SAFETY ANALYSIS METHODOLOGY FOR UNMANNED AERIAL VEHICLE (UAV) COLLISION AVOIDANCE SYSTEMS

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Abstract

The integration of Unmanned Aerial Vehicles (UAVs) into civil airspace requires new methods of ensuring collision avoidance. Concerns over command and control latency, vehicle performance, reliability of autonomous functions, and interoperability of sense-and-avoid systems with the Traffic Alert and Collision Avoidance System (TCAS) and Air Traffic Control must be resolved. This paper describes the safety evaluation process that the international community has deemed necessary to certify such systems. The process focuses on a statistically-valid estimate of collision avoidance performance developed through a combination of airspace encounter modeling, fast-time simulation of the collision avoidance system across millions of encounter scenarios, and system failure and event sensitivity analysis. Example simulation results are provided for an implementation of the analysis process currently being used to evaluate TCAS on the Global Hawk UAV.

Introduction

There is a clear demand for Unmanned Aerial Vehicles (UAVs) in civil and military roles including border patrol, environmental observation, cargo delivery, and military surveillance. Many of these missions require UAVs to co-exist with civilian aircraft during one or more phases of flight. The main challenge of integrating UAVs into civil airspace is the fact that even under Instrument Flight Rules (IFR), there is a requirement that aircraft be able to see and avoid one another [1]. The see-and-avoid requirement necessitates the use of either external assets such as ground radar or chase aircraft or robust on-board collision avoidance systems.

Whether UAVs will be permitted to integrate with civil air traffic is contingent on extensive safety analyses to demonstrate that traffic collision avoidance systems for UAVs are safe. The need for safety analyses is especially critical due to the lack of widespread operational experience with aircraft that do not have pilots on board. This paper describes the safety analysis methodology that has been vetted with the Federal Aviation Administration (FAA), Eurocontrol, and the International Civil Aviation Organization (ICAO) Surveillance and Conflict Resolution Systems Panel (SCRSP) as a valid approach to assessing UAV collision avoidance system performance.

Background

The work described here is funded by the U. S. Air Force to assess the safety of the Traffic Alert and Collision Avoidance System (TCAS) on the Global Hawk UAV. Although TCAS and Global Hawk are the initial focus, we are designing the safety analysis process such that other UAVs and collision avoidance systems can be examined within a single framework that has been accepted by the FAA and ICAO.

Global Hawk began operating out of Beale Air Force Base in California in 2005. Beale is not covered by restricted airspace and is surrounded by small uncontrolled airports. Even though Global Hawk cruises above most air traffic (above FL500), it may encounter a variety of aircraft during departure and arrival, some of which may not carry a radio or transponder. Currently, the Air Force must provide five-day advance notification to the FAA before flying Global Hawk, file an IFR flight plan, and use a combination of ground radar, observers, or chase aircraft to ensure an "equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft" [2,3]. The Air Force has begun pursuing on-board sensors as see-and-avoid surrogates, commonly termed sense-and-avoid systems. Electro-optical, infrared, radar, and beacon-based systems such as TCAS, if shown to be safe, will improve operational efficiency by reducing some or all of the constraints on the flight of Global Hawk in civil airspace.

A complete analysis of collision risk requires considering many elements and complex interactions, including airframe and powerplant reliability, vehicle performance, Air Traffic Control (ATC) procedures, command and control latency, software, human interfaces, and, ultimately, the efficacy of last-minute collision avoidance systems and human visual acquisition. Of key interest here is the increment to

safety that may be achieved by equipping UAVs with on-board collision avoidance systems.

Collision Avoidance Concerns

The safety of a Collision Avoidance System (CAS) for UAVs needs to be evaluated with regard to several factors. First, it is important that the CAS be used in an appropriate manner. TCAS, for example, was designed under the assumption that a pilot was on-board the aircraft to interpret displays and perform visual acquisition. The TCAS traffic display is intended to aid visual acquisition by indicating the proper sector to search out the cockpit, but does not by itself provide sufficient bearing or altitude rate accuracy to support avoidance maneuvers. The role of a TCAS traffic display in a UAV ground control station is therefore under debate.

Second, sensor coverage and observability need to be considered. TCAS detects only transponder-equipped aircraft and so cannot serve as a complete see-and-avoid surrogate. At higher altitudes (above 10,000 ft in the U.S.), however, all aircraft are required to be transponder-equipped and so TCAS may serve an important role in improving safety in some phases of flight.

Third, the flight profile and characteristics of a UAV may vary significantly from a conventional aircraft, and so UAVs may be involved in different types of close encounters with other aircraft than has generally been the case to date. Maneuverability constraints may also affect the degree to which a UAV can comply with CAS maneuvering advisories.

