REMOTELY PILOTED VEHICLES IN CIVIL AIRSPACE: REQUIREMENTS AND ANALYSIS METHODS FOR THE TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM (TCAS) AND SEE-AND-AVOID SYSTEMS

A. C. Drumm, J. W. Andrews, T. D. Hall, V. M. Heinz, J. K. Kuchar, S. D. Thompson, J. D. Welch
MIT Lincoln Laboratory, Lexington, MA

Abstract

The integration of Remotely Piloted Vehicles (RPVs) into civil airspace will require new methods of ensuring aircraft separation. This paper discusses issues affecting requirements for RPV traffic avoidance systems and for performing the safety evaluations that will be necessary to certify such systems. The paper outlines current ways in which traffic avoidance is assured depending on the type of airspace and type of traffic that is encountered. 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). Finally, the paper outlines an established safety evaluation process that can be adapted to assure regulatory authorities that RPVs meet level of safety requirements.

Introduction

Background

The military will make increasing use of Remotely Piloted Vehicles (RPVs), some of which have proven highly effective in recent wartime roles. Small RPVs, deployed in-theatre with limited range and altitude capabilities, normally do not pose a threat to civilian aircraft. Larger RPVs, such as Predator and Global Hawk, must co-exist with civilian aircraft as they execute their missions. For example, these aircraft fly through civil airspace while going to and from battle areas, and may be used in homeland defense roles such as monitoring shipping lanes and borders.

Problem

The Federal Aviation Administration (FAA) currently requires advance notification when the military desires to fly RPVs in the National Airspace System (NAS). Global Hawk flights require five business days notice [1]. The goal is to make it possible for the FAA and international civil aviation authorities to allow RPV operations to file flight plans and fly immediately, as is done with conventional aircraft. The key issue is to ensure safe separation of RPVs from conventional air traffic.

Approach

This paper provides an overview of traffic avoidance issues related to RPVs. To provide some orientation, Figure 1 shows a generalized view of the traffic avoidance process. First, different types of traffic can be encountered (left side of Figure 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 likewise affect the types and geometries of encounters. Moving to the right in Figure 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.

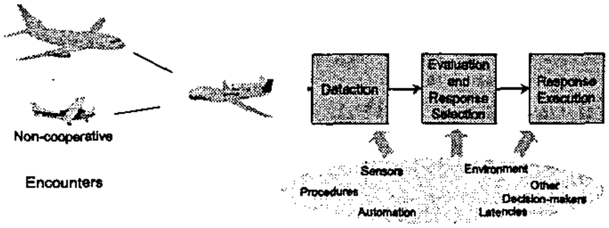

Figure 1. Traffic Avoidance Process.

The process in Figure 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

0-7803-8539-X/04/$20.00 © 2004 IEEE

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 using radar and transponder data 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 the traffic avoidance 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 the current role of see and avoid in the NAS, and how this role and the traffic that may be encountered vary across different classes of airspace. Next, it focuses on the detection function in Figure 1 and describes a quantitative approach for modeling the crucial visual acquisition phase of see and avoid. This approach evolved during TCAS development and benefited from years of national and international review. The paper then discusses other surveillance technologies that might be used by RPVs to perform the traffic avoidance process in Figure 1 when encountering cooperative and non-cooperative traffic.

The next section describes the role of TCAS and examines the certification process that led to its international acceptance. This process involved detailed safety studies and encounter simulations that may be adapted for the RPV community in seeking approval for file-and-fly capability on civil air routes. The paper closes with a summary of conclusions and recommends analyses required to certify RPVs in different types of airspace.

The Role of See and Avoid in the National Airspace System

See and Avoid Requirements

The concept of see and avoid in the National Airspace System levies requirements on pilots and crews, but the requirements are general in nature and its effectiveness in providing separation is not quantified. Specifically the Federal Aviation Regulations (14 CFR Part 91.113 b) state:

> *"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. When a rule of this section gives another aircraft right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear"*

This see-and-avoid requirement applies to all airspace, but the exact role of see and avoid in providing separation from other aircraft depends on the class of airspace in which an aircraft operates. Additionally, the type of airspace an RPV is in will affect what types of traffic may be encountered, as represented on the left in Figure 1.

