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Coloured Petri net-based traffic collision avoidance system encounter model for the analysis of potential induced collisions

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A B S T R A C T

The Traffic Alert and Collision Avoidance System (TCAS) is a world-wide accepted last-resort means of reducing the probability and frequency of mid-air collisions between aircraft. Unfortunately, it is widely known that in congested airspace, the use of the TCAS may actually lead to induced collisions. Therefore, further research regarding TCAS logic is required. In this paper, an encounter model is formalised to identify all of the potential collision scenarios that can be induced by a resolution advisory that was generated previously by the TCAS without considering the downstream consequences in the surrounding traffic. The existing encounter models focus on checking and validating the potential collisions between trajectories of a specific scenario. 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. This approach provides valuable information at the operational level. Furthermore, the proposed encounter model can be used as a test-bed to evaluate future TCAS logic changes to mitigate potential induced collisions in hot spot volumes. In addition, the encounter model is described by means of the coloured Petri net (CPN) formalism. The resulting state space provides a deep understanding of the cause-and-effect relationship that each TCAS action proposed to avoid an actual collision with a potential new collision in the surrounding traffic. Quantitative simulation results are conducted to validate the proposed encounter model, and the resulting collision scenarios are summarised as valuable information for future Air Traffic Management (ATM) systems.

1. Introduction

A series of mid-air collisions have occurred over a period of 30 years (1956–1986) (DoT, 2011; NTSB database, 2015). These collisions spurred the Federal Aviation Administration (FAA) to launch the development of an effective collision avoidance system that would act as a last-resort when there is a failure in air traffic controller (ATC)-provided separation services (DoT, 2011). The resulting Traffic Alert and Collision Avoidance System (TCAS) was developed using comprehensive analysis and abundant flight evaluations. The traffic display (which depicts the detailed states of nearby traffic) assists pilots in the visual acquisition of surrounding traffic, providing them time to prepare to manoeuvre the aircraft in the event TCAS advisories are issued. It is particularly important that pilots maintain situational awareness and continue to use good judgment

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in following TCAS advisories. Maintain frequent outside visual scan, "see and avoid" vigilance, and continue to communicate as needed and as appropriate with ATC (DoT, 2011). This system constitutes a last-resort means, which is accepted worldwide, for effective and significant reduction of the collision probability between aircraft (Netjasov et al., 2013).

TCAS equipped in an aircraft does not control the vehicle directly; the TCAS only issue advisories to pilots on how to manoeuvre vertically to prevent collision. Evidently, the human behaviour (pilot response) has a decisive impact on the collision avoidance (CA) results. However, recorded radar data indicate that pilots do not always behave as assumed by the TCAS logic. The collision of two aircraft in 2002 over Überlingen demonstrated that not anticipating the spectrum of responses limits TCAS's robustness (Johnson, 2004).

When TCAS is operative on both aircraft that are involved in a one-on-one encounter, each vehicle transmits interrogations to the other via the Mode S link to ensure collision avoidance (CA) coordination in the process of encounter resolution. TCAS executes independently of ground-based systems, and it relies fully on relevant surveillance equipment on-board the aircraft. TCAS I and its improved version, TCAS II, have been defined and approved by the International Civil Aviation Organisation (ICAO). These versions differ primarily in their alerting capability (DoT, 2011). TCAS I provides traffic advisories (TAs) to assist the pilot in the visual acquisition of intruder aircraft, while TCAS II provides both TAs and resolution advisories (RAs). A TA warns pilots of the potential encounter with neighbouring traffic. A RA is issued to prevent a collision by commanding the pilots to execute an avoidance manoeuvre in the vertical direction. TCAS II version 7.1 is the system that is currently in use. The basic operations are the following (DoT, 2011):

- TCAS broadcasts inquiries and receives answers from neighbouring aircraft to monitor the surrounding airspace constantly.
- TCAS generates a TA when an intruder comes within range of the aircraft and a collision is predicted to occur within 20–48 s (depending on the altitude). TCAS aims to draw the flight crew's attention to the potentially hazardous situation, and it provides a traffic display as well as an audio alert to help the crew to prepare for any resolution manoeuvre that may be required.
- If the situation deteriorates, and a collision is predicted to occur within 15–35 s (depending on the altitude), and TCAS subsequently issues an RA, which is always in the vertical plane. With communication between the TCAS to ensure complementary manoeuvres, the RA could be passive (do not climb, do not descend) or active (climb, descend), depending on the situation. If a RA is issued, then the pilot should respond in a timely and calmly manner (normally the reaction time is set to be 5 s) to achieve a safe separation.
- When the threat has passed, TCAS provides a "Clear of Conflict" (CoC) advisory.

The use of the TCAS has had a positive influence on the safety of flights, being effective, beneficial, and significant in reducing the collision probability (Billingsley et al., 2012). According to (DoT, 2011), "*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*". However, there is growing interest in civil applications of Remotely Piloted Aircraft Systems (RPAS) (Wildmann et al., 2014). There is also increasing demand for air travel (Isaacson et al., 2014). With applications such as surveillance, in which various aircraft would cooperate and compete for a certain target (Yousefi and Zadeh, 2013), it is expected that the traffic airspace density will increase considerably in certain small areas during short time periods. These highly congested regions could be regarded as hot spots (Nosedal et al., 2014).

The increased airspace usage can induce a secondary threat as a result of a RA issued by a TCAS, which may issue an inappropriate suggested resolution that resolves a one-on-one encounter with a first threat. Therefore, research that explores such potential collision scenarios is needed to enable Air Traffic Management (ATM) to avoid such accidents.

From 1 January 2005, all civil fixed-wing, turbine-powered aircraft having a maximum take-off mass exceeding 5700 kg (ICAO, 2014), or a maximum approved passenger seating configuration of more than 19, are required to be equipped with TCAS II (DoT, 2011), i.e., most but not all aircraft are forced to be equipped with TCAS. Therefore, there would be four equipage/response situations: none–none (no TCAS on either aircraft), TCAS–none (TCAS on only one aircraft), TCAS–TCAS (TCAS on both aircraft and both follow the advisory), and TCAS–no response (TCAS on both aircraft but only one follows the advisory). Our research purpose is to explore the potential induced collision scenarios resulting from TCAS logic for one-on-one encounters in which the involved aircraft are all TCAS equipped and the pilots climb/descend to resolve threats by perfectly following the TCAS advisories. We utilise the standard model of pilot response to the TCAS advisories. This model involves a 5-s pilot response delay followed by a 0.25 g manoeuvre in compliance with the advisory. Multi-threat encounters will not be formalised in the model. The focus of the causal model is on the proper analysis of secondary threats induced by TCAS logic rather than the analysis of TCAS logic in the presence of a secondary threat (Billingsley et al., 2009).

The subject of this research is the design of an encounter model to identify all of the potential collision scenarios that are representative of possible hazardous situations that may occur in the actual airspace. The dynamics formalised in the model consider the final phases of a collision. Based on aviation safety studies, the final phases generally occur over a period of time of one minute or less. The model is fed the specification of the initial state, which consists only of one aircraft trajectory and the number of aircraft to be considered as surrounding traffic during the experiment. The objective of this paper is to characterise the surrounding traffic scenarios that involve an induced collision.

Data results generated by the model could be processed to provide valuable information at the operational level for future ATM scenarios. The results are summarised as a set of potential collision scenarios that could be used not only to help ATCs