Also, command and control delays may affect the outcome of a maneuver in response to a CAS. It is known that the performance of TCAS, for instance, is sensitive to the total delay between the display of a Resolution Advisory (RA) and the response of the pilot and aircraft to begin maneuvering. A sufficiently large delay can induce instability in the maneuvering solutions, resulting in reduced separation between aircraft. Also requiring study is the ability of a ground pilot to use a keyboard and mouse to control an aircraft as accurately and promptly as an on-board pilot using a yoke or sidestick. Fully-automating the response to a CAS may be possible, but needs to be studied carefully in terms of reliability and the means by which a ground pilot could intervene if necessary.

Finally, a CAS operates as one component of a larger, complex air traffic system. Other aircraft, pilots, air traffic controllers, and TCAS units may be detecting a traffic conflict, generating solutions, and performing maneuvers. A new UAV CAS will need to operate compatibly with these other systems to ensure that advisories are coordinated. Even if TCAS is not intended for use on a particular UAV, the interaction between the UAV's CAS, TCAS on an intruder aircraft, and ATC needs to be studied.

Accepted Safety Analysis Process

To meet the needs identified in the Introduction, Lincoln Laboratory has developed a process for making safety assessments of UAV CAS concepts. This process traces its roots to TCAS safety studies for conventional aircraft that have been performed over two decades by several organizations. The framework for TCAS analysis was first developed and applied by MITRE Corp. in the early 1980s [4,5]. Subsequent studies applying this framework were conducted by the FAA William J. Hughes Technical Center, Lincoln Laboratory, and Eurocontrol [6-9]. Over time, TCAS assessment evolved into a multi-step process that has been accepted by RTCA Special Committee 147 and ICAO SCRSP as a domestic and international standard for safety studies [10]. With important modifications, the same methodology is currently being applied by Lincoln Laboratory to study UAVs and new CAS concepts.

The accepted safety analysis process is based on a comprehensive, statistically-valid set of data describing CAS performance across a wide range of encounter situations. Specific problem situations also need to be identified and judged as to their criticality and likelihood. Extensive flight testing is required to support modeling communications latency and availability, sensor performance, automation, human interaction with CAS advisories, and flight characteristics. However, flight tests alone cannot provide enough data to make a complete system assessment. Thus, a combination of modeling based on flight experience and fast-time simulation of many encounters is needed.

The key performance metric is the reduction in collision risk achieved by equipping with a CAS. Prior studies have measured risk in terms of Near Mid-Air Collision (NMAC) events, defined to occur when separation between two aircraft is less than 100 ft apart vertically and 500 ft horizontally. The probability of Near Mid-Air Collision, P(NMAC), when the CAS is used is estimated and compared to P(NMAC) without the CAS over a wide range of potential encounter situations. The ratio of P(NMAC) with a CAS to P(NMAC) without a CAS is commonly referred to as the risk ratio. A risk ratio

less than one indicates a risk reduction; a risk ratio greater than one indicates an increase in risk.

It should also be noted that other issues may play a significant role in the acceptance of a CAS, including expected nuisance alarm rates or impact on air traffic management. The initial focus here, however, is on those elements that directly affect collision risk.

It is difficult to assess safety using a single model or approach. Instead, several tools must be brought to bear, each focusing on a different aspect of the overall system. In particular, the collision risk problem can be partitioned into two regimes: an outer-loop regime that encompasses system failures and events that lead up to a critical close encounter event, and an inner-loop regime that covers the details of what occurs second-by-second in a dynamic analysis of an encounter given the conditions that were defined in the outer-loop regime.

Two analytical tools have been used extensively in prior TCAS studies and are applicable to UAV CAS studies. A fault tree is used 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. For example, the probability that an encounter would occur in visual conditions can be estimated in the fault tree, and P(NMAC) for that type of encounter can be computed in a detailed fast-time simulation. Results are then combined in the fault tree with corresponding performance data and probabilities for other conditions including intruder aircraft equipage, system failures, etc., leading to a global estimate of system safety. Sensitivity studies can then be performed by modifying event probabilities in the fault tree and observing their impact on overall risk without requiring new fast-time simulations. More detail on the outer and inner loop regimes of analysis are provided in the following sections.

