in the strategic-level CDR could be handled by tactical-level CDR, and the failure of tactical-level CDR generally is repaired by onboard TCAS. This review concentrates on the final phase of a threat, i.e., in TCAS course, which has the risk to deteriorate to be a collision. Therefore, through promoting the TCAS performance, it could be conceivable to realize the avoidance of faults, which may be latent in the lack of mechanism integration of trajectory-separation-conflict management for future ATM hectic scenarios. Up to present, ICAO has approved TCAS I, and TCAS II that is the new-generation edition. They are mainly different in the alerting capabilities, traffic advisory (TA, TCAS I and TCAS II) that is to help the crew in the visual perception of intruders, and resolution advisory (RA, only TCAS II) that is to suggest escape strategies [33]. Several published literatures represent the TCAS operating mechanism, and improve the capability for collision avoidance [34]–[36].

B. TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM

On account of the MAC/NMAC, which occurred over the thirty years of 1956-1986, the Federal Aviation Administration (FAA) started developing the last-resort of safety net, i.e., the effective TCAS, for resolving the failures in the separation services that is provided by the ATCo [29]. TCAS takes effect on communicating the detected conflict to the crews, and aids them to resolve the conflict by suggesting an avoidance measure. Ordinarily, in most cases it keeps quietly as the alert system. When there is an encounter and several actions are required, TCAS draws the attention of the pilots to the reported conflict. The following represents the main procedure of the TCAS II operations:

1) Normally, TCAS transmit inquiries and receipt responses from nearby aviation vehicles, and it uninterruptedly carries out surveillance of the surrounding airspace.
2) Specially, TCAS produces a TA when one aircraft comes close to another aircraft and a potential collision is conceivable to appear within 20-48s. It is used to offer a visual illustration of the risk situation.
3) TCAS produces an RA when the scenario worsens, and a collision is conceivable to appear within 15-35s. The proposed strategies are always suggested in the vertical plane (upward, downward). The crew should react timely to realize the enough separation when a RA is announced.
4) After the encounter is resolved successfully, TCAS produces "Clear of Conflict".

The tests of time and distance are checked on each closer aviation vehicle. If the time to the closest point of approach (CPA) satisfy the horizontal and vertical restrictions, the intruder aircraft is regarded as an encounter. In addition, for the slow-closure-rate encounters, their distance should be smaller than the dimensions of safeguarding domain, formed by distance modification (DMOD) and altitude threshold (ZTHR). The time and dimension thresholds are different in corresponding sensitivity levels (SLs). TABLE I [29] represents the numerical values to touch off different advisories. Besides, at CPA the altitude limit (ALIM) supplies the expected vertical minimum separation.

In the threat case illustrated in Fig. 2, for *Aircraft i* the descending manoeuvre would be suggested by TCAS and synchronously for *Aircraft j* the climbing manoeuvre is advised, because they are non-crossing to achieve the safer follow-up situation in the process of attaining greater vertical separation [29]. Subsequently, the RA strength is determined, and its value is minimized disruptive to the current trajectories while still keeping at least ALIM of separation between them at CPA [29].

TABLE 1. Threshold values of different altitudes.

Own Altitude (feet)	SL	Time (second)		DMOD (NM)		ZTHR (feet)		ALIM (feet)
		TA	RA	TA	RA	TA	RA	RA
<1000	2	20	N/A	0.30	N/A	850	N/A	N/A
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

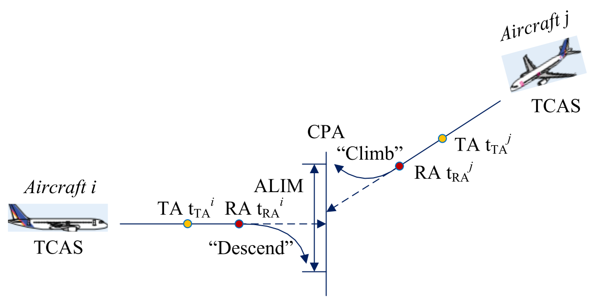

FIGURE 2. TCAS conceptual model.

