Modeling for UAS Collision Avoidance

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Abstract

For UAS to be granted full access to civil airspace, their safety case must address collision avoidance, including the lack of an onboard pilot who could see-and-avoid other traffic, as on conventional aircraft. This paper discusses several methods and tools that have been accepted for modeling and evaluating the safety of collision avoidance for manned aircraft. Example results are illustrated. Issues and additional work for extending their use to UAS are discussed.

Today, many manned aircraft are equipped with the Traffic Alert and Collision Avoidance System (TCAS II), the world standard system for collision avoidance. However, simply installing that system aboard UAS is problematic for a number of reasons affecting the safety calculation.

Introduction

It will be necessary to evaluate all aspects of safety in order to certify Unmanned Aircraft Systems (UAS) for access to civil airspace. One of the key safety concerns is collision risk. Wherever aircraft coexist in the airspace, some collision avoidance capability is required as a last-ditch safety measure. The UAS will need to provide some means of substituting for in-cockpit see-and-avoid capability, and its systems may also provide an automated detection and resolution function for impending collisions.

This paper describes work being undertaken as part of the MITRE Research Program. The results should prove useful to the process of developing UAS Sense and Avoid standards within RTCA SC-203, as well as to certifying authorities within the Federal Aviation Administration.

Need for Modeling

The industry has tended to demonstrate candidate UAS collision avoidance technologies using flight trials. These typically are limited to small numbers of encounters with targets, and cannot explore a wide variety of conditions. It is easier to demonstrate target acquisition with a sensor than it is to flight test a complete end-to-end avoidance capability, and consequently the experience is especially thin regarding algorithmic or pilot performance.

However, the regime of certifying safety drives the need to evaluate performance for all credible hazards, and to do so over the full range of credible conditions, from simple to stressing.

Fault Tree Method

One accepted means of evaluating the complexities of collision avoidance safety is to construct a fault tree and evaluate its elements. The tree structure provides the mathematical basis of combining the separate event probabilities to determine the overall risk. The fault tree method, which gained prominence within the nuclear power industry, was used for the acceptance of the Traffic Alert and Collision Avoidance System (TCAS), the worldwide standard system for manned aircraft above a specified passenger or cargo capacity. The method develops one or more fault trees for “top events”, and through deductive logic shows every condition or causal element that could lead to that event. The tree also shows the benefit of mitigating factors. Since encounters with various hazard types are essentially independent, the structure and mathematics of the evaluation is more straightforward, and allows each type to be explored separately.

Figure 1 shows the top levels of a midair collision fault tree. The top event is divided into two main branches: midair collisions that are not prevented, and those that are created by a maneuver presumably intended to avoid the collision. Figure 2 begins to develop the “unresolved” portion of the tree. Further expansion of the tree (not shown) would develop causes for neither the pilot nor the collision avoidance system having avoided the event.

