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A Safety Analysis Process for the Traffic Alert and Collision Avoidance System (TCAS) and See-and-Avoid Systems on Remotely Piloted Vehicles

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The integration of Remotely Piloted Vehicles (RPVs) into civil airspace will require new methods of ensuring traffic avoidance. This paper discusses issues affecting requirements for RPV traffic avoidance systems and describes the safety evaluation process that the international community has deemed necessary to certify such systems. Alternative methods for RPVs to perform traffic avoidance are discussed, including the potential use of new see-and-avoid sensors or the Traffic Alert and Collision Avoidance System (TCAS). Concerns that must be addressed to allow the use of TCAS on RPVs are presented. The paper then details the safety evaluation process that is being implemented to evaluate the safety of TCAS on Global Hawk. The same evaluation process can be extended to other RPVs and traffic avoidance systems for which thorough safety analyses will also be required.

I. Introduction

THERE is increasing demand for the use of Remotely Piloted Vehicles (RPVs) in civil and military roles such as border patrol, sea lane monitoring, vehicle tracking, environmental observation, cargo delivery, and military surveillance. Many of these missions require RPVs to co-exist with civilian aircraft either during transit to and from an observation site or potentially throughout the entire mission.

The RQ-4A Global Hawk, for example, is slated to begin operating out of Beale Air Force Base in California in late 2004. Beale is not covered by restricted airspace and is surrounded by small uncontrolled airports. Global Hawk may encounter a variety of other aircraft (some of which may have no radios or other avionics) as it departs and arrives. Ensuring that Global Hawk and other RPVs can mix safely with civil air traffic is a significant concern. The Federal Aviation Administration (FAA) currently requires five days advance notification when the military desires to fly Global Hawk in the National Airspace System (NAS).[1] Additionally, assets such as chase aircraft or primary radar must be used to ensure separation from other air traffic. Ultimately, the Air Force's goal is to be able to file flight plans for an RPV and fly immediately with no significant delay or additional assets required. This is often referred to as "file and fly" access. To achieve this goal, new technologies must be developed and evaluated to ensure safe and robust operation.

To address traffic avoidance issues, it is useful to have a common framework for discussion and orientation. Figure 1 shows a generalized view of the traffic avoidance process. First, different types of traffic can be

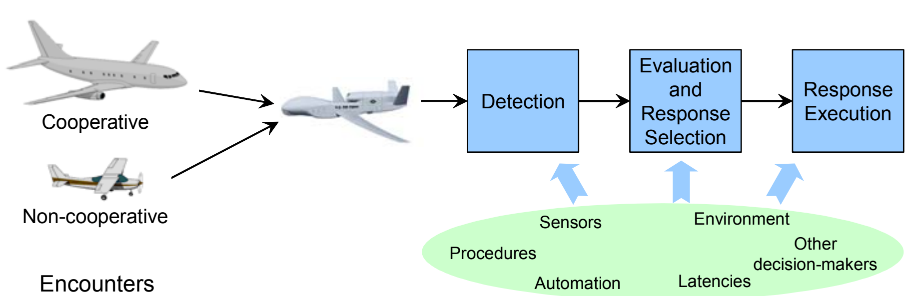

Figure 1: Traffic avoidance process

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encountered (left side of Fig. 1) depending on the type of airspace. Whether traffic is cooperative (carrying transponders) or uncooperative affects the types of sensors and procedures needed to ensure separation. Vehicle performance and mission profile also affect the types and geometries of encounters. Moving to the right in Fig. 1, any traffic conflicts must first be detected and then evaluated to determine the appropriate action, if any, to avoid a collision. Finally, the chosen response needs to be executed.

The process in Fig. 1 can be implemented in many ways depending on what airspace the aircraft is in and what type of traffic is encountered. For example, a pilot using visual see-and-avoid procedures must visually acquire traffic, judge whether the traffic is a threat, and then determine and execute an avoidance maneuver. Aircraft being positively separated by Air Traffic Control (ATC) have the detection and evaluation processes performed by the air traffic controller. The pilot then executes any conflict avoidance maneuvers received from ATC. A third example involves automation such as the Traffic Alert and Collision Avoidance System (TCAS). TCAS detects and evaluates cooperative traffic by interrogating transponders and may advise the pilot to climb or descend to avoid a collision. A completely automated maneuver response is also an option for RPVs, as has been demonstrated in joint U.S. Air Force and Swedish flight tests.[2]

There are many other factors that affect the efficacy of the traffic avoidance process, including what sensors or automation systems are available, what procedures are being used, latencies in communication or decision-making, and the environment (e.g., visibility). There are also multiple people and systems performing this separation process simultaneously. At the same time that the pilots on each aircraft may be attempting to visually acquire traffic, TCAS may be tracking the aircraft, and ATC may be monitoring the situation using radar. Any solutions to traffic conflicts need to be compatible with all of these decision-makers.

This paper begins by reviewing current requirements for traffic avoidance. The paper then describes the potential role of TCAS on RPVs and the issues that must be resolved before TCAS could be accepted in that role. A safety analysis process for TCAS on RPVs is then outlined based on prior accredited techniques used to certify TCAS on civil transport aircraft. This process is currently being applied by Lincoln Laboratory to study the safety of TCAS on Global Hawk. The paper closes with a summary of conclusions and recommends additional analyses required to certify RPVs.

A. Equivalent Level of Safety and See-and-Avoid Requirements

Safe flight in domestic and international airspace is ensured through a range of air traffic control services, some of which require aircraft to be equipped with specialized avionics such as an altitude-reporting transponder in certain types of airspace.[3] One consistent FAA requirement over all classes of airspace, however, is *"when weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft"*.[4] Even though mid-air collisions can occur when see-and-avoid separation is in effect, flight safety is generally perceived to be supported by a pilot present in the cockpit. A pilot communicates directly with ATC and conducts visual searches for nearby aircraft with his personal safety at stake. This concept of see and avoid in the NAS levies requirements on pilots and crews, but the requirements are general in nature and its effectiveness in providing separation is not quantified.