Outer Loop: Fault Tree Analysis

The outer-loop analysis is used to define what conditions apply, and how likely those conditions are, in a critical close encounter event. Outer-loop conditions include:

- Altitude of the close encounter
- Characteristics and criticality of the close encounter
- Environmental conditions
- Intruder aircraft equipage (e.g., transponder, TCAS, 100 ft or 25 ft altimeter encoding)
- CAS sensor or tracker failures (e.g., missing altitude report or loss of intruder track)
- System component failure (e.g., loss of the traffic display)
- Command and control system status (e.g., communication latency or drop-outs)
- Pilot response to CAS advisories (e.g., standard, fast, slow, or no response)
- Air Traffic Control involvement in resolving the close encounter

As an example, Figure 1 shows a representative fragment from fault trees used in prior studies of TCAS [4,11]. The portion of the fault tree shown in Figure 1 emphasizes the effect of visual conditions on NMAC risk. Other branches of the complete fault tree would address the other outer-loop issues listed above. As shown, an NMAC can occur when the systems in place (e.g., TCAS) fail to prevent or
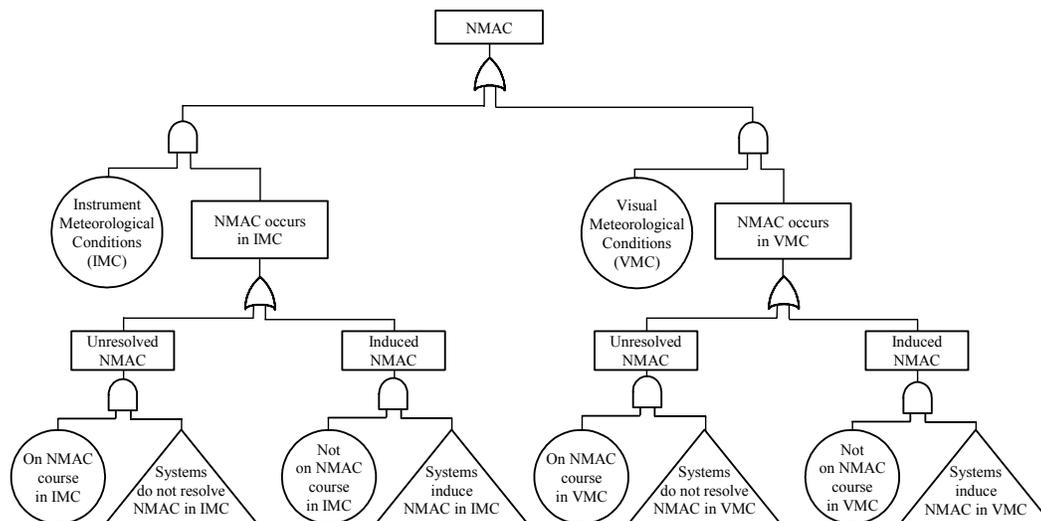

Figure 1. Example fault tree fragment

induce an NMAC, and the encounter will occur in either visual or instrument conditions.

The circular nodes in Figure 1 represent basic event probabilities (e.g., the likelihood that visual meteorological conditions are present during a close encounter). The triangles in Figure 1 represent probabilities that are computed from other sub-trees and inner-loop simulations. The probability that TCAS fails to resolve an NMAC situation, for example, is computed using millions of simulation runs over a given combination of intruder equipment types, environmental conditions, pilot responses, etc. The performance of TCAS in each combination of conditions is evaluated in a separate inner-loop simulation. The final probability of NMAC is then computed by using logical AND (multiplication) and OR (addition) operations on the underlying probabilities in the tree.

The main benefit of fault tree analysis is that it facilitates sensitivity studies. For example, the probability of instrument meteorological conditions can be changed and a new value of P(NMAC) computed without rerunning any simulations. Other studies could include changes in the intruder equipage mix, hardware reliability, or the consistency of pilot responses to RAs. Fault trees can become quite complex, however. The Eurocontrol TCAS fault tree covers 51 diagrams such as that in Figure 1, and includes 61 different event probabilities, such as the probability of visual acquisition, slow pilot response, or TCAS display failure [11].

One area of improvement being pursued as part of the Lincoln Laboratory effort is shifting visual acquisition elements out of the fault tree and into the inner-loop dynamic simulation. The Eurocontrol TCAS fault tree applies a single probability of visual acquisition regardless of the actual encounter geometry. We are injecting a validated visual acquisition model into the dynamic simulation that computes the probability of visual acquisition at each time step. The model takes into account environmental conditions, aircraft size, orientation, position within the cockpit field of view, number of pilots searching, and whether those pilots have been cued by TCAS or ATC with a traffic advisory. The new model will improve the fidelity with which visual acquisition is modeled while also simplifying the fault tree. More detail on the visual acquisition model is provided in a following section.

Other changes to the fault tree are necessary for UAVs. These include the addition of command and control system failure probabilities, the probability of faulty TCAS altitude information (which a UAV could only detect through the use of additional sensors), or autonomous-response system reliabilities.