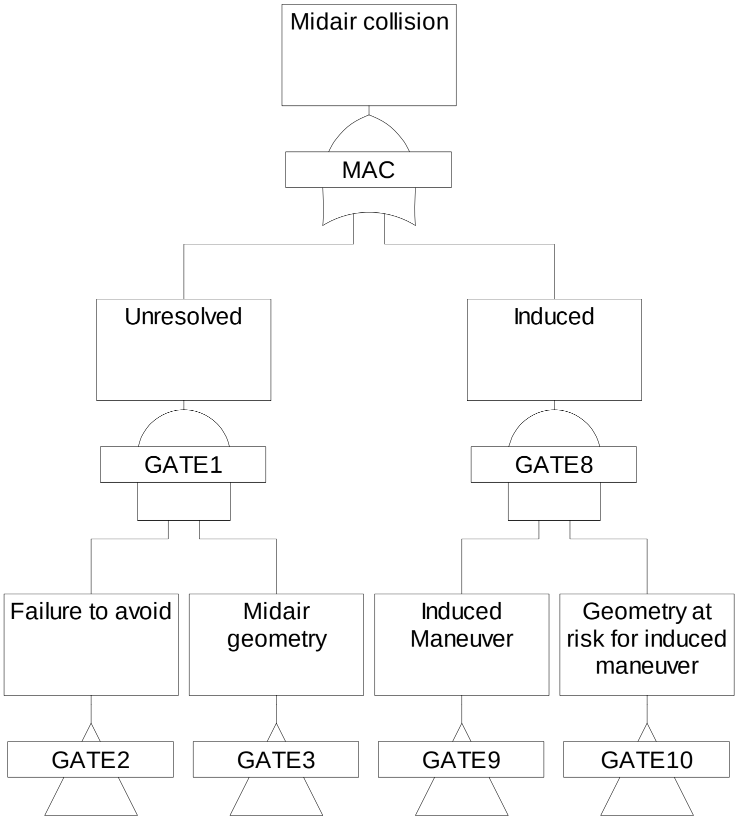

Figure 1. Top levels of midair collision fault tree

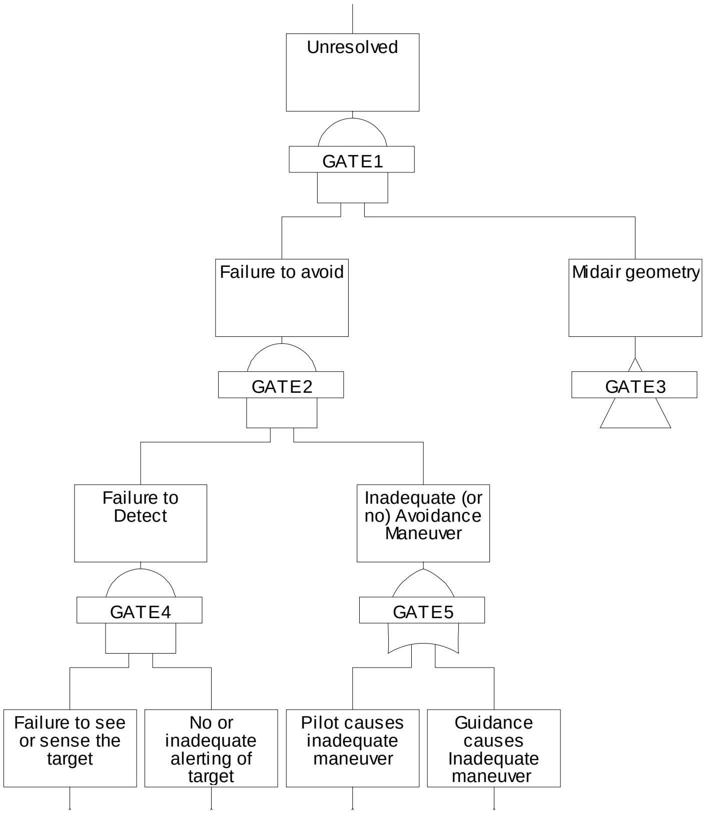

Figure 2. fault tree branch for unresolved collision

The fault tree previously developed for TCAS [1] serves as a good model to adapt to new uses such as installing either TCAS or an alternative system aboard UAS, but the tree must be adapted to encompass differences in the operating concept. The evaluation needs to consider all of the hazards delegated to the Collision Avoidance System (CAS). For TCAS, transponder-equipped ("cooperative") traffic was the only hazard included. In contrast, a UAS will also need to avoid non-cooperative traffic, weather, and terrain. It is likely that different sensors would deal with these various hazards, and each sensor's performance must be modeled. If separate algorithms are used to determine avoidance maneuvers for the separate hazards, they must be integrated, if for no other reason than to avoid issuing conflicting advice.

Fast-Time Simulation Method

The remainder of this paper addresses the hazard of modeling midair collision with traffic. This may be the most difficult hazard to model, as both the UAS and the other traffic are moving objects. Similar methods could be used for terrain and airspace avoidance.