RPVs are not immune from the see-and-avoid requirement. FAA Directive 7610.4J states that such vehicles must provide an "*equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft*" to operate in the NAS.[5] To help RPVs compensate for the lack of an onboard pilot, a surrogate see-and-avoid system is needed.

To determine whether these surrogate systems provide an equivalent level of safety requires a thorough study of the complete traffic avoidance process in Fig. 1. It is not sufficient, for example, to only ensure that a new sensor provides better detection range than is possible with human vision. Rather, the complete system, composed of sensors, alerting threshold logic, collision avoidance logic, and methods for implementing collision avoidance maneuvers, must be evaluated in an end-to-end manner to determine how well it prevents mid-air collisions. The safety study described in this paper is based on defining performance in terms of the ultimate *outcomes* of traffic encounters (e.g., mid-air collisions or false alarm events).

B. See-and-Avoid Surrogates

Several types of safety enhancement systems have been proposed for RPVs to compensate for their lack of conventional see-and-avoid capabilities.[6-13] These can be divided into two general categories: those that protect against cooperative threats (aircraft with transponders) and those that protect against non-cooperative threats. Sensors for each type of threat are discussed in more detail in the following sections. A diagram of potential traffic information flow paths to the RPV operator is shown in Fig. 2. Information can be provided to the RPV operator via

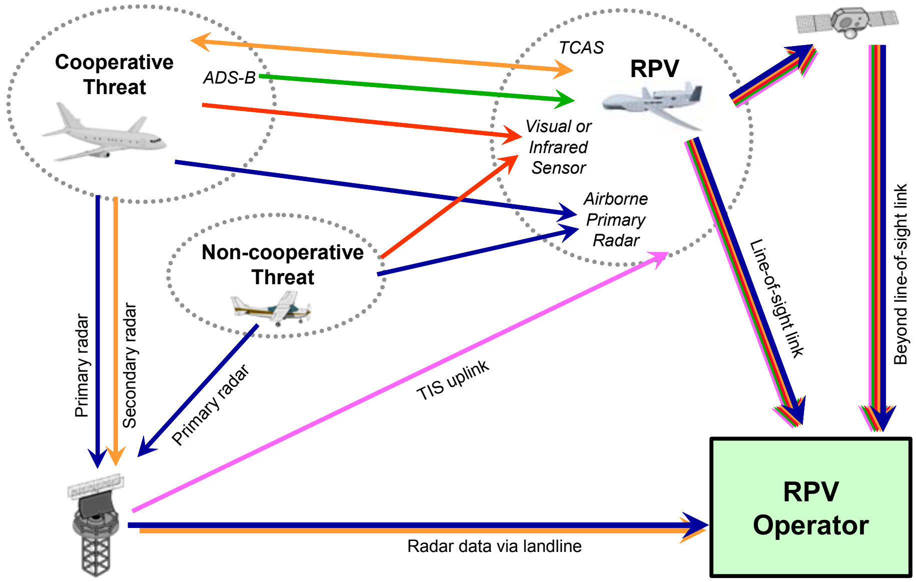


Figure 2: Traffic information flow

line-of-sight and satellite links with the RPV itself, or using terrestrial communication links from radar and air traffic control sites.

1. Cooperative Threats

With cooperative threats, the following sensor technologies are possible:

- Airborne transponder-interrogating systems
- Ground-based primary and Secondary Surveillance Radars (SSR)
- Automatic Dependent Surveillance – Broadcast (ADS-B)

Airborne transponder-interrogating systems provide air-to-air surveillance of other aircraft equipped with a transponder. Almost all aircraft have transponders but their use is not mandated in all airspace.[3,14] TCAS is a mature transponder-interrogating technology but it is not yet certified for use on RPVs. TCAS information could be used on-board the RPV or downlinked to the RPV operator. The potential use of TCAS on RPVs forms the core of the discussion in the remainder of this paper.

Alternatively, ground-based radars can provide surveillance information via a digital data-link. An example of this type of system is the Traffic Information Service (TIS), which is operational in the NAS.[15] TIS gives pilots a traffic display and traffic advisories for transponder-equipped threats within a 7 nautical mile radius. An aircraft can subscribe to TIS if it is equipped with a compatible Mode S transponder and is within 55 nautical miles of a terminal Mode S interrogator. As shown in Fig. 2, TIS information could be uplinked to the RPV and then downlinked to the RPV operator. Additionally, the FAA's proposed Surveillance Data Network will collect surveillance data from all FAA radars and will disseminate the data to users virtually anywhere with approximately a two second delay. These data could be provided directly to ground-based RPV pilots via terrestrial communication networks. RPVs that rely upon ground-based radars might avoid the expense, weight, and power requirements of air-to-air see-and-avoid equipment. However, the surveillance data would be available only when the RPV is within coverage of a radar providing the service.

Finally, ADS-B relies on aircraft self-reporting their position as determined by GPS or some other navigation system. Like TCAS, ADS-B information could be used on-board the RPV or sent to the RPV operator on the ground. Equipage levels for ADS-B are not expected to achieve useful levels for some time, so this is a consideration only for the future.

2. Non-cooperative Threats

For surveillance against non-cooperative (and cooperative) threats, the following alternatives can be considered:

- Airborne primary radar
- Airborne passive infrared
- Airborne passive visual
- Ground-based primary radar
- Chase aircraft

Airborne primary radar is attractive because it gives both bearing and range to non-cooperative and cooperative threats.[6] However, the antenna aperture requirements, power requirements, limited field-of-view, stealth requirements (possibly requiring shut-down in hostile areas), and limited ability to track large numbers of threats are significant challenges. If the antenna does not have sufficient vertical aperture, it may be unable to determine the relative altitude of threat aircraft.