Encounter Modeling

A key component of the outer-loop modeling effort is a valid model of the types of close encounters that may occur. Such a model is used to generate millions of representative traffic encounter situations for the inner-loop simulation. Three encounter models currently exist from prior TCAS safety studies: one based on 1980s-era U.S. airspace [4,5], an ICAO standard model representing a combination of U.S. and European airspace in the 1980s and 1990s [12], and one specific to European airspace in 2000 [13]. These models were derived from air traffic radar data so that the encounters have similar characteristics and frequencies as actual encounters occurring in the airspace.

Each encounter model specifies a number of parameters that are selected randomly in every fast-time simulation run. The most recent encounter model, developed by Eurocontrol to represent European airspace, includes 30 different randomly-selected parameters for each encounter situation [13]. Key variables include the horizontal and vertical miss distance, speeds, headings, and bearing at closest point of approach, plus maneuvers that may take place before the closest point of approach (e.g., a level-off maneuver or turn). The initial conditions needed to start the fast-time simulation (position, altitude, speed, heading, and vertical speed) are then derived from these parameters starting at the closest point of approach and working backwards using reverse-kinematics.

The general encounter modeling process is shown in Figure 2. The process begins by collecting thousands of hours of actual air traffic radar data. Close encounters between aircraft (where TCAS may become involved) are extracted from the radar data
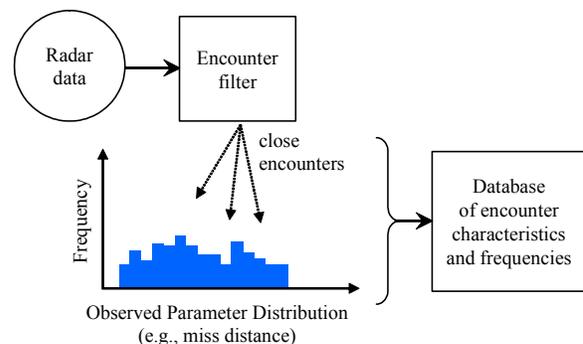

Figure 2. Encounter modeling process

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using a set of filters. The characteristics of each filtered close encounter are then used to build a statistical distribution describing the likelihoods of various parameter values. When generating encounter scenarios, a separate set of software randomly selects parameter values from these distributions, computes the initial conditions for the simulation, and stores the results in an input file.

RA Removal

Each encounter scenario is executed twice in the dynamic simulation: once without a CAS, and once with a CAS. These two runs, using identical initial conditions, facilitate making a direct estimate of the incremental safety provided by equipping with the CAS. A side-effect, however, is that it is necessary to remove any actual CAS effects from the radar data being used. Due to the significant proportion of aircraft currently equipped with TCAS, close encounters that are retained through the filtering process may involve maneuvers in response to TCAS RAs. Simulating such an encounter in a non-TCAS condition would result in a trajectory similar to that which occurs when running in a TCAS-equipped condition. The result would be little observed benefit to equipping with TCAS. Consequently, additional processing is required to remove the effects that TCAS may have had on encounters that are retained from radar data.

RA-removal processing involves interpolating the radar data to 1-second updates and then passing the tracks through TCAS logic to determine whether a TCAS RA may have occurred. If so, then the resulting trajectories are extrapolated using the current aircraft rates as if TCAS had not been in place. RA removal was not a significant concern in early encounter models due to the low level of TCAS equipage at the time, but it is now more of a consideration and is being addressed in the Lincoln Laboratory effort.

Extensions for UAVs

Existing encounter models represent situations that have been observed to occur between conventional air traffic. Due to differences in their flight profiles, UAVs may experience a different mix of encounter types than conventional aircraft. Global Hawk, for example, flies at a relatively low airspeed and high climb rate, resulting in a steeper climb profile than typically occurs with transport aircraft. It is also more likely that Global Hawk would be climbing or descending through the populated flight levels than cruising there. As a result, encounters with Global Hawk may involve a larger proportion of climbing or descending situations than is reflected in the existing encounter models. A larger proportion of climbing or descending situations impacts the effectiveness of a CAS in resolving these situations, ultimately impacting the risk ratio.

There currently are no radar data that include UAV close-encounter events. To compensate, Lincoln Laboratory has developed a process whereby existing encounter models are modified to account for UAV flight profiles through the use of Bayesian probability calculations. If the UAV is usually climbing or descending through air traffic, the result is a natural shift of probabilities toward climbing or descending cases. To balance the analysis, we will evaluate safety using both the existing and adjusted encounter models. Examining performance under each encounter model provides insight into the safety impact from unconventional UAV flight profiles.