Airspace Classification

The FAA categorizes airspace into classes according to the International Civil Aviation Organization (ICAO) standards as shown in Figure 2. Classes A through E are "controlled airspace" within which air traffic control service is provided according to the airspace classification and within which all aircraft operators are subject to pilot qualifications, operating rules, and equipment requirements.

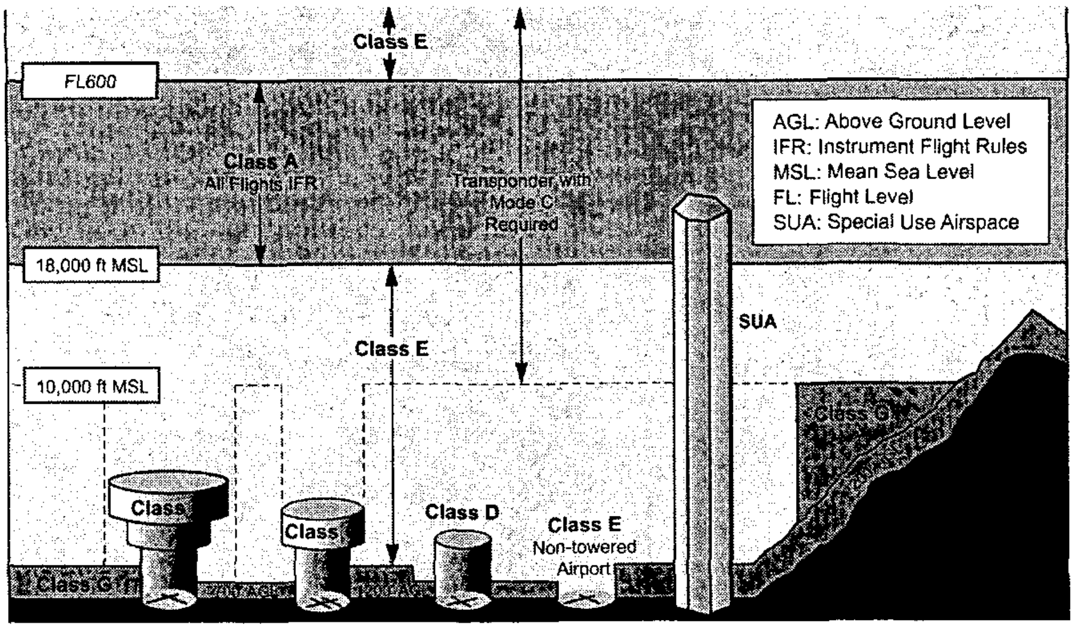

Figure 2. U.S. Airspace Classifications.

The airspace from 18,000 feet mean sea level (MSL) to Flight Level (FL) 600 (60,000 feet) is Class A airspace. Below 18,000 feet, altitude is expressed as feet above mean sea level to ensure terrain clearance, and the aircraft's altimeter is set to the local altimeter setting. At or above 18,000 feet, all aircraft set their barometric altimeter to a datum of 29.92 inches of mercury and the altitude is expressed in terms of flight levels, FL390 representing 39,000 feet, for example.

Class B airspace surrounds the largest and busiest major airports. The Class B airspace extends from the airport's surface in a tiered "upside-down wedding cake" fashion to a height of between 7,000 and 12,000 feet MSL with an upper tier radius of approximately 30 nautical miles. Class B airspace is individually tailored to the airport(s) being served and the local terrain. There are 30 sites with Class B airspace in the United States, some expanded to serve more than one major airport.

Class C airspace surrounds airports that have operational towers and radar approach control, but are not as busy as the primary airports under Class B airspace. Class C is also individually tailored, but usually consists of an inner cylinder of airspace with a 5-nautical mile radius extending from the surface to 4,000 feet above the airport elevation surrounded by an outer cylinder with a 10-nautical mile radius that extends from 1,200 feet above the airport elevation to 4,000 feet above the airport elevation.