Passive infrared and visual systems overcome the power and stealth issues. Resolution can be traded off for field of view using optics. Since the sensors can be quite small, field of view can also be increased by using multiple sensors. The number of threats that can be tracked is only limited by processing power. Range can only be determined using stereoscopic techniques and, given the likely aperture of an RPV-mounted system, such range estimates will probably be inaccurate unless the threat is very close. This could result in a high rate of false alarms in denser airspace. Questions also arise about the use of such systems in marginal meteorological conditions. These limitations may be acceptable if the RPV follows Instrument Flight Rules and allows ATC to maintain separation from other aircraft when in instrument meteorological conditions. Since the characteristics of primary radar and visual/infrared are somewhat complementary, combined installations may be of interest.[8] Similarly to TCAS and ADS-B, information collected from airborne sensors could be used on-board or downlinked to the ground operator.

Ground-based primary radars are able to track most non-cooperative aircraft. This surveillance information could also be circulated to RPV operators via landline channels. Alternatively, RPVs could rely on ATC service providers to use primary radar data to provide separation from non-cooperative threats. While possible, this option may not be acceptable because of the resulting increase in air traffic controller workload. In addition, a lack of height-finding capability would limit avoidance to the horizontal dimension, introduce position uncertainty, and result in increased numbers of false alarms.

Finally, the use of chase aircraft to detect potential traffic conflicts with an RPV is an option. However, the significant expense and logistics involved make this option unattractive and contrary to the desired "file and fly" goal.

Recalling Fig. 1, sensor technologies can provide the means to perform the detection function. New methods for evaluating a detected aircraft, determining an appropriate resolution maneuver, and for executing that maneuver will also need to be developed for RPVs. These new solutions may rely entirely on the human RPV operator, on some combination of human and automation, or they could be performed entirely autonomously. The best solution will depend on issues such as the quality of information available about threat aircraft and compatibility with existing separation methods.

A thorough discussion of technologies and issues for threat evaluation and response is beyond the scope of this paper. However, one technology in particular has been suggested as a potential safety enhancement: equipping RPVs with TCAS. Because TCAS is already on conventional aircraft and has been proposed for RPVs, its role is discussed in more detail in the next section.

II. Role of TCAS on RPVs

TCAS performs airborne surveillance of transponders in order to determine the range, altitude, and bearing of nearby aircraft. Two versions of TCAS exist, designated in the United States as TCAS I and TCAS II. Both versions provide the pilot with a traffic display and alerts called Traffic Advisories (TAs). In addition, TCAS II provides vertical maneuver commands known as Resolution Advisories (RAs). TCAS II coordinates RAs with other TCAS II aircraft using the Mode S data link. TCAS II provides an additional, independent means of performing detection, evaluation, and maneuver selection functions for cooperative aircraft that have not been avoided through the normal separation process.

A. TCAS History

TCAS development began in the early 1970s under FAA sponsorship.[16-18] The International Civil Aviation Organization (ICAO) began standardization activities when the FAA proceeded with domestic TCAS implementation. ICAO is the United Nations body charged with standardizing air traffic control systems worldwide so that aircraft encounter smooth transitions as they fly from country to country. Separate ICAO Panels and Working Groups have responsibility for individual components of the air traffic control system. Responsibility for airborne collision avoidance was charged originally to the SSR Improvements and Collision Avoidance Systems Panel (SICASP) and then transitioned into the current Surveillance and Conflict Resolution Systems Panel (SCRSP). These panels obtained worldwide consensus for requirements and evaluation methods that led to successful international certification of the Airborne Collision Avoidance System (ACAS), the international designation for TCAS. In particular, a multi-step process for assessing the level of safety provided by TCAS has been defined and accepted by

ICAO and serves as the standard for future safety studies. The panels' activities benefited from the participation of engineers, equipment manufacturers, airline representatives, pilots, air traffic controllers, and civil aviation authorities.

Given the maturity of evaluation techniques developed for TCAS and the large investment in certification, equipment, and aircraft installations, it is understandable that potential new uses of TCAS will be carefully evaluated by civil aviation authorities. Studies of the type already employed for TCAS certification will be needed if the RPV community is to obtain approval for TCAS on RPVs to safely fly on civil air routes. Many of the current TCAS models, evaluation tools, and analysis methods can also be used to analyze candidate TCAS modifications for RPVs.

B. TCAS-on-RPV Concerns

The use of TCAS on RPVs may enhance the safety of RPV operations. However, several concerns exist regarding compatibility of design and manner of use. First, the current surveillance, display, and algorithm designs of TCAS were developed and validated for aircraft with onboard pilots. ICAO panels (SICASP Working Group 2 and SCRSP Working Group A) have advised against using existing TCAS on RPVs, citing, in particular, interactions with other aircraft carrying ACAS.[19,20] Additionally, SCRSP Working Group A has stated that the ICAO mandate requiring TCAS on large piloted aircraft does not apply to RPVs.[21]

A second concern is that TCAS was never intended to replace see and avoid. Currently TCAS presumes the existence of normal separation processes, including air traffic control and see and avoid. TCAS Traffic Advisories are intended to enhance visual acquisition capabilities, not to allow maneuvers based on the advisories. Insofar as RPVs may wish to use TCAS in a fundamentally different manner, the appropriateness of the TCAS surveillance, display, and collision avoidance logic must be reconsidered.

It should also be noted that TCAS is designed to alert very shortly before a potential collision, when other systems appear to have failed to maintain separation. TCAS is not suitable for providing routine separation and should not be relied upon as a primary separation method.

1. TCAS Surveillance and Display Limitations

Because TCAS operates by interrogating air traffic control transponders, it cannot detect the non-transponder-equipped aircraft that RPVs might encounter in low-altitude airspace. In certain regions below 10,000 ft, aircraft can operate without a transponder and without controller communication.