Inner Loop: Dynamic Simulation

The inner-loop dynamic simulation takes the status of system components and the environment and computes P(NMAC) over a representative range of encounter situations. Because of the need to examine many different situations, it is necessary to run a fast-time Monte Carlo simulation. Four models are essential to this simulation:

1) The encounter model as described above. The characteristics of an encounter directly affect CAS performance – some encounters can be more easily resolved than others. Thus, it is important to have an accurate model of the types and frequencies of encounter situations so that risk ratios are realistic.

2) CAS sensor coverage, noise, and altimetry error. The capacity to directly measure certain states (e.g., range or horizontal position) affects the ability of a CAS to generate an accurate estimate of miss distance or time to impact. Sensor noise affects the quality of resolution advisory decisions. Altimetry error results in the actual vertical separation between aircraft varying from what the CAS logic computes.

3) CAS decision thresholds and logic. The sophistication of the algorithms and sensitivity of decision thresholds impacts the timing of advisories and the maneuvers that will be used to resolve a close encounter, ultimately affecting the achieved vertical and lateral separation.

4) Pilot and vehicle response. Once a CAS advisory has been generated, communication and control latencies, coupled with pilot response time (if a human pilot is in the loop) and vehicle control system latency and dynamics affect when and how the aircraft maneuvers to avoid a collision.

The above models are used to determine P(NMAC | situation), a metric that is conditional on the given encounter type, sensors, CAS logic, pilot, and vehicle response. Varying any one of these elements could change the computed value for P(NMAC | situation). When aggregated over many different encounter situations, the overall probability of NMAC is computed by weighting each situation by its likelihood:

$$P(NMAC) = \sum P(NMAC \,|\, situation) \; P(situation)$$

Analysis therefore requires a means of estimating P(situation) and P(NMAC | situation). The former is obtained from an accurate encounter model that describes the types and likelihoods of encounter situations, and the latter necessitates a simulation that is able to model sensors, CAS algorithms, pilot response, and vehicle dynamics. The main considerations of the simulation are discussed in more detail in the following section.

Fast-Time Simulation Model

Lincoln Laboratory recently designed and implemented (using Matlab / Simulink) a fast-time Monte Carlo simulation capability called the Collision Avoidance System Safety Assessment Tool (CASSATT). CASSATT takes encounter model data as an input and simulates aircraft motion over a period of approximately 60 seconds near the closest point of approach. Included in the simulation are options to use a CAS as well as variable pilot response models (e.g., standard, slow, or fast responses to CAS advisories). Aircraft motion is represented using point-mass dynamics with acceleration constraints related to aircraft type. Aircraft and CAS states are monitored throughout the simulation, with consideration of sensor errors. P(NMAC) is computed for each simulation run based on the measured vertical separation at closest point of approach and on an altimetry error probability density function. As discussed above, each encounter scenario is run twice, once with a CAS and once without, to allow for direct comparisons of performance.

The simulation includes several integrated sub-models, as shown in Figure 3. These sub-models include TCAS logic, a visual acquisition model, a pilot response model, and a vehicle dynamics model. A sensor noise model is also included as specified by ICAO standards [12]. A performance analysis module examines the aircraft trajectories to determine miss distances and to compute P(NMAC). The major sub-models are discussed in more detail below.

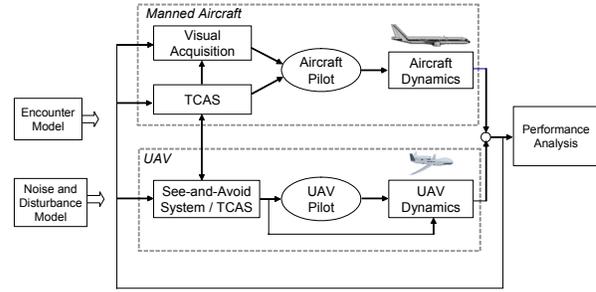**Figure 3. Simulation sub-models**

CAS Logic

The simulation includes flight-certified TCAS code obtained from a TCAS II vendor. The logic in the simulation is thus identical to that in actual aircraft, providing high fidelity and an ability to replicate the full range of logic behavior. Information from the TCAS logic is passed to the pilot response model (to respond to RAs), to the visual acquisition model (resulting in improved pilot search efficiency) and to the other aircraft's TCAS unit (if equipped) to handle maneuver coordination. The update cycle between each TCAS unit can be offset in time to examine its potential impact on maneuver coordination. In the case of an automated response to TCAS RAs, it is also possible to pass the TCAS outputs directly to the UAV dynamic model, with the addition of necessary delay or modifying elements.