Other airports with control towers are surrounded by Class D airspace when the towers are operational. Class D airspace extends from the surface to 2,500 feet above the airport elevation. The airspace is generally a cylinder with a 5 statute mile radius, but is tailored to contain airspace needed for instrument approach procedures.

Generally, if the airspace is not Class A, B, C, or D and is controlled airspace, it is Class E airspace. Class E airspace extends upward from either the surface or a designated altitude to the overlying controlled airspace. When not extending upward from the surface, Class E is generally designated to begin at either 700 feet above the surface or 1,200 feet above the surface.

Class G, uncontrolled airspace, lies under Class E airspace, generally extending from the surface to 700 or 1,200 feet above ground level. In some cases Class G airspace can extend to higher altitudes. Class F is an ICAO class not used in the U.S.

Special Use Airspace (SUA) includes Prohibited Areas, Restricted Areas, Warning Areas, and Military Operations Areas which impose various limitations on operations of civil aircraft. Military operations are routinely conducted in Restricted Areas to avoid conflicts with civilian traffic. RPV operations in Restricted Areas do not need to meet FAA safety criteria for see and avoid.

Aircraft operating in Class A airspace, in or above Class B or C airspace, within 30 nmi of a major airport, and in Class E airspace above 10,000 feet are required to have altitude-reporting transponders.

Only aircraft operating under Instrument Flight Rules (IFR) are allowed in Class A airspace, and ATC provides positive separation for all aircraft there. In Class A airspace, all aircraft have altitude-reporting transponders so ATC can track them with secondary radar, and all aircraft follow flight plans with known routings. Most aircraft are equipped with TCAS for additional collision avoidance protection, and the controller has automation tools to aid in conflict prediction. A see-and-avoid capability is seldom needed in Class A airspace and, because of the high speeds typically found at these altitudes, the effectiveness of see and avoid is minimal.

Of controlled airspace, Class E imposes the fewest requirements on aircraft equipage. In Class E, ATC provides positive separation only between IFR aircraft. Aircraft are allowed to operate under Visual Flight Rules (VFR) in Visual Meteorological Conditions (VMC). Aircraft are not required to have a transponder below 10,000 feet in Class E airspace (except within 30 miles of a Class B airspace primary airport or over Class B or C airspace). VFR aircraft are also not required to be in contact with ATC. Unpowered aircraft, such as gliders or balloons, may also operate in this airspace.

Notice from Figure 2 that in all instances, unless restricting operations to special use airspace, it is necessary to fly in Class E airspace in order to enter Class A airspace. Therefore it is important to examine the role of see and avoid in Class E airspace.

Aircraft in Class E Airspace

Table 1 lists the classes of potential collision threats that an RPV, operating under Instrument Flight Rules, can encounter in Class E airspace. In addition, the table lists services that ATC provides to aircraft on instrument flight plans to separate them from threats, and it summarizes the role of see and avoid against each threat class.

Federal Aviation Regulations assign the RPV responsibility for see and avoid in visual meteorological conditions while on an IFR flight plan. This imposes requirements for visual acquisition of both threats pointed out by ATC and threats not pointed out by ATC.

Table 1. Potential Threats in Class E Airspace and the Role of See and Avoid.

Potential Threats	ATC Separation Service for RPV	See-and-Avoid Responsibility of RPV (in VMC)
Other IFR traffic	• Positive separation	• Only if visual separation requested by ATC and accepted by pilot
VFR traffic under "flight following" with discrete transponder code	• Traffic advisories including altitude and intent • Vectors to avoid (coordinated) upon request • Advisories to VFR aircraft workload permitting	• Required • Visual acquisition assistance from ATC
VFR with 1200 transponder code	• Traffic advisories (altitude unconfirmed or no altitude) • Vectors to avoid (uncoordinated) upon request	• Required • Visual acquisition assistance from ATC
VFR with no transponder (below 10,000 feet)	• Traffic advisories only if controller can track primary radar returns	• Required • Visual acquisition assistance unlikely

IFR traffic and VFR traffic for which ATC is providing traffic advisories (sometimes referred to as "flight following") are in communication with ATC and on known flight paths with confirmed altitude information. Both the RPV operator and other IFR aircraft will receive traffic advisories from ATC. ATC will provide advisories to VFR aircraft to the extent possible depending on workload.