In addition, there are limitations on the use of the TCAS traffic display by pilots. Although pilots routinely monitor their TCAS traffic displays when flying in high-density airspace and depend upon them to verify the operating integrity of their TCAS equipment, the displayed information by itself is not adequate to support avoidance maneuvers. TCAS antennas do not produce sufficiently accurate bearing measurements to allow safe horizontal avoidance maneuvers. Nor do the displays directly provide the range rate, altitude rate, and coordination information needed to allow safe vertical avoidance maneuvers.

TCAS Traffic Advisories do play a role in the visual acquisition part of the see-and-avoid process. Traffic Advisories help alert pilots to the presence of nearby aircraft so that they can narrow their visual scan to specific quadrants and increase the likelihood of spotting the threat. However, in the absence of direct visual contact or Resolution Advisories, pilots are not permitted to use TCAS traffic displays or Traffic Advisories to maneuver in response to threat aircraft.

2. Appropriateness of Existing TCAS II Resolution Advisory Logic for RPVs

The TCAS II Resolution Advisory (collision avoidance) logic was designed for civil air carrier aircraft. RPV encounters can differ from those of civil aircraft, and the existing TCAS design must not increase the probability of collision for an RPV. For example, the most difficult encounters for TCAS are those involving high vertical rates or accelerations. Vertical rate constraints for high-performance RPVs may be necessary to ensure TCAS effectiveness.

The TCAS design assumes an onboard pilot with specific pilot response times. Response times for a remote operator could differ both due to communication latency and to alternate control methods such as the use of a computer mouse rather than a control yoke. Remote control delays could decrease maneuver effectiveness and retard or negate TCAS-TCAS coordination. Lack of visual cues to check TCAS integrity or maneuver reasonableness could also increase collision risk.

Because of the above surveillance, display, and collision avoidance logic concerns, SICASP Working Group 2 and SCRSP Working Group A have recommended in the near term that RPVs be equipped with 25-ft altitude-reporting Mode S transponders and not be equipped with TCAS.[22] Mode S transponder equipage would allow ground controllers and TCAS-equipped aircraft to track the RPV with precision, and TCAS and other controlled aircraft could maneuver to avoid the RPV.

Ultimately, a safety benefit may be gained by equipping RPVs with TCAS II and programming them to immediately respond to TCAS Resolution Advisories. This would effectively automate the entire detect-evaluate-execute process shown in Fig. 1 for cooperative aircraft. Analysis of encounters between piloted aircraft has shown that delays in pilot responses to Resolution Advisories increase collision risk.[23] In European airspace scenarios, the end-to-end probability of collision, when averaged and weighted over all encounter geometries, is decreased by approximately a factor of three when the pilot of the TCAS aircraft always responds correctly to Resolution Advisories. This means that allowing an RPV to autonomously respond to TCAS Resolution Advisories might offset its lack of a direct pilot see-and-avoid capability in airspace where transponders are required.

C. TCAS Development Lessons for RPVs

The TCAS development history illustrates important points applicable to the certification of TCAS or other see-and-avoid systems for RPVs.

1. The Certification Process is Rigorous

Any system required for flight safety must undergo a rigorous international certification process. An accepted certification process was pursued during the three-decade-long worldwide TCAS/ACAS development. Cognizance of this process and preparation for engagement in it may save substantial time for an RPV system.

2. Flight Testing is Required

Extensive flight testing was required to provide data for safety analyses and to validate operational concepts. This began with prototype equipment, progressed to pre-production equipment not viewed by the pilot, to production equipment on revenue aircraft with pilots executing maneuvers, to current-day routine data collection on selected revenue aircraft. RPVs must undergo similar flight testing, including evaluation of ground control methods and pilot interfaces to determine the characteristics of TCAS RA responses.

3. Comprehensive Safety Analyses are Necessary

Safety analyses provided the basis for TCAS certification on civil aircraft. Analyses were performed first in the United States and later in other parts of the world. The evaluation techniques remained essentially unchanged, although airspace models varied with location, and these techniques are applicable to RPVs.

Early planning for flight tests and analysis as well as adherence to established international processes for safety studies and encounter simulations can help the RPV community expedite the approval process to file and fly in civil airspace.

D. Global Hawk TCAS Safety Study

In 2003, the U.S. Air Force asked Lincoln Laboratory to begin a comprehensive safety study of the use of TCAS II with Resolution Advisories on the Global Hawk RPV. Although TCAS is the initial focus, other see-and-avoid surrogate systems may need to be evaluated in the future. Regardless of the means that are developed to perform the traffic avoidance process shown in Fig. 1, a safety analysis is required for certification of RPVs in civil airspace. The recommended safety analysis is based on a 2002 ICAO paper that defined a Safety Analysis Plan for RPV flight in civil airspace.[24] This employs established procedures that were developed to certify the current TCAS design. The procedures apply to any RPV collision avoidance configuration considered for routine use in civil airspace, including an RPV equipped with an existing TCAS unit, an RPV equipped with a modified TCAS design, or an RPV equipped with other types of sensing, evaluation, or maneuver execution equipment to emulate the see-and-avoid capability. An overview of the safety analysis methodology is provided in the next section.

III. Safety Analysis Process

The success of a system such as TCAS depends on the complex interaction of many factors including normal ATC procedures for separating traffic, vehicle characteristics, human factors, and alerting system algorithm performance. It is therefore difficult to assess safety using a single model or approach. Instead, several different tools must be brought to bear, each focusing on a different aspect of the overall system. Two primary tools used in prior TCAS safety studies are fault trees and fast-time Monte Carlo simulations of traffic encounters.

A fault tree is a high-level logical diagram of the possible failure modes of a system. Each component in the system can be modeled with a certain level of reliability, and combinations of failures can be propagated through the tree to estimate overall risk. This tool is useful for examining design tradeoffs such as the benefits of using redundant sub-systems, but is unable to manage dynamic details such as the interaction between two aircraft as they maneuver in response to TCAS Resolution Advisories.