There are complex interrelationships between several elements in the “chain” of events that describe collision protection. These elements include:

- The onboard surveillance system that sees nearby targets
- The prediction of relative motion with respect to the other aircraft
- The pilot, who develops situational awareness from a variety of sources, including the system’s information on nearby traffic
- The algorithm that decides when an avoidance maneuver is necessary and recommends the specific maneuver
- The final decision and execution of the maneuver – by the pilot, or possibly autonomously by the UAS vehicle itself
- The aerodynamic response of the aircraft in maneuvering as instructed
- The simultaneous behavior of the other (“threat”)aircraft

There is inevitably some variability in each of these segments, but overall there must be a high probability of successful performance in avoiding collisions.

Any calculations of CAS effectiveness must consider a variety of encounter geometries. This includes aspect angle, vertical rates and accelerations, speeds, and lateral maneuvers. The TCAS studies used an encounter model [2] developed from Air Traffic Control radar tracks of airplane traffic at multiple locations. Statistical distributions were developed so that many encounters could be simulated, enabling the results to be combined in realistic proportions. The existing model would not be appropriate for UAS missions that did not operate like manned aircraft (e.g., travel from one airport to another, frequently using airways). Many proposed uses [3], e.g., patrol or loitering, do not resemble the bulk of manned operations, and it is logical that the statistical proportions of their encounter geometries would differ from the model. Other aspects may or may not affect the result. The slow speeds of many UAS aircraft should not change a manned TCAS aircraft's performance in avoiding it, but the effect on any new algorithm would need to be examined. TCAS does not detect an aircraft based on its size or reflected radio signals, but an alternative surveillance means (e.g., optical or radar-based) might be affected.

While TCAS evaluation for manned aircraft traditionally has assumed the pilot always responded to advisories (or never did, for special evaluations [4]), a UAS evaluation using a remote pilot concept would need to also consider the two-way communication link reliability and model it as well, as this could affect the timing, or indeed the total absence, of a response.

The use of the model is in connection with a Monte Carlo simulation technique [2], [5]. This fast-time modeling capability replicates encounters between aircraft by moving them along a pair of chosen paths. At the same (simulated) time intervals that the CAS system would operate, the simulation determines the measured data for the threat aircraft and exercises the threat algorithms. If an avoidance maneuver is indicated, another model representing the pilot response – a delay and maneuver accuracy – determines when the aircraft is to begin maneuvering. Yet another model may be used for the aircraft, such as its acceleration and limitations if it were unable to achieve the maneuver intended by the pilot. This type of limitation is particularly a concern for collision avoidance for some UAS aircraft types (see [6] for a compilation of maneuver capabilities), either over their entire operating regime or a part [7]. If the encounter takes place between two TCAS-equipped aircraft, the encounter simulation is repeated with reversed perspective: the subject aircraft becomes the threat, and vice-versa. The two TCAS units coordinate to assure compatible advisory senses. Finally, the point of closest approach of the two aircraft is observed and their separation is compared to that which would have occurred without any collision avoidance maneuver.

Since the UAS response to Resolution Advisories (RAs) could be delayed, either by communication link latency, slow pilot response, or some combination thereof, simulations were run to explore the sensitivity of TCAS logic to incremental maneuver delay beyond the accepted standard. The response specified during TCAS pilot training is to begin maneuvering within 5 seconds after an original RA, and to respond within 2.5 seconds following any subsequent change of RA strength or sense. Figure 3 depicts a

UAS responding with some delay in an encounter against a manned TCAS aircraft responding normally. Figure 4 depicts the UAS responding with delay against a non-TCAS aircraft. In each case, the Risk Ratio[1] is seen to be sensitive to delay, and roughly doubles when the response begins 5 seconds late. These examples used the normal encounter statistics gathered for manned aircraft, and would need to be updated for more representative UAS mission characteristics. They also did not incorporate any limitations in the UAS meeting the acceleration or climb/descent rates advised by TCAS RAs. Additional simulation results for those limitations are expected to be available shortly.