VFR traffic with a transponder code of 1200 may or may not be in contact with ATC. If the VFR traffic is not in contact, ATC cannot give it traffic advisories, but the RPV operator will receive traffic advisories and may request vectors from ATC to avoid potential collisions with all transponder-equipped threats.

The most challenging requirements for RPV see and avoid in Class E airspace occur below 10,000 feet, where VFR traffic is permitted to fly without transponders. The frequency of such encounters is unknown and will depend on the region. It is possible that such traffic will not have a primary radar track. In this case, traffic advisories will not be available for such threats, and the RPV operator must rely solely on see-and-avoid procedures to avoid collisions.

Additional ATC Uses of Visual Separation in the NAS

The air traffic control system obtains significant operational benefits when controllers shift primary separation responsibility to pilots flying in VMC. Pilot acceptance of visual separation procedures eliminates radar separation requirements and reduces controller workload, thereby increasing airspace capacity. An inability of RPVs to accept the responsibility for visual separation could eventually have a negative impact on ATC capacity. However, the number of RPVs in high density airspace will initially be small, so that their effect on capacity is not an immediate concern.

Other ATC Considerations of Human in the Cockpit

A remote aircraft operator can impact ATC in other important ways. Current propagation delay in ground-air-ground voice communications is typically less than a millisecond, which is imperceptible to pilots and controllers.

Remote operators must at times communicate with RPVs via satellite relay links. Satellite communication may increase the latency of the voice link between the controller and the remote aircraft operator to a second or more. This could disrupt already overloaded air traffic control communications by increasing the probability of premature transmissions between remote operators and controllers. Communication latency makes it difficult for a remote operator to correctly gauge when to talk. If, for example, the remote operator begins to transmit after the controller has begun to speak, the controller may need to repeat a compromised clearance, thereby significantly increasing the occupancy of the voice channel. This problem could require that RPVs communicate with ATC via a separate dedicated link when flying in dense airspace.

Pilots in the cockpit hear all other controller messages broadcast on the common voice channel. This "party line" effect, which increases the situational awareness of all flight crews, is particularly valuable when remote operators control aircraft in civil airspace. The importance of other pilots knowing the position and intent of the RPV reinforces the need to minimize communication latency for RPVs flying in dense airspace.

Another advantage of humans in the cockpit is that pilots are able to associate traffic displayed on the TCAS traffic advisory display, or on other cockpit displays of traffic information, with traffic acquired visually. Visual cues provide indications of aircraft type and performance as well as aircraft attitude, which serve as early indications of maneuver intent.

See and Avoid Modeling

See and Avoid in the NAS Today

Although ATC technology has evolved considerably during the last 100 years of flight, see and avoid (where the onboard pilot performs the traffic avoidance process in Figure 1) is still regarded as an essential component of flight safety. FAA Directive 7610.4J states that unmanned air vehicles (UAVs) must provide an "*equivalent level* *of safety, comparable to see-and-avoid requirements for manned aircraft*" to operate in the national airspace system. Even though mid-air collisions 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. To help RPVs compensate for the lack of an onboard pilot, a surrogate see-and-avoid system is needed.

Comparative safety analyses of encounters between RPVs and conventional aircraft should include a quantitative estimation of the contributions of see and avoid to the safety of flight in conventional aircraft. This can be accomplished by using computer models that take into account the many variables that impact see-and-avoid performance. Such models may also be modified to handle certain RPV safety systems that emulate see and avoid.

As was shown in Figure 1, the see-and-avoid process involves several successive phases: visual acquisition (detection), threat evaluation, maneuver selection, and maneuver execution. Accident investigations have shown that failure to visually acquire is the most common reason for the failure of see and avoid, hence modeling visual acquisition is important. However, accidents have occurred despite visual acquisition, and a complete safety model must allow for this possibility.