The interactions between aircraft dynamics, TCAS alerting logic, and human response are too complex to model and evaluate analytically. Instead, to fully assess the performance of the TCAS logic, it is necessary to perform millions of fast-time traffic encounter simulations with the TCAS logic running in the loop. A statistical estimate of logic performance can then be obtained by examining the frequencies of outcomes such as near mid-air collisions

(NMAC, defined as aircraft separation less than 100 ft vertically and less than 500 ft horizontally). To provide a reference point, TCAS performance is benchmarked by also running the simulation without TCAS using the same set of encounters.

Figure 3 shows the major components involved in safety analysis of TCAS or other traffic avoidance systems. This process is based on that used in prior certification studies for TCAS on civil transports, but has been extended where necessary to incorporate RPV-specific issues.[24]

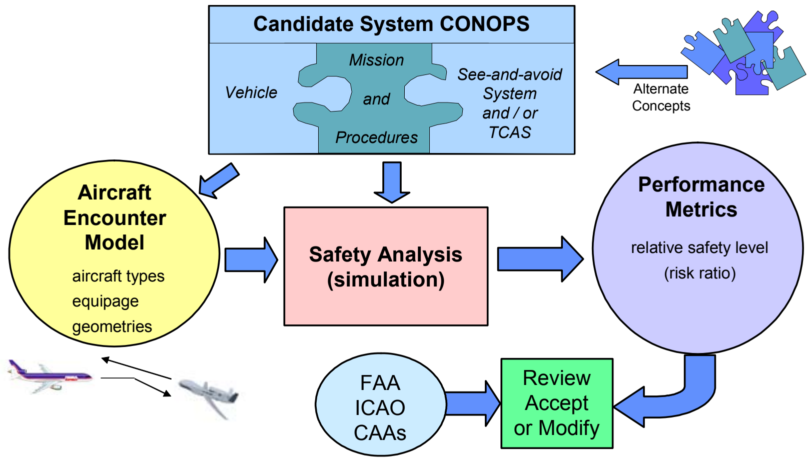


Figure 3: Safety analysis process

As shown in Fig. 3, the safety analysis process has five major components. First, at the top of Fig. 3, a concept of operations (CONOPS) of the candidate system must be developed. The CONOPS involves (1) defining and modeling the RPV to be studied, including parameters such as performance characteristics and control latencies, (2) defining the mission and procedures to be followed, which in turn drives the types of airspace that will be involved and traffic that may be encountered, and (3) defining the specific traffic avoidance system to be studied, such as TCAS with an autonomous or ground-pilot response. Each of these three components of the CONOPS could later be modified, in which case it may be necessary to re-evaluate system safety.

Once the CONOPS has been defined, an aircraft encounter model is developed. The encounter model is used to drive a fast-time simulation of air traffic encounters in which the performance of the TCAS logic can be examined in detail. Performance metrics from these simulations can then be reviewed by civil aviation authorities, and the CONOPS can be accepted or modifications can be proposed.

The techniques used in developing the encounter model and in running the simulation are discussed in the following sections of this paper.

A. Encounter Model

The encounter model is used to generate millions of traffic encounter situations that are later used in the fast-time encounter simulation. Three encounter models currently exist from prior TCAS safety studies: one based on 1980s-era U.S. airspace, an ICAO standard model representing a combination of U.S. and European airspace in the 1980s and 1990s, and one specific to European airspace in 2000. To build each encounter model, thousands of hours of actual air traffic radar data were collected. Close encounters between aircraft (where TCAS may become involved) were then extracted from the radar data and used to build a statistical model describing the encounter geometries.

Each encounter model specifies a number of parameters that are selected randomly in each fast-time simulation run. The result is a mix of many different types of encounter situations. Key variables include the horizontal and vertical miss distances, speeds, headings, and bearing at closest point of approach, maneuvers that may take place near the closest point of approach (e.g., a level-off maneuver or turn), the initial conditions needed to start the fast-time simulation (initial position, altitude, speed, heading, and vertical speed), and aircraft type and equipage (e.g., equipped with Mode C or Mode S transponder). Further, the encounter model applies weights to the random selection of parameters such that the frequency of a given encounter in actual operations is reflected accurately in the simulations. By running through the mix of encounter types, the intent is to exercise the TCAS logic against a set of situations that is representative of the actual air traffic environment.

The existing encounter models represent encounters that have been observed to occur between conventional air traffic. RPVs, however, due to differences in their flight profiles, 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 jet transports. As a result, encounters with Global Hawk may involve a larger proportion of high vertical rate situations than is reflected in the existing encounter models.

As part of the Global Hawk safety study at Lincoln Laboratory, we have developed a process for adjusting the existing encounter models to account for RPV flight profiles. Existing encounter models encode the unconditional probability of various types of encounters occurring. For example, there is some probability that an encounter will involve two climbing aircraft, and a different probability that an encounter will involve two level aircraft. These probabilities are based on radar observations of conventional traffic patterns. For RPV analysis, we can define one aircraft to be the RPV with a certain known flight profile. The encounter probabilities are then recomputed, but this time as conditional probabilities given the RPV profile. The result is a natural shift of probabilities toward climbing or descending cases, for example, if the RPV is usually climbing or descending through air traffic.

This method of adjustment is essential because actual RPV radar encounter data do not exist. The underlying assumption is that RPVs are treated by air traffic control in an identical manner to conventional aircraft. To balance the analysis, we will evaluate safety using both the existing and adjusted encounter models. Examining performance under each encounter model will also provide insight into the magnitude of the safety impact induced by unconventional RPV flight profiles.