III. TCAS INDUCED COLLISIONS

TCAS II was constructed and expected to take effect in the aviation densities of up to 24 aviation vehicles within a 5 NM radius, that was the most hectic airspace with the highest aviation density predicted over the next 20 years [29]. Its positive function on the aviation safety has been approved to be beneficial and effective to reduce the probability of collisions. Yet there has been an incremental requirement for aviation transportation, e.g., air travel and air freight, which will cause the increasing aviation density, in particular the airport's surrounding airspace. The congested aviation traffic would initiate a secondary encounter as the consequence of measure advised by TCAS to resolve the primary threat, and this has the possibility to initiate improper manoeuvres.

The potential collision scenarios that TCAS could not resolve the emergent encounter are precious few when there are only two aircraft; however the possibility of these situations would raise for a hot spot in which there are multiple aircraft. The example scenario illustrated in Fig. 3 shows the occurrence procedure of a potential induced collision in the four-aircraft scenario in which TCAS invalids [37]. In this representative case of four aviation vehicles which are all TCAS equipped, there are two primary detected conflicts. Between *Aircraft 1* and *Aircraft 2* it is defined as *conflict 1*, and between *Aircraft 3* and *Aircraft 4* it is named as *conflict 2*. Variable $t_{TA}^i (i = 1, 2, 3, 4)$ indicates the TA appearance time, and variable t_{RA}^i $(i = 1, 2, 3, 4)$ is the RA emergence time. Originally, *Aircraft 1* cruises at FL150 and *Aircraft 2* cruises at FL170 on an opposite direction. When *Aircraft 2* descends and bursts into the *Aircraft 1's* safety range, a TA warning is generated by the equipped TCAS to catch the crew's attention to inform that a collision may occur within t_{TA}^1. And subsequently an RA is announced at t_{RA}^1 to instruct the pilots to adopt measures for achieving adequate separation of safety. When the encounter is confirmed, *Aircraft 1* utilizes a downward operation and *Aircraft 2* flies upward to supply the feasible distance at CPA. Generally, the ALIM is used as the smallest separation for safety guarantee in the selection of the RA strength, and it needs a minimal amendment of speed value. In the meantime, an analogously TCAS execution, including the TA and RA procedures, is in the motion between *Aircraft 3* and *Aircraft 4*. When they approach and a collision would appear, a TA is announced at t_{TA}^3 and an RA is generated at t_{RA}^3. The pilots in *Aircraft 3* follow RA by trying to fly downward, while *Aircraft 4* attempt to climb to realize the strength of ALIM. However, although both encounters has been exactly resolved based on the RA's resolutions, a new encounter as the secondary conflict is induced between *Aircraft 1* and *Aircraft 4*, due to the influence of previous operations. It could be found promptly and the pilots have to deal with the new encounter. But, the time left is deficient for the crew response, and therefore a potential induced collision would suddenly emerge. This exceptive situation could be called as Tang-Piera four aircraft deadlock.

In view of the data from the radars spread all over the USA, collected by the FAA and several Department of Defense sites [38], over 95% involve three aircraft, and even one involved seven aircraft through checking 3803 multi-aircraft situations. The four-aircraft collision scenario may induce a potential collision, and the same towards three-aircraft scenario or the others [39]. Thus, it is necessary to analyse the TCAS operations and improve the TCAS performance in multi-aircraft situations. Many researchers and institutes engage in the related topic, and the surveys are represented below.

IV. SURVEY ON TCAS ANALYSIS

Potential induced risk is the domino influence of the TCAS operations to cause an emergent collision which does not exist in the absence of equipped TCAS [40]. Research which aims to explore these collision scenarios is prerequisite to achieve the safe, reliable and robust ATM system. Therefore, rigorous algorithms and technologies are used to analyse the avoidance process of potential induced collisions, to check the TCAS logic in multi-aircraft scenarios, and to seek out all the failure situations which should be resolved in advance.

For example, in the congested and hectic unsegregated airspace, there would be a complex situation that TCAS issues improper manoeuvres to deal with one-on-one threats between traditional aircraft while a new secondary encounter is induced to the nearby RPA of previous operations.

A. COLLISION RISK MODELS

The risk assessment of MAC/NMAC occurrence and the mathematical description of evolution steps of potential collisions have been in development for nearly 60 years [41]. Marks [42] and Reich [43] started the research and discussion about collision possibilities for aviation vehicles were initially in the early 1960s. Particularly, the Reich model primarily evaluates the collision possibility for a trajectory architecture, containing several parallel routes. In the exploration of standards to estimate safe distance/interval and specify the required navigation level, the core is based on the concentration of execution mistakes in operational circumstances [44]. Adopting some little enhancements of Reich model, ICAO utilized it in the North Atlantic Organised Track System (NAOTS) to estimate the optimal intervals between involved trajectories [44]. In [45], the model completes the risk assessment consisting of two irrelevant sub-models: one is to illustrate the effect of collision risk on the trajectory network, i.e., the possibility of two aviation vehicles to intersect to be an air disaster; the other one is based on the various equipments' performance for the surveillance and detection, the ground communication, the airborne transmission and the aircraft dynamic.