Visual Acquisition Model

A well documented model for air-to-air visual acquisition performance was developed at MIT Lincoln Laboratory to support validation of TCAS [3]. This model has been applied to accident investigations, safety analyses, and regulatory processes. The following paragraphs will describe the features of this model that are relevant to RPV safety assessments.

In the MIT model, the search process is characterized by an instantaneous acquisition rate, λ, defined as the probability of visual acquisition per instant of time. If λ were constant, visual acquisition would then be modeled as a classic Poisson process. But because visual conditions are not constant (e.g., the apparent size of the approaching aircraft is increasing), we must make λ a function of time. This produces a *non-homogeneous Poisson process*. The cumulative probability of visual acquisition by some time T can then be written

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

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

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

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 is decreasing 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 equation 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.

Visual Acquisition Performance

Because the visual acquisition model has been calibrated to reproduce the results of flight tests, it provides important insights into how well see and avoid can be expected to perform under real-world conditions. A significant conclusion is that in situations involving high closing rates and no traffic advisories, the probability of timely visual acquisition can be fairly low. Figure 3 provides an example for a scenario based upon a collision that took place off the coast of Namibia in 1997 involving a USAF C-141 and a Lufthansa Tu-154. The figure shows that for the unalerted search that existed, the probability of visual acquisition at 12 seconds prior to collision (the approximate point at which maneuvering would need to begin) was somewhere between 0.25 to 0.35 for each aircraft.

Traffic advisories to the C-141 would have increased the acquisition probability to over 0.90.

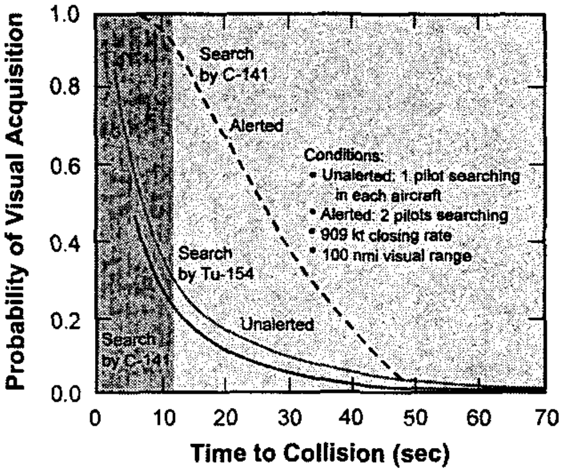

Figure 3. Visual Acquisition Performance for a Mid-Air Collision Scenario.

See and avoid makes important contributions to safety of flight, but its effectiveness depends upon encounter characteristics. In making safety comparisons between RPVs and conventional aircraft, it is important to assess visual acquisition for the specific mix of encounters that will arise in RPV operations. Visual acquisition using currently accepted see-and-avoid procedures is of limited effectiveness in certain encounters. Performance requirements applied to RPVs should acknowledge the practical limitations in the current see-and-avoid process. There is an opportunity to develop a detection capability for RPVs that exceeds human visual acquisition performance. However, it is also important to note that simply exceeding human visual detection performance does not mean that a new RPV system is safer. The threat evaluation, response selection, and execution functions (see Figure 1) still must be performed effectively by the RPV operator or automation.

Safety Enhancement Systems for RPVs

Background

Several types of safety enhancement systems have been proposed for RPVs to compensate for their lack of conventional see-and-avoid capabilities. In this section, we review the general characteristics of these systems and the contributions that each can make to safety of operations.

There are a number of sensor technologies being investigated as RPV enhancement systems for the detection function in Figure 1 [4-11]. These can be divided into two general categories: those that protect against cooperative threats and those that protect against non-cooperative threats.

Sensor Technologies - Cooperative Threats

With cooperative threats, the following sensor technologies are possible:

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

Airborne transponder-interrogating systems will provide air-to-air surveillance of other aircraft equipped with a transponder. Almost all aircraft have transponders [12] but their use is not mandated in all airspace as discussed earlier. TCAS II is a mature transponder-interrogating technology but it is not yet certified for use on RPVs. TCAS is discussed more thoroughly in the following section.