B. Fast-Time Monte Carlo Simulation

The fast-time Monte Carlo simulation takes the encounter model 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 TCAS (or not) as well as variable pilot response models (e.g., standard, slow, or fast responses to Resolution Advisories). Aircraft motion is represented using point-mass dynamics with acceleration constraints related to aircraft type and pilot responses based on the encounter model. Relative aircraft position is monitored throughout the simulation, with the addition of altimetry and TCAS range-measurement errors according to ICAO standards. Whether an NMAC occurs in each simulation run is then determined and recorded. Each encounter scenario is run twice, once with TCAS and once without, to allow for direct comparisons of performance.

To support the Global Hawk TCAS safety study, Lincoln Laboratory has implemented a fast-time simulation using the Matlab / Simulink programming environment, with the major components as shown in Fig. 4. We are basing the simulation on methods used in prior TCAS analysis, but are extending prior capabilities to ensure that other types of traffic avoidance systems and RPVs can be evaluated within the same framework. Each aircraft in the simulation includes several integrated sub-models, as shown in Fig. 4. These sub-models include the TCAS logic, the visual acquisition model, the pilot response model, and the vehicle dynamics model. A measurement noise and disturbance model are also included as specified by ICAO standards. A performance analysis module examines the aircraft trajectories to determine miss distances and whether an NMAC has occurred. Due to the modular nature of the Simulink environment, future see-and-avoid systems or other vehicle dynamic models can be inserted as needed. Each of the major aircraft sub-models in the simulation is discussed in more detail below.

1. TCAS 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, thereby providing high fidelity and an ability to replicate the full range of

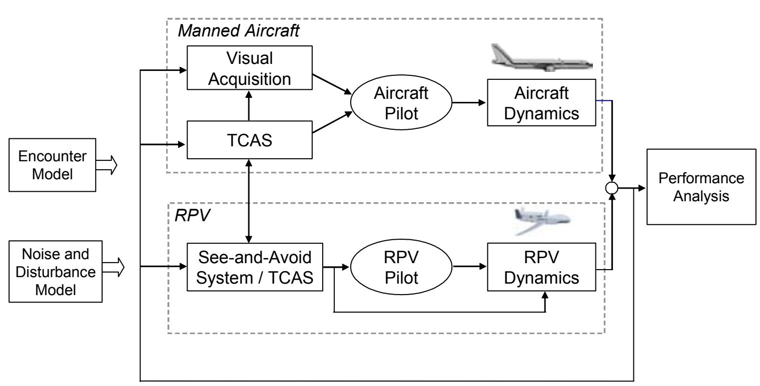


Figure 4: Simulation sub-models

logic behavior. Information from the TCAS logic is passed to the pilot response model (to respond to RAs), to the visual acquisition block (to model improved pilot search in response to a TA or RA) and to the other aircraft's TCAS unit (if equipped) to handle RA maneuver coordination.

2. Visual Acquisition Model

The visual acquisition model uses a validated technique developed for accident investigations, safety analyses, and regulatory processes.[25] The search process is such that the cumulative probability of visual acquisition by some time T before closest point of approach is

$$P[\text{acquire by } T] = 1 - \exp\left[-\int_{-\infty}^{T} \lambda(t)\,dt\right] \tag{1}$$

Flight experiments with subject pilots established the experimental result that λ is proportional to the solid angle subtended by the target aircraft, i.e.

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

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 situation, r decreases with time, so the acquisition rate increases smoothly until the point of closest approach.

Many different search scenarios can be modeled by properly defining $\lambda(t)$ and conditioning the integral in Eq. 1. Currently, the model is able to correct for effects such as target size, closing rate, atmospheric visibility, traffic alerts, and cockpit field of view. Flight tests conducted under FAA sponsorship have determined suitable values of β for unalerted search and for visual search with a TCAS Traffic Advisory.

The visual acquisition model has been implemented in a stand-alone analysis package and is currently being translated into a form compatible with the Monte Carlo simulation. When injected into the simulation, the visual acquisition model can accurately estimate the probability of a pilot visually detecting another aircraft. This information can then be used to modify the pilot's response, or just simply to note which NMACs occur that the pilot may have avoided due to prior visual acquisition. Use of the visual acquisition model provides a baseline for measuring equivalent level of safety as well as allowing interoperability issues to be studied.

This is a significant increase in fidelity over prior modeling of visual acquisition in TCAS safety studies. Earlier TCAS studies used a single, static probability to represent the potential for a pilot making visual acquisition of another aircraft. Unlike those earlier studies, the new simulation dynamically models changes in visual acquisition probability due to aircraft position, size, closure rate, and aspect.

3. Pilot Response Model

The pilot response model nominally follows a scripted set of maneuvers that has been specified in the encounter model. These scripted maneuvers can include one segment of vertical and/or lateral acceleration such as a level-off or turn. If additional information from TCAS or the visual acquisition model becomes available to the pilot, the pilot model then 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. Other pilot responses can be easily inserted into the model to examine issues such as the latency introduced by communication channels.