To support the validation and analysis of TCAS performance, various encounter models via different techniques and methods have been constructed over these years. They aim to create encounter scenarios for assessing the ratio of NMAC/MAC accidents in which aviation vehicles are regarded as mass points. Kochenderfer *et al.* [46] represent a technique for modelling encounters on account of the Bayesian statistical framework, and it is utilized for the safety assessment of manned and unmanned aviation vehicles in collision avoidance. Kuchar *et al.* [47] attempt to apply a fault tree in modelling the outer-loop system defaults, or events which set the circumstances for the approaching threat simulation based on the fast-time Monte Carlo inner-loop method. Zeitlin *et al.* [48] define the safety analysis steps to evaluate the TCAS performance in general and unmanned aviation vehicles. Netjasov *et al.* [49] develop a typical threat model consisting of the procedural, operational, personnel, and systematic agents of TCAS execution. This model has been validated to be effective for a historical MAC accident [50], and it was extremely valuable in estimating the most critical elements which is propitious to the nonzero collision risk. Several other researchers paid close attention to pilot reactions which could take effect on the flight safety. Lee and Wolpert [51] integrate Bayes nets with game theory to calculate the operation of hybrid systems containing both human-related and electronic modules, therefore predicting the crew response in possible MAC scenarios. Chryssanthacopoulos and Kochenderfer [52] improve the crew reaction module in which the response is not deterministic to TCAS alerts to improve the robustness of system performance. Garcia-Chico and Corker [53] supply an elaborate analysis of the human operational faults which could raise the collision probability.

Besides, the famous Massachusetts Institute of Technology (MIT)-Lincoln Laboratory has maintained the successive study of TCAS to evaluate collision possibility and improve the CDR techniques [54]. Their TCAS-related research and development date back to 1974, when the FAA asked them to take part in the design of an airborne collision system. In the late 1970s, they started monitoring of aviation vehicles in the airspace of Boston, utilizing their developed sensor of prototype Mode S. And in the mid-1990s, they were required to analyse the TCAS logic in resolving the detected encounters. In addition, since the beginning of this century, it has carried out safety assessment, and made tentative improvements of the providing strategies. Reference [55] epitomizes the main difficulties of some TCAS extensions which are demanded to evaluate the safety level of a RPA which are installed with TCAS. In [56], a novel encounter model for cooperative transponder-equipped aviation vehicles is developed to create random close threats using fast-time Monte Carlo simulations to assess the concepts and procedures of collision avoidance systems. Furthermore, the U.S. correlated encounter model is constructed in [33] by adopting significant sampling techniques to improve the results precision and estimate the safety influence of the latest TCAS version. In [57], Lincoln Laboratory primarily develops the next-generation collision avoidance system equipped in the aircraft acting on pilots. It evidently rethinks how this novel system is engineered, requiring the system to supply a high-level safety without interfering with normal operations. An innovative approach is represented to discuss the coordination and interoperability in specific encounters with multiple threats, and it has been validated to be effective in supporting the requirement for safe, non-disruptive collision protection as the airspace continues to evolve [58].

What needs to be highlighted is the InCAS, i.e., Interactive Collision Avoidance Simulator, that is issued by EuroControl [59]. InCAS is absolutely based on TCAS logic, and it is developed for the display of a simulated or a synthetic situation. It is interactive for the specialized demonstration, estimation and simulation on TCAS. In addition, it can offer a relatively precise reconstruction of reality to simulate events. Though it is not a standardized tool for the safety assessment based on modelled TCAS operations [59], InCAS supplies valuable data for operational comprehension and also for application training on TCAS equipment. In addition, Lincoln Laboratory utilizes Matlab generation code to create stochastic routes [56], to simplify the TCAS operations, or to model some correlative sub-modules, such as the vehicle dynamic sub-module, TCAS sub-module, and crew reaction sub-module [38].