Other CAS concepts for UAVs can be included in the simulation as well. To do so, the CAS sensors, algorithms, and pilot and/or vehicle response need to be modeled in a manner that is compatible with fast-time simulation. Fast-time simulation may be a challenge for some proposed CAS concepts that use video image processing, for example, because generating a simulated video image and running the processing algorithms may be computationally intensive. It may be necessary to develop approximate sensor models that can be used in fast time to estimate when traffic threats would be detected. These models could be based on flight test results that specify expected threat detection ranges, for instance, without running the actual image processing algorithms.

Pilot Response Model

The pilot response model normally follows a scripted set of maneuvers as specified by the encounter model. These maneuvers can include one segment of vertical and/or lateral acceleration such as a level-off or turn. If additional information from a CAS or the visual acquisition model becomes available to the pilot, the pilot model transitions to a new set of control behaviors as appropriate. For

example, if a TCAS RA is presented to the pilot, the ICAO standard pilot model will initiate a 5-second delay and then begin to pull-up or push-over the aircraft at 0.25 g until reaching the commanded vertical speed [12]. Other response models can be used to examine issues such as the latency introduced by remote communication and control.

Vehicle Dynamic Model

The vehicle model employs point-mass dynamics that are adequate to handle aircraft motion during the 60 second time window of a typical encounter. The pilot model provides commands of longitudinal acceleration, bank angle, and vertical acceleration (load factor). These three elements are integrated to determine velocities, position, and attitude at each time step. The simulation uses a time step of 0.1 s, compared to 1 s time steps used in prior simulation models. Constraints on aircraft performance (e.g., speed, vertical speed, or acceleration limits) can be modified based on the specific vehicle under study.

Visual Acquisition Model

The visual acquisition model uses a validated technique developed for accident investigations, safety analyses, and regulatory processes [14]. The model's basis is that visual acquisition is limited by target search time over a given volume of space. In the model, the probability of visually acquiring a threat during one time step is given by

$$\lambda = \beta \frac{A}{r^2}$$

where β is a constant, A is the visual area presented by the target, and r is the range to the target. In a collision-course situation, r decreases with time, so the acquisition probability increases smoothly until the point of closest approach. The value of A may change as an aircraft changes its aspect angle. The value of β depends on visibility, contrast, number of pilots searching, and whether those pilots have been cued by an ATC or TCAS traffic advisory. Values for β have been validated in flight experiments [14].

When injected into the simulation, the visual acquisition model estimates the probability of a pilot visually detecting another aircraft by a certain time. This information can be used to track which encounters might have been avoided by visual acquisition, or to dynamically modify pilot response.

The visual acquisition model is a significant increase in fidelity over prior TCAS studies. Unlike earlier studies, the new model handles changes in visual acquisition probability due to aircraft position, size, closure rate, and aspect angle.

Example Results

Figure 4 shows two example plots generated by the simulation for a situation with two aircraft in a head-on encounter. The vertical axis represents aircraft altitude. Time is shown along the bottom for each aircraft as it nears the closest point of approach at 40 s, denoted with a vertical dashed line. The dashed lines in Figure 4 show the planned vertical path of each aircraft based on the encounter model (without TCAS). As Figure 4 shows, one aircraft is climbing from left to right and intends to level off at approximately 4600 ft. At the same time, another aircraft is flying level at 4800 ft from right to left and
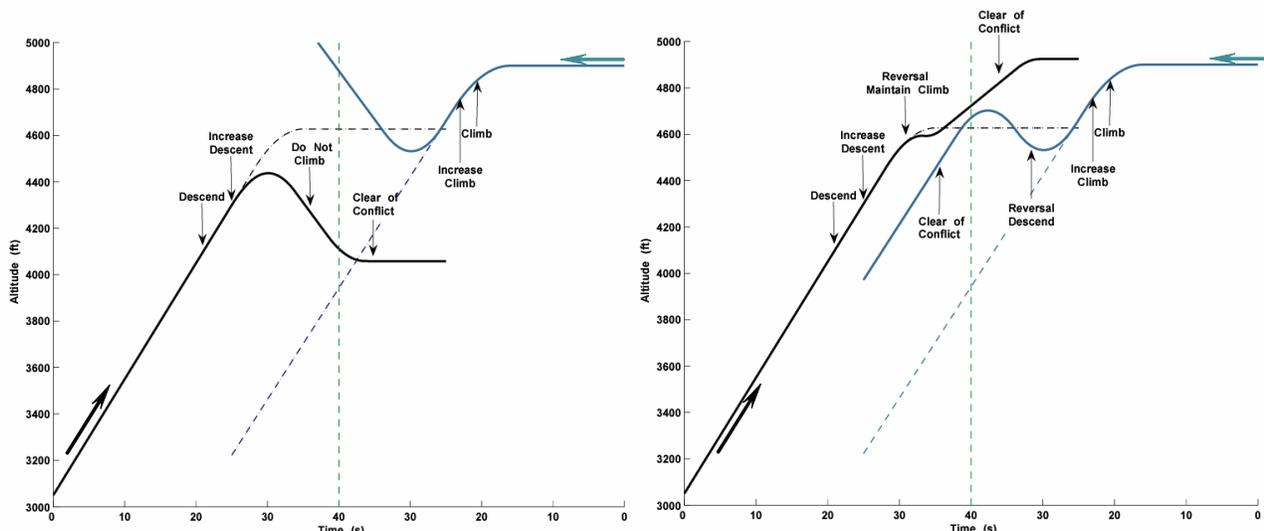
(a) 5 s RA response delay for both aircraft   **(b)** 10 s RA response delay for left aircraft
Dashed lines: planned trajectories from encounter model (without TCAS)   *Solid lines: trajectories with TCAS*
Figure 4. Example simulation trajectories