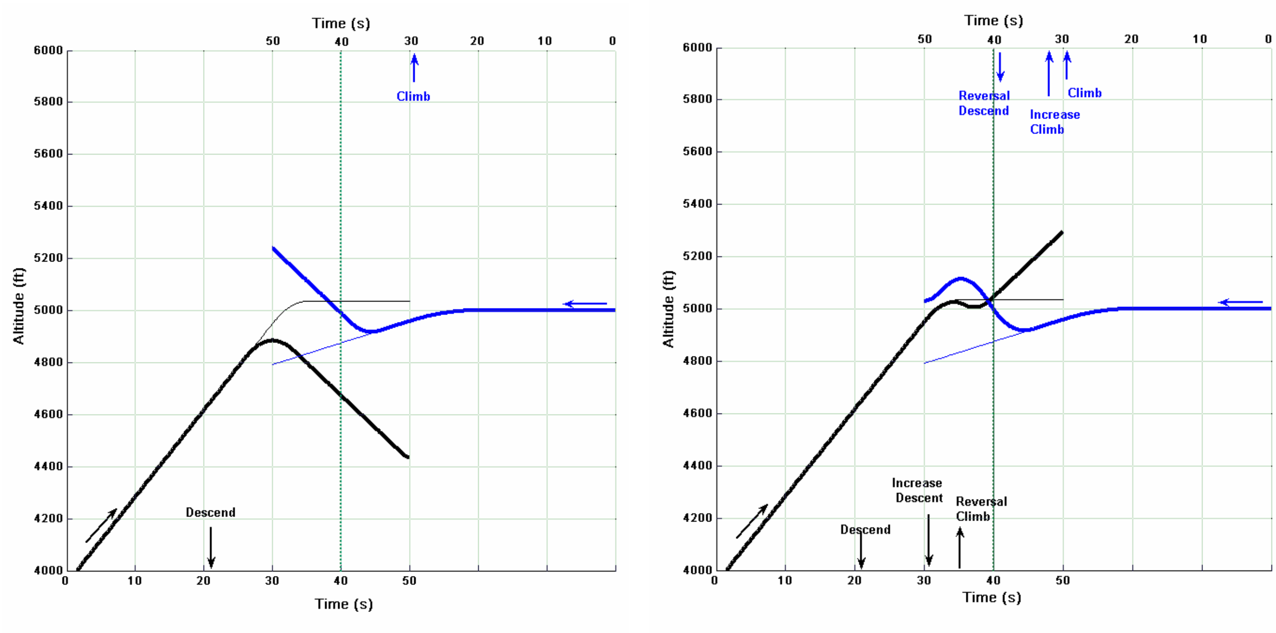
4. Vehicle Dynamic Model

The vehicle dynamic model employs point-mass dynamics. This has been found to be adequate to model the main aircraft motions during the 60 second time window of a typical encounter. Constraints on aircraft performance are included in the model (e.g., speed, vertical speed, and acceleration limits) and can be modified based on the specific vehicle under study.

C. Simulation Outputs

The simulation computes aircraft states (three-dimensional position, speed, vertical velocity, and heading), pilot actions (vertical acceleration, bank angle, and longitudinal acceleration), and pilot information (e.g., TCAS status, visual acquisition status). These data are updated and archived every 0.1 seconds in the simulation, providing sufficient resolution to examine the dynamics of an encounter in detail.

Figure 5 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, and time is shown along the bottom for the aircraft coming from the left and along the top for the aircraft coming from the right. The thin lines in Fig. 5 show the planned



(a) 5 s RA response delay for both aircraft **(b)** 10 s RA response delay for left aircraft

Thin lines: planned trajectories from encounter model (without TCAS)

Thick lines: trajectories with TCAS

Figure 5: Example Simulation Trajectories

vertical path of each aircraft based on the encounter model (without TCAS). As Fig. 5 shows, one aircraft is climbing from left to right and intends to level off at approximately 5000 ft. At the same time, another aircraft is flying level at 5000 ft from right to left and plans on beginning a descent approximately 25 seconds into the simulation. Without TCAS, the aircraft cross in position 40 s into the simulation with a vertical separation of approximately 160 ft.

When simulated with TCAS operating on each aircraft, RA events occur as annotated on the time axes for each aircraft. The resulting aircraft trajectories in response to the TCAS RAs are shown with thick lines. Figure 5(a) shows the situation when both aircraft have a 5 second delay in response to TCAS RAs. This is the standard response latency assumed in the design of the TCAS logic. As shown, the left aircraft receives a descend command from TCAS at approximately 21 seconds, followed shortly by the right aircraft receiving a climb command. The result is an increase in vertical separation from approximately 160 ft to 320 ft.

As one example of how increased response latency might affect encounters, Fig. 5(b) shows the same encounter scenario but where the aircraft on the left now has a 10 second RA response delay. The aircraft on the right still has a 5 second response delay. Note that the additional 5 seconds of delay on the left aircraft in Fig. 5(b) changes the encounter from one in which TCAS increases separation to one in which TCAS decreases separation, from approximately 160 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 Fig. 5 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 a complete and accurate estimate of overall performance.

D. Logic Risk Ratio Metric

Over a total of N simulated encounters, the number of NMAC events are recorded for two conditions: without TCAS, n_0, and with TCAS, n_1. The NMAC risk without TCAS and with TCAS over all scenarios can be estimated simply as

$$P_0 = \frac{n_0}{N} \qquad P_1 = \frac{n_1}{N} \tag{3}$$

P_0 describes how often NMACs occur across the entire encounter set if TCAS is not used, while P_1 is a similar metric describing how often NMACs occur if TCAS is used.

A "Logic Risk Ratio" can then be formed to represent the degree to which TCAS reduces mid-air collision risk:

$$\text{Logic Risk Ratio} = \frac{P_1}{P_0} = \frac{n_1}{n_0} \tag{4}$$

A risk ratio less than one implies that TCAS, overall, improves safety. As one example, a 2001 Eurocontrol study of TCAS obtained a Logic Risk Ratio of 0.090 for conventional aircraft where pilots responded appropriately to Resolution Advisories.[23] In other words, by equipping with TCAS and responding correctly, an aircraft reduces its risk to 9% of that which existed if it was not TCAS-equipped.

Equation 4 can be further broken down into two components to examine the degree to which TCAS is either unsuccessful in resolving an NMAC, or alternatively induces NMACs. This requires examining each simulation run in isolation to determine whether an NMAC that occurred with TCAS also occurred without TCAS. Separate counts of unresolved, n_{1u}, and induced, n_{1i}, NMACs are then recorded and used as shown in Eq. 5.

$$\text{Logic Risk Ratio} = \text{unresolved risk ratio} + \text{induced risk ratio} = \frac{n_{1u}}{n_0} + \frac{n_{1i}}{n_0} \tag{5}$$

The Eurocontrol study, for example, found that the previously-described risk ratio of 0.090 could be broken down into 0.053 for unresolved incidents and 0.037 for induced incidents. [23] These results suggest that TCAS is quite effective at resolving NMACs that would occur normally (reducing the risk to 0.053 of that which existed before), but that TCAS also induces NMACs in some scenarios that otherwise would not have had NMACs.