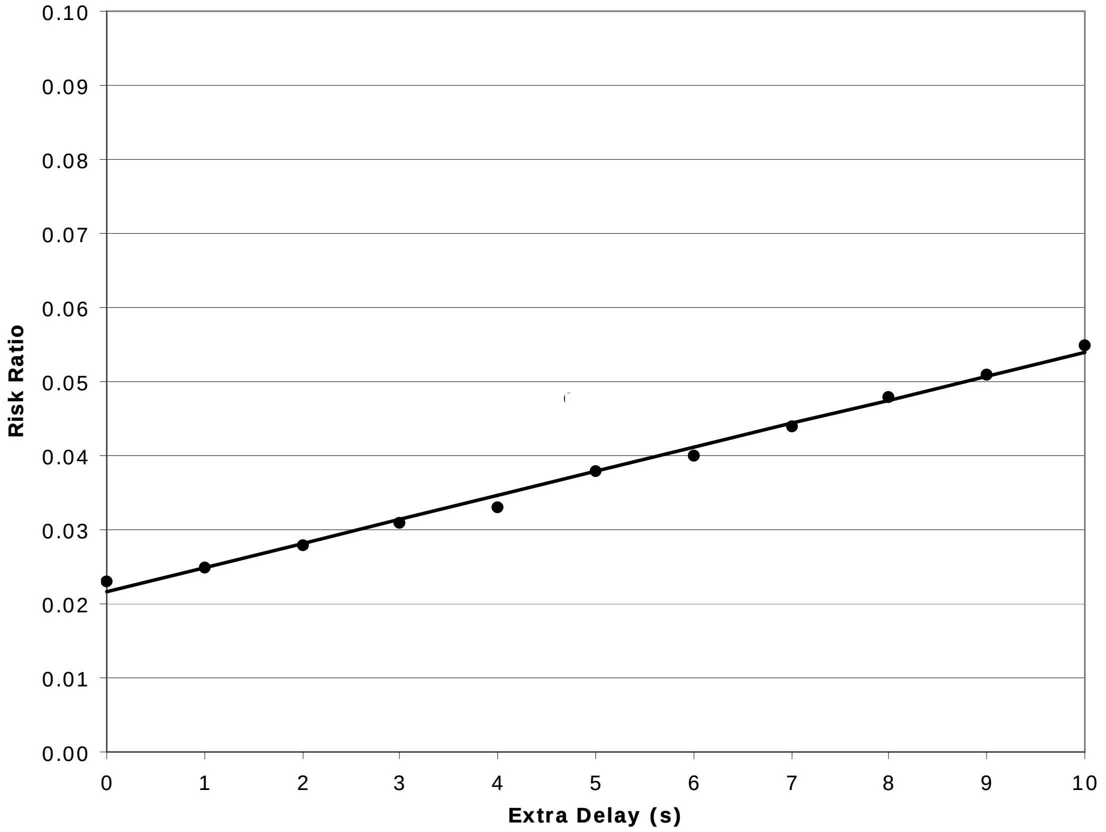

Figure 3. Simulated risk vs. incremental delay for UAS encountering manned TCAS aircraft

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[1] Risk Ratio is the standard metric of safety for collision avoidance, defined as the risk of Near-Midair Collision using collision avoidance relative to the risk in identical encounters without collision avoidance.