B. STATE SPACE-BASED CAUSAL ANALYSIS

The initial data of the available models to check the TCAS capacity in various situations are several provided states of routes. Thus, these models can be applied to test whether a possible detectable collision exists in the current situation. Yet there is an absence of valuable models to explore all the possible collision situations for a specific number of aviation vehicles in the high-density airspace. For future ATM, it can be employed to supply referenced information and advisories for operation.

The published papers [37], [39], [60], [61] of this author and collaborators implement a series of encounter models based on a Discrete Event System (DES) technique, i.e., Coloured Petri Net (CPN) [62], to improve the causal analysis of TCAS capability, thinking about its impact on surrounding aircraft. They are designed to handle the future hectic traffic. The state space analysis, as the core advantage of CPN formalism, reinforces the quantitative method and techniques, and explores all the system's reachable states from a given initial input [63]. The system state is represented through the various tokens, i.e., the entity with the value, distributed in their corresponding data storage units [64]–[66]. It also can be graphically displayed called reachability tree or occurrence diagrams [67]–[70]. Its fundamental theory is that a directed graph contains the nodes to record all reachable states, and the arcs to represent the evolution process of states. The new states are generated by arousing all the enabled data computing units, and these form the state space. The reachability tree of the simulated system's operations used for a specific scenario, offers a deeper comprehension of their potential cause-effect relationships, and the display of an operation evolving upstream and downstream for the whole operations. It is feasible to analyse and verify various properties of the simulated system such as boundedness, reachability, activeness, among others [71].

The TCAS operations could be modelled as a series of discrete events with the time evolution; the occurrence of each event is expressly at a particular time, and a state change of the objective system would be generated [72]. Besides, although the mandatory and popular TCAS has been in use with continuous evolvements for more than 30 years up to present [29], key portions of its causal analysis, particularly the weakness of TCAS logic in multi-aircraft situations, have not yet been perfectly exhibited. Therefore CPN models could be proposed as a core method to generate the state space of hectic traffic scenarios, in which the high-risk situations are detected, and the surrounding traffic are characterized.

In [37], a causal model is utilized as an assistant means to detect TCAS defects in hectic scenarios. It is described to identify potential collision scenarios, conducting as an impactful software for validation and implementation of new proposed TCAS logics. In [39], the causal model focuses on characterizing the surrounding traffic, which has the risk to induce a collision with own aircraft, and the generated simulation results can be utilized for the comparison with the actual flights to decrease the rate of potential induced collision. The characterized state space can be in the storage of a database, and an advanced alert would be automatically announced when the multi-aircraft traffic matches one of them. In [60], a quantitative state space analysis of identified TCAS weaknesses generates all the possible prospective situations for a given amount of the involved aviation vehicles over a short period. This approach represents an overall perspective on the system dynamics and scenario evolutions, and provides an intuitionistic process display to comprehend the collision occurrence. It could be applied to estimate the influence and effectiveness of the local operations and decisions. In [61], based on an agent-based modelling approach, it improves the encounter models using the CPN formalism to contain the agent "pilot reaction time" which simulates the variable time of behaviour delay to study its effect on collision risk. The results illustrate that the collision risk rises as the delay value grows.

The encounter models based on TCAS logic could act as auxiliary tools for ATCo and pilots, to better comprehend the interdependence between the involved aviation vehicles. In addition, it also could be used to check for future updates of TCAS logic. The developed discrete event-based models possess the following emblematical characteristics:

- Complex, the actions and decisions would be various in each process. The proposed encounter models have a plenty of potential interrelated causal relationships which make the sub-modules interact in the running, and it would lead to different simulation results.
- Dynamic, each event in state space could exhibit the results of corresponding operation. The characteristic of dynamic could form complex patterns of system operation to explore the uncertainties, expressly the undiscovered effects of unreasonable decisions which could cause uncertain results.
- Conditional, the advisories are provided by TCAS announced at the setting time with several conditions, e.g., manoeuvres have to be adopted and executed by pilots. When all the established constraints are met, the expected object can be realized, otherwise not.

V. SURVEY ON TCAS IMPROVEMENT

The development of modern systems has made it possible to deal with the growth of air traffic, and keep the obligatory safety level [20], [73], [74]. The TCAS has been proven effective to reduce the risk of MAC/NMAC and is currently mandated on all large transport aircraft [75]. Although there are technical advances in equipping electronic systems which are used as DSTs, accidents still occur when the minimum safe separation provision is violated because of the human/technical error [76]. Any failures of the separation standard have the possibility of MAC risk. These airborne systems could initiate unnecessary alarms with high rates, particularly in crowded terminal areas [77]–[81], pilots become stressed and wrong actions can be made [77]. Therefore, researchers try to improve the TCAS by different methods. The overall features are listed in the TABLE II.