The pilot response model within the simulation can also be modified to examine the effect of different types of pilot response to RAs. For example the Eurocontrol study also ran simulations in which pilots responded slowly to RAs. In this case, the Logic Risk Ratio increased to a total of 0.633, of which 0.337 was the induced risk component. This result underscores the importance of following RAs promptly and correctly, and acts as an indicator that an autonomously-responding RPV that consistently and correctly responds to RAs may operate favorably, especially when compared to more variable human response times that have been observed in the field. Similarly, a ground-pilot response to an RA, with its increased latencies due to the communication link and control interface, may significantly reduce the effectiveness of TCAS. A quantitative understanding of these issues is the focus of the current efforts at Lincoln Laboratory to extend this type of safety analysis to TCAS on RPVs.

E. System-Level Analysis

The simulation discussed above focuses only on the performance of the TCAS logic assuming that all components are operating properly, although under the influence of range and altimetry measurement errors. Simulation results can also be used as inputs to a larger system-level analysis. The Eurocontrol study, for example, computed Logic Risk Ratios for several possible pilot response models and incorporated these into a fault tree. The fault tree described the probability that a pilot might react slowly, or rapidly, or not at all. The fault tree also incorporated the probability that TCAS would not operate properly, due for example to a faulty antenna or data link dropouts. The probability that a pilot would make visual acquisition of the other aircraft was also considered. Additionally, the fault tree considered the probability that a TCAS aircraft might encounter a non-transponder-equipped aircraft, in which case TCAS would be of no benefit. The result of combining the fast-time simulation data that characterizes Logic Risk Ratios with a larger system model is a more comprehensive safety estimate, termed the System Risk Ratio.

To provide perspective, the same 2001 Eurocontrol study[23] estimated a System Risk Ratio of 0.272. That is, considering variations in pilot response times, non-compliance, and sub-system failures, the ideal Logic Risk Ratio of 0.090 increased to a System Risk Ratio of 0.272. This highlights the need to consider the entire system when estimating safety, as the difference between ideal conditions and conditions in which failures may occur can be significant.

The combination of a Monte Carlo simulation to determine Logic Risk Ratios and a fault tree to determine System Risk Ratios will be necessary to provide input to certification decisions. We are currently redesigning the fault tree used in prior TCAS safety studies to adapt it to the current study of TCAS on Global Hawk. Major changes to the fault tree involve the transfer of visual acquisition modeling from the fault tree into the dynamic simulation and introduction of models for communication links and systems for potential autonomous RA response. As discussed earlier, the visual acquisition model transition will enable a higher-fidelity estimate of the impact of visual acquisition on safety due to the ability to now dynamically update acquisition probabilities based on the actual situation being simulated. Introducing models of the other Global Hawk systems is necessary to ensure that the reliability of RPV components in considered.

F. Future Efforts

We will first use the simulation model to evaluate TCAS performance on Global Hawk over a range of situations using several encounter models, including the standard ICAO model, Eurocontrol model, and an updated U.S. model which will be developed in coordination with RTCA Special Committee SC-147. We will also adjust these encounter models to take into account Global Hawk flight characteristics, primarily by adjusting the distribution of vertical rates to better match the expected vertical profile of the RPV as discussed earlier.

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 this into two components: the likelihood of a multiple-aircraft encounter, and a study of the criticality of those encounters. This requires further examination of the traffic environment to estimate how often three or more aircraft may be involved in the vicinity of TCAS RAs, and dynamic simulation of TCAS operating in multiple-aircraft situations 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 see-and-avoid systems (e.g., infrared or radar 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.

IV. Summary

This paper outlined the major issues involved in enabling and evaluating conventional file-and-fly access for RPVs into civil airspace. To be accepted, one must demonstrate that an RPV meets or exceeds the safety levels of conventional aircraft, which in turn requires examining in detail how traffic avoidance systems operate dynamically in preventing mid-air collisions. The type of vehicle and its mission profile place varying requirements on what must be demonstrated in safety analyses and what equipment is required on the RPV.

TCAS may provide an additional safety benefit, but it was not designed to be a sole means for see and avoid. Currently TCAS presumes the existence of conventional separation processes, including air traffic control and visual separation. Also, the current surveillance, display, and algorithm designs of TCAS were developed and validated for aircraft with onboard pilots. Of special concern are at least four issues:

1) TCAS can detect only transponder-equipped aircraft.

2) Maneuvering is not permitted on the basis of the TCAS traffic display or Traffic Advisories because of limited bearing accuracy and vertical rate information.

3) Latencies in reacting to Resolution Advisories due to remote control may result in maneuvers that induce collisions.

4) It may be difficult for an RPV pilot to detect anomalous situations such as altitude encoding errors or incompatibly maneuvering intruders.

However, a reliable, consistent autonomous response to Resolution Advisories by an RPV may significantly improve safety relative to current pilot behavior. Further study into the performance of TCAS on RPVs is needed to resolve the concerns noted above and to validate autonomous response to Resolution Advisories.

Regardless of the means that are proposed for separating RPVs from other air traffic, it is imperative that thorough safety studies be performed. International and domestic certification authorities require that these safety studies include consideration of the types and likelihoods of traffic encounters that may occur and that millions of different encounters be simulated in detail.

We are adapting a validated safety analysis methodology, used to certify TCAS on conventional aircraft, to study TCAS on Global Hawk. Our analysis will provide data on the safety of operating with TCAS relative to not using TCAS, which in turn will inform certification authorities about the potential value of adding such equipage to Global Hawk. In the future, the same methodology can be extended to other RPVs and see-and-avoid surrogate traffic avoidance systems.

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