Ground-based radars can provide surveillance to RPVs via a digital data-link. An example of this type of system is the Traffic Information Service (TIS), which is operational in the NAS [13]. 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. TIS information could be uplinked to the RPV and then downlinked to the RPV operator.

The FAA's proposed Surveillance Data Network (SDN) will collect and fuse primary and beacon surveillance data from all FAA radars and will disseminate the data to users virtually anywhere with at most a two second delay. The 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 only be applicable for airspace within coverage of FAA radars.

ADS-B relies on aircraft self-reporting their position as determined by GPS or some other navigation system. Equipage levels for ADS-B are not expected to achieve useful levels for some time, so this is a consideration only for the future.

Sensor Technologies - Non-Cooperative Threats

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

- Airborne primary radar
- Airborne passive infrared
- Airborne passive visual
- Ground-based primary radar
- Combinations of the above

Airborne primary radar is attractive because it gives both bearing and range to non-cooperative threats [4]. 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 participates in the IFR system and allows ATC to maintain separation from other aircraft when in IMC. Since the characteristics of primary radar and visual/infrared are somewhat complementary, combined installations may be of interest [6].

In some airspace, 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.

Evaluation, Response Selection, and Execution Technologies

Sensor technologies can provide the means to perform the detection function in Figure 1. 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 solution: 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.

Role of TCAS in RPVs

TCAS Description

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 Resolution Advisories with other TCAS II aircraft using the Mode S data link. Accordingly, TCAS II provides an additional, independent means of performing the detection, evaluation, and maneuver selection functions in Figure 1 for cooperative aircraft that have not been avoided through the normal separation process.

TCAS History

TCAS development began in the early 1970s under FAA sponsorship [14-16]. 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. 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 RPVs to use TCAS to safely file and 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.

TCAS-on-RPV Concerns

The use of TCAS on RPVs may enhance the safety of RPV operations. However, two 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 [17-18]. Additionally, SCRSP Working Group A has stated that the ICAO mandate requiring TCAS on large piloted aircraft does not apply to RPVs [19].

A second concern is that TCAS was never intended to replace see and avoid. Currently TCAS presumes the existence of normal separation processes, including IFR 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.

TCAS Surveillance and Display Limitations

Because TCAS operates by interrogating air traffic control transponders, it provides reliable surveillance only in airspace where all aircraft are required to have altitude-reporting transponders (Class A, B, and C, and Class E above 10,000 feet). TCAS cannot detect the non-transponder-equipped aircraft that RPVs would encounter in low-altitude Class E airspace. Such aircraft can operate under VFR in VMC with no 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, pilots are not permitted to use TCAS traffic displays or Traffic Advisories to maneuver in response to threat aircraft.

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. Thus any safety analysis must ensure that the existing TCAS design will not increase the probability of collision for an RPV.

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. 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 [20]. 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 in Figure 1 for cooperative aircraft. Analysis of encounters between piloted aircraft has shown that delays in pilot responses to Resolution Advisories increase collision risk [21]. 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.

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.

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.

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.

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.

Safety Analysis Recommendations

Regardless of the means that are developed to perform the traffic avoidance process shown in Figure 1, a safety analysis will be required for certification of RPVs in civil airspace. Lincoln Laboratory is currently pursuing such an analysis for the use of TCAS on the Global Hawk RPV [22]. The recommended safety analysis is based on a 2002 ICAO paper that defined a Safety Analysis Plan for RPV flight in civil airspace [23]. This safety analysis employs established procedures that were developed to certify the current TCAS design. The procedures could 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.

The recommended safety analysis tasks include:

- Develop a Concept of Operations (CONOPS) to provide information, for example, on RPV flight characteristics, the environment in which the RPV will operate, responsibilities of the ground pilot, and communication protocols.
- Develop an Encounter Model to enumerate the encounter geometries that are expected to occur and their relative frequencies of occurrence.
- Compute Risk Ratios (e.g., risk of collision with TCAS/risk of collision without TCAS) using large numbers of simulated encounters.
- Develop a Fault Tree Analysis to identify all events that could lead to a failure in the end-to-end collision avoidance process and to estimate either absolute or relative system risk.
- Conduct Special Analyses to examine, for example: RPV performance in TCAS-TCAS coordinated encounters, encounters with high vertical rates, late maneuvers, or command reversals.