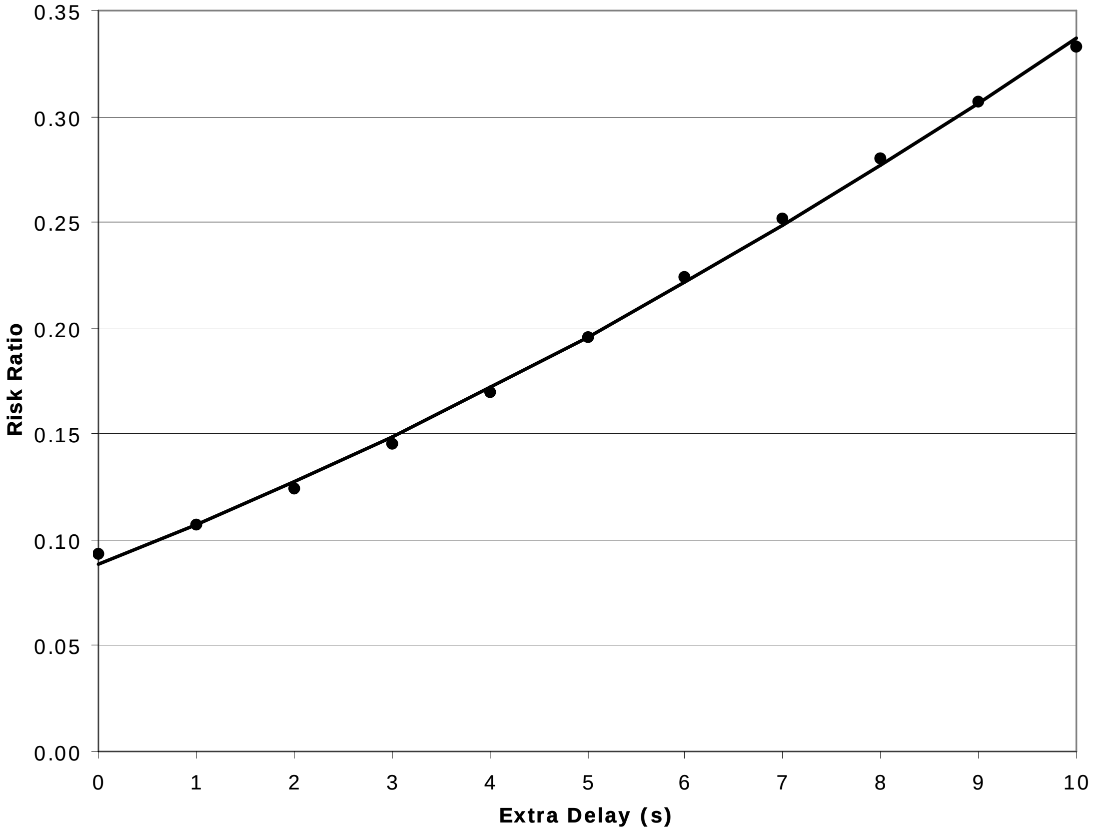

Figure 4. Simulated risk vs. incremental delay for UAS encountering non-TCAS aircraft

Although the TCAS safety simulations were based solely upon maneuvers resulting from RAs, which in turn were based upon detecting transponder replies from targets, collision avoidance also can make use of visual acquisition of targets. An onboard-pilot visual acquisition model was developed and validated for certain conditions [8], and this could provide a probability and time distribution for modeling target detection. The pilot's performance in avoiding a visually detected target, however, has received little attention. Some UAS concepts would use optical technologies to provide a remote pilot with an image of nearby traffic, and the safety of this approach likewise would need to be modeled, using parameters based upon experimental evidence.

Just as a CAS algorithm must be appropriately matched to the surveillance data it receives, a simulation must represent both the surveillance and the algorithm with fidelity. Early versions of TCAS used only its measured range and altitude data in determining threats and advisory selection, so the horizontal motion was far less important to simulate. The latest TCAS logic added a horizontal miss distance filter that makes use of second derivatives of range and uses bearing as a cross-check. This capability required more attention in the modeling of horizontal motion of encounters.

For UAS, any limitations in maneuver performance, such as maximum climb and descend rates or accelerations, must be faithfully considered in the model. If these vary in some conditions, such as by weight or altitude, those again need to be accurately represented for each encounter that is simulated.

Conclusion

To comprehensively evaluate the safety of UAS collision avoidance, methodical evaluation will be required using several steps:

- UAS and CAS systems and the hazards to be avoided will need to be clearly specified.
- System performance will need to be evaluated for each hazard. Due to the dynamic nature of aircraft encounters, a fast-time simulation offers the best means of evaluating many encounters over a broad range of conditions.

- To successfully simulate the hazards and the desired avoidance, statistical performance models of the aircraft, CAS systems, and pilots need to be developed and integrated.
- A structure such as a fault tree is a useful tool for systematically combining the separate risks and their mitigating elements (systems and pilot actions).
- The development of standards for UAS collision avoidance will benefit from the use of consistent tools and metrics such as those described here.

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