begins a descent approximately 18 seconds into the simulation. Without TCAS, the aircraft cross in position 40 s into the simulation with a vertical separation of approximately 700 ft, as shown by the dashed lines.

When simulated with TCAS operating on each aircraft, RA events occur as annotated on the trajectories for each aircraft. The resulting trajectories in response to the RAs are shown with solid lines. Figure 4(a) shows the situation when both aircraft have a 5 s delay in response to RAs (the ICAO standard). As shown, at approximately 21 s the left aircraft receives a descent advisory and the right aircraft receives a climb advisory. The result is an increase in vertical separation from approximately 700 ft to 780 ft.

As one example of how increased response latency might affect encounters, Figure 4(b) shows the same encounter scenario but where the aircraft on the left now has a 10 s RA response delay. The aircraft on the right still has a 5 s response delay. Note that the additional 5 s of delay on the left aircraft in Figure 4(b) changes the encounter from one in which TCAS increases separation to one in which TCAS decreases separation, from approximately 700 ft to 50 ft. The additional latency results in the situation becoming less stable, with TCAS reversing between descent and climb commands on both aircraft.

It should be noted that the scenario in Figure 4 was intentionally chosen to illustrate potential performance problems with increased response latency. This scenario is possible, but not likely to occur in actual operations. Using an encounter model, as described previously, to weigh each scenario by its likelihood would allow for an accurate estimate of overall performance.

CASSATT was also used to compute complete risk ratios for the existing European and ICAO encounter models for conventional aircraft. Figure 5 shows one example of how the estimates of P(NMAC) with TCAS and P(NMAC) without TCAS converge as the number of simulation iterations increases. As shown (for altitude layer 1 of the European encounter model) the estimates of P(NMAC) have largely converged after approximately 80,000 iterations. This type of analysis helps in determining the number of iterations needed for statistically-valid results. Recalling the earlier discussion, the risk ratio is then computed by taking the ratio of these two NMAC probabilities.

The aggregated risk ratios over all altitude layers are shown in Table 1 and compared against
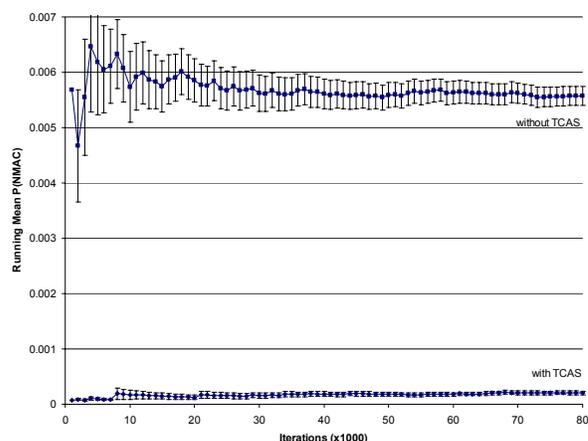

Figure 5. P(NMAC) estimates for European model
(Error bars = 1 standard error of the mean)

prior TCAS studies by MITRE Corp., Centre d'Études de la Navigation Aérienne (CENA), and Defense Evaluation and Research Agency (DERA, now QinetiQ). As shown, the values from the Lincoln Laboratory CASSATT simulation compare favorably with the prior studies using both the ICAO and European encounter models.