A. HORIZONTAL RA EXPANSION

Some researchers consider that the next generation TCAS (TCAS III [91]) has superior CDR performance. It could deliver both vertical and horizontal RAs. For instance, in an emergent situation, one aircraft may be instructed, "turn right, climb" while the other would be instructed "turn right, descend". Obviously it could take effect on further increasing the total separation between aviation vehicles, in both horizontal and vertical planes. Horizontal instruction is significant in an encounter which is close to the ground, i.e., not enough vertical manoeuvring airspace. The idea

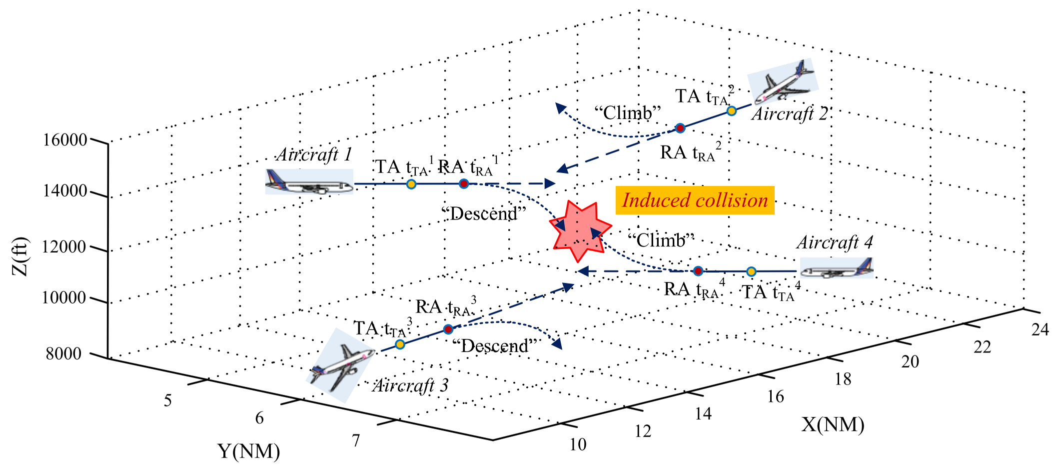

FIGURE 3. Four-aircraft collision scenario.

TABLE 2. Typical improved TCAS methods and respective character.

Methods	Horizontal escape	Added instrument	Number of aircrafts considered	Other necessary information
[85]	✓	✗	2	GPS, ADS-B
[86]	✓/✗	✗	2	ADS-B
[87]	✓/✗	✗	2	✗
[88]	✓/✗	✗	2	ADS-B, Satellite data
[89]	✗	✗	2	✗
[90]	✗	dual bandwidth receiver	2	✗
[91]	✗	✗	2	ADS-B
[92]	✗	✗	2	Radar data
[93]	✗	✗	2	Higher resolution radar data
[94]	✗	✗	multiple	✗

✓ fully supported, ✗ not supported, ✓/✗ partially supported

is best illustrated in [82]. It studies a new generation of TCAS based on the Global Positioning System (GPS) and Automatic Dependent Surveillance Broadcast (ADS-B). Two kinds of horizontal escape manoeuvres are represented: change speed without amending flight direction, and change flight direction without amending speed.

In some other contributions, researcher consider combining the horizontal and vertical RAs. Reference [83] presents the results of research which is implemented to determine the positive effect of ADS-B on TCAS. However, the simulation results show that in-apparent improvements in avoidance performance of TCAS could be achieved through the integration with ADS-B, with some other modular factors, e.g., the aircraft dynamic performance and input data, possessing more impacts.

A simple encounter model is introduced in [84] to ease the evaluation of the indicators for pair-wise encounters. The aim is to assess the coherence between threat detection indicators, provided by the complexity metric and TCAS indicators, and to determine whether or not the proposed complexity metric can allow an operational integration in the detection process between Separation Management (SM) and the Collision Avoidance (CA) layers. It has been shown that the proposed horizontal complexity metric and variable in TCAS behaves similarly, in terms of the range between aircraft when alert thresholds are reached or all relative angles and speeds. A novel structure of TCAS is proposed in [77] to remedy some limitations of ATC performance, and reduce the possibility of unnecessary alerts. It aims to represent visual information based on ADS-B satellite data in the aircraft cockpit, which permits crews to verify of the right operations and assist them to operate reliably with less stress, particularly in Control Terminal Area (CTA).