The results of the risk ratio calculations can be used to select the most effective collision avoidance logic for RPV implementation. The results of the fault tree analysis can determine if the RPV plus its proposed collision avoidance system provides an equivalent level of safety to that of conventional aircraft.

The current ICAO fault tree analysis process includes a single parameter estimate of the probability of visual acquisition by a piloted aircraft. The computer see-and-avoid model described earlier can improve this estimate by accounting more accurately for the variables that impact visual acquisition. If the initial analysis of autonomous Global Hawk collision avoidance indicates that a see-and-avoid capability is necessary to achieve the safety of conventional aircraft, the visual acquisition model can be modified to analyze RPV safety systems that emulate see-and-avoid capability.

Programming an RPV to autonomously respond to TCAS Resolution Advisories could offset a lack of human see-and-avoid capability. Initial analysis should focus on encounters involving a Global Hawk that is equipped with a full-capability air-carrier TCAS, has no special see-and-avoid provisions, and is programmed to autonomously and correctly respond to TCAS Resolution Advisories. This analysis would determine if the level of safety of encounters involving an autonomous Global Hawk with no see-and-avoid sensor is greater than or less than that of a piloted TCAS aircraft. A positive result from this analysis could accelerate the certification of autonomous Global Hawk collision avoidance in civil airspace used by aircraft with altitude-encoding transponders.

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, RPVs must be able to demonstrate that they meet or exceed the safety levels of conventional aircraft. Depending on the type of vehicle and its mission profile, this places varying requirements on what must be demonstrated in safety analyses and what equipment is required on the RPV.

An RPV that flies exclusively in Class A airspace would encounter only other IFR traffic and would receive positive separation control by ATC. It is possible that the necessary improvement in safety could be achieved merely by equipping such an RPV with a 25-ft altitude-reporting Mode S transponder, a reliable low-latency communication link between ATC and the RPV operator, and a means of handling lost link and emergency (e.g., engine failure) operations. In this case, safety analysis need not await the definition of new surveillance and avoidance algorithms.

More operational flexibility is available to the RPV if it can gain access to fly in or above Class B and Class C airspace, or in Class E airspace above 10,000 ft. In those airspace regions, the RPV will encounter only cooperative (transponder-equipped) aircraft, although the threats may be flying VFR as well as IFR. ATC may not be able to provide positive separation from VFR traffic, so the RPV will need some means of maintaining separation from VFR aircraft without prompting from ATC. Since all aircraft in this airspace have a transponder, it may be sufficient to employ see-and-avoid surrogates, such as TCAS surveillance, that detect only cooperative aircraft.

To provide the most operational flexibility, access to Class D or Class E airspace below 10,000 ft will be desirable. An RPV operating here will need the capability to safely maintain separation from non-cooperative aircraft.

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 IFR 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.

Prior studies have shown that as responses to Resolution Advisories become more reliable and consistent, there is a larger safety benefit from TCAS. An autonomous response by an RPV may therefore be an attractive option. 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. A validated safety analysis methodology, used to certify TCAS, has been outlined in this paper. A similar safety analysis performed for RPVs will inform regulators, manufacturers, and operators about options for providing RPVs with a see-and-avoid capability leading to routine access to civil airspace.

Acknowledgments

This paper was sponsored by the United States Air Force Global Hawk System Management Office within Air Combat Command (ACC/DR-GH SMO) in Hampton, VA and the Global Air Traffic Operations/Mobility Command and Control System Program Office (GATO/MC2 SPO), Electronics Systems Center, Hanscom AFB, MA. The authors gratefully acknowledge the technical advice and leadership provided by Roger Elstun, Tee Mans, Mark Bryner, Capt. Matt Nuffort, Lt. Gregory Vandyk, Roger Francis (MITRE Corp.) and Craig Hodgdon (Titan Systems).

References

[1] FAA, 2003, Certificate of Waiver or Authorization, Global Hawk Remotely Operated Aircraft (ROA) Operating Area, August 13.