Table 1. Risk Ratio Comparison

Simulation	ICAO Model	European Model
MITRE [4]	2.8%	--
CENA [6,7]	1.1%	2.99%
DERA [6,7]	1.5%	3.68%
Lincoln Laboratory CASSATT	1.8%	3.60%

The risk ratios in Table 1 represent only one case specified in the outer-loop fault tree: where intruder aircraft are TCAS-equipped, have 100 ft altitude encoding, there are no system failures, visual acquisition is not considered, and pilots respond to TCAS with the ICAO standard response. Each other case would also need to be simulated, and then combined in the fault tree to obtain an overall system risk ratio. As one example, in the Eurocontrol TCAS study, when taking into account the expected frequencies of various intruder equipage, system failures, pilot response types, and visual acquisition, the risk ratio from the fault tree increased to 27.2%, underscoring the importance of these outer-loop factors as contributors to risk [12].

Future Efforts

We will use the CASSATT simulation model to evaluate TCAS performance on Global Hawk over a range of situations using several encounter models, including the standard ICAO model, European encounter model, and an updated U. S. model which will be developed in coordination with RTCA Special Committee 147. Lincoln Laboratory has begun collecting current radar data at its Lexington, MA site; wider data collection is anticipated in the near future. We will also adjust encounter models to take into account Global Hawk flight characteristics by modifying the distribution of airspeeds and vertical rates to better match the expected profile of the UAV.

The analysis will also vary the pilot response model to examine the effect of response latency on separation performance. A fully autonomous RA-response mode will also be examined. The logic performance from the simulation described here will then be injected into a larger system-level safety analysis based on a fault tree structure as in prior TCAS certification studies.

Additionally, it will be necessary to examine the potential for multiple-aircraft encounters and their effect on safety. Prior TCAS studies broke multiple-aircraft encounters into two components: the likelihood of a multiple-aircraft encounter, and a study of the criticality of those encounters. Further examination of the traffic environment is required to estimate how often three or more aircraft may be involved in the vicinity of TCAS RAs. Simulation of TCAS in multiple-aircraft situations is also needed to ensure that safe resolutions take place.

Finally, the overall safety evaluation process can be extended to other vehicles (e.g., Predator-B) or new CAS concepts (e.g., electro-optical sensors). New vehicles, sensors, or collision avoidance logic can be modeled in a similar way as has been done for Global Hawk, and injected into the same simulation framework for study.

Conclusion

In the near term, TCAS may provide a safety benefit for some UAVs, especially at higher altitudes where all aircraft are required to have transponders. New sense-and-avoid system concepts are also under development that have the potential to enable traffic avoidance against non-transponder-equipped aircraft. Extensive safety studies are required before these systems may be certified for UAVs. The certification process for UAV collision avoidance systems is expected to be rigorous. Early involvement toward developing appropriate models and analysis techniques for UAVs will reduce the time required to reach a certification decision.

Past experience with TCAS over more than two decades has led to an accepted standard for the type of modeling and analysis to achieve certification of a complex collision avoidance system. The FAA and ICAO have agreed that UAV concepts need to go through a similar process involving detailed airspace encounter modeling, dynamic simulation of collision avoidance system performance, and system failure and event sensitivity studies. Although flight tests and demonstrations are a necessary part of this effort, a comprehensive, statistically-valid simulation study is key to certification decisions.

Lincoln Laboratory is modifying prior methods used for TCAS analysis so that they can be applied to UAVs. In particular, existing airspace encounter models are being modified to reflect UAV flight profiles and performance characteristics. An updated U.S. encounter model is also required. The effort to develop a new U.S. encounter model has begun for Boston-area traffic, but requires a significant nation-wide data-collection effort to obtain and filter radar information. The new model will be used to generate representative parameter distributions for simulation.

Flight tests and human-in-the-loop simulation studies are also required to develop models to describe how UAV pilots (or an autonomous system) would respond to collision avoidance system advisories. Accurate modeling is important due to capture command and control reliability and latency and the effect of human interfaces that are not the same as those used in conventional cockpits. It is also important to develop models of new sense-and-avoid system concepts so that they can be studied in fast-time simulations.

The Lincoln Laboratory CASSATT simulation facility is now being applied to evaluate TCAS safety on Global Hawk. Some of the added functionality of CASSATT over prior simulations are a higher-resolution time step (0.1 s vs. 1.0 s), the ability to specify a phase lag between TCAS unit updates, an in-the-loop visual acquisition model, and a modular framework intended to facilitate study of new CAS concepts, pilot response models, and UAV dynamics.

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Keywords

Biography

James Kuchar focuses on collision avoidance systems and aviation safety with the Air Traffic Control Systems Group at MIT Lincoln Laboratory. He received S.B., S.M., and Ph.D. degrees in Aeronautics and Astronautics at MIT, where he also served on the faculty from 1995 to 2003.