In general, methods allowing horizontal escape usually need other information, such as ADS-B satellite data, GPS information, Radar system and so on. Consequently, the resolution manoeuvre would be totally different with the current system, just providing advisories in altitude, and need more accurate information provided by more advanced hardware.

B. OTHER IMPROVEMENT STRATEGIES

Other methods and technologies improve the original CA logic, and do not consider the horizontal resolution manoeuvre. Reference [85] represents an RA detection algorithm on account of the TCAS II mathematical model. It is similar to a CD algorithm, but not calculating the loss of safe interval, it detects RAs of multiple aircraft. In addition, the algorithm has been accurately verified with a kinematic model of routes. It exactly characterizes all threat geometries between each pair of aircraft that initiate an RA within a given time in advance. A dual bandwidth receiver is utilized in [86] to realize the extended operation range of TCAS. During conventional operations, the radio signals of current equipped TCAS are screened out by a band pass filter that passes all TCAS relevant radio signals. When the extensional range is expected, the band pass filter is more narrow, which permits only designative TCAS radio signals and ameliorates the noise ratio of signals. The TCAS equipped on own aircraft changes the range mode to detect intruder aircraft with different distances.

Besides, some methods also combine other information, such as ADS-B information and radar system. Reference [87] integrates ADS-B broadcasting information with original TCAS, which broadcasts and receives states of the neighbouring aircraft. Fusing the data of TCAS and ADS-B could decrease the interruption ratio of TCAS radio, extend the range surveillance and improve its precision. The combination of a radar with a GPS-based TCAS is put forward in [88] for separation guarantee between all instrument flight rules (IFR) routes and visual flight rules (VFR) routes executed as steerable flights. Reference [89] proposes an improved TCAS logic and device, wherein the input data are augmented by higher resolution radar data. By using radar to search out targets, altitude information can be developed for those aircraft not equipped with altitude reporting transponders. The improved accuracy also allows angle/angle perspective display of air traffic and thus provides enhanced situational awareness. In [90], this causal encounter model generates all the reachable downstream states to strengthen the subsequent decision making of the crew, via integrating state data which are relative to collision information. In addition, some innovative techniques, e.g., removing the scenarios in which the involved aircraft is separating without the possibility of initiating new secondary threat, are adopted to raise the calculative efficiency and effectively resolve the common expansive problem in state exploration.

What is more, TCAS could be extended in the application of RPA [92]–[95]. The solution proposed by [96] has the potential to meet the requirement for a cooperative collision avoidance capability required to achieve preliminary integration of RPA into airspace classes A-C.

Based on the amendment of heading angle, [97] proposes a geometric model to provide feasible collision avoidance manoeuvre in the horizontal plane. An algorithm is utilized to consider the electronic and mechanical operation time. An enclosed analytical approach based on the Galilean relativity principle is used to calculate the separation in advance. The Influence degree of electronic and mechanical operation time on the Horizontal Miss Distance (HMD) [98] and the reserved time (Tau) [82] are computed and investigated.

VI. CONCLUSION

TCAS constitutes a last-resort measure of security network, which is utilized worldwide, effectively and significantly to reduce the collision risk between approaching aircraft. It is airborne system which works independently of ATCo and ground-based systems. It entirely relies on the interrelated surveillance devices equipped on the aviation vehicles. TCAS does not take over the flight control system in critical situations; it just issues TA/RA proposals to pilots on how to operate in vertical direction to avoid collisions. However, a secondary encounter as the negative domino effect of advised manoeuvres may be initiated and there is a risk to induce a collision in the congested regional airspace. This paper contributes to the summarization for the conflict detection and resolution approaches, mainly including Long term CDR, Medium term CDR and Short term CDR on three different levels classified based on the acting period. The illustration of TCAS induced collision makes a deep comprehension of the RA induced effects. Finally, reviews on TCAS analysis in view of collision risk models and causal encounter models, and TCAS improvement on account of conventional horizontal RA expansion and other improvement strategies, are briefly outlined to assist the related researchers to possess a global perspective of this research evolution.

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