[2] Swihart, *et al.*, 2001, "An Automatic Air Collision Avoidance System (Auto ACAS)" 8th Saint Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, Russia, May 28-30.

[3] Andrews, J. W., 1991, "Air-to-air Visual Acquisition Handbook", ATC-151, MIT Lincoln Laboratory, 27 November.

[4] Wolfe, R., 2003, "NASA ERAST Non-Cooperative DSA Flight Test," Proc. AUVSI Unmanned Systems 2003, Baltimore, MD, July.

[5] Brusgard, T. C., 1999, "Distributed Aperture Infrared Sensor Systems," Proc. of Infrared Technology and Applications XXV, Orlando, FL, pp. 58-66, April.

[6] McCalmont, J., *et al.*, 2002, "Detect and Avoid Technology Demonstration," Proc. of AIAA 1st Unmanned Aerospace Vehicles, Systems, Technologies, and Operations Conference and Workshop, Portsmouth, VA, May.

[7] Ogloza, A., *et al.*, 2003, "Detect See and Avoid (DSA) Technology for Enabling UAV Operation in the NAS," Proc. AUVSI Unmanned Systems 2003, Baltimore, MD, July.

[8] Pipitone, F., *et al.*, 2001, "Three Dimensional Computer Vision for Micro Air Vehicles," Proc. SPIE Enhanced and Synthetic Vision 2001, Orlando, FL, pp. 189-97, April.

[9] Soreide, D. C., *et al.*, 2002, "Development of an Optical Sense and Avoid Guidance and Control System with Staring Infrared Cameras," Proc. of AIAA 1st Unmanned Aerospace Vehicles, Systems, Technologies, and Operations Conference and Workshop, Portsmouth, VA, May.

[10] Takken, E. H., *et al.*, 1998, "Feasibility of a Passive Collision Avoidance System (PCAS) Based on Staring Infrared Sensors," 1998 IRIS Proceedings, January.

[11] Tank, W., *et al.*, 2003, "Certification of Unmanned Air Vehicles for Use in the National Airspace System," Proc. AUVSI Unmanned Systems 2003, Baltimore, MD, July.

[12] Airplane Owners and Pilots Association, 2003, http://www.aopa.org/special/newsroom/facts.html

[13] RTCA, 1997, "Minimum Operational Performance Standards for Traffic Information Service (TIS) Data Link Communications", DO-239, April 2.

[14] Zeitlin, A., 1979, "Active Beacon Collision Avoidance System – Collision Avoidance Algorithms", Report MTR-79W00110, April.

[15] MITRE Corp., 1983, "System Safety Study of Minimum TCAS II", Report MTR-83W241, December.

[16] Harman, W. H., 1989, "TCAS: A System for Preventing Midair Collisions", *The Lincoln Laboratory Journal*, Vol. 2, No. 3.

[17] SICASP Working Group 2, 1999, Final Minutes, Section 7.69, Montreal, Canada, May.

[18] SCRSP Working Group A, 2002, Final Minutes, Section 6.8.1, Kobe, Japan, March.

[19] SCRSP Working Group A, 2002, Working Paper A/3/112, Kobe, Japan, March.

[20] Law, J., Rapporteur, 2002, SCRSP Working Group A, Letter to Global Hawk Program Office, December.

[21] Arino, T., *et al.*, 2002, "ACAS Analysis Programme ACASA Project Work Package 1 Final Report on Studies on the Safety of ACAS in Europe", Version 1.3, EEC Brétigny, March.

[22] Kuchar, J., *et al.*, 2004, "A Safety Analysis Process for the Traffic Alert and Collision Avoidance System (TCAS) and See-and-Avoid Systems on Remotely Piloted Vehicles", 3rd AIAA Unmanned Unlimited Conference, Chicago, IL, September 20-23, 2004.

[23] Drumm, A. C., 2002, "TCAS on Unmanned Aerial Vehicles: Defining a Safety Analysis Plan", SCRSP/WGA, WP/A/4-145, Langen, Germany, October.

Disclaimer

This work is sponsored by the United States Government under the Air Force Contract #F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Government.