

UNMANNED AIRCRAFT COLLISION AVOIDANCE – TECHNOLOGY ASSESSMENT AND EVALUATION METHODS

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Abstract

Collision avoidance is emerging as a key issue for UAS access to civil airspace. Numerous technologies are being explored in the community to develop a solution for collision avoidance. The problem is multi-dimensional and needs to be addressed at the system level. Requirements for collision avoidance capabilities are complex and vary with the intended airspace of operation and the corresponding potential hazards. The appropriate mitigations are likely to be equally complex. A suite of several sensor technologies is likely to be required in order to address the full set of collision hazards.

The intent of this paper is to present a perspective on the challenges associated with UAS collision avoidance from a civil aviation perspective and to present results from some of MITRE's research addressing collision avoidance technologies and systems performance analysis.

Introduction

Interest in unmanned aircraft is growing worldwide. According to Nicholas A. Sabatini, FAA Associate Administrator for Aviation Safety, "the development and use of unmanned aircraft systems (UAS) is the next great step forward in the evolution of aviation." [1] Applications abound from military and homeland security to commercial services. [2, 3, 4] For UAS operators, the operation of unmanned and manned aircraft in the same airspace, including civil airspace, is an important capability that will enable growth in the industry, expansion of applications, and greater utility for all operators.

Collision avoidance is emerging as a key issue for UAS access to civil airspace. Numerous technologies are being explored in the community, including research sponsored by the National

Aeronautics and Space Administration [5], the United States Air Force [6], the Defense Advanced Research Projects Agency [7, 8], The MITRE Corporation and others.

The intent of this paper is to present a perspective on the challenges associated with UAS collision avoidance from a civil aviation perspective and to present results from some of MITRE's exploration into collision avoidance technologies and systems performance analysis.

Avoiding Collision in the National Airspace System

In today's National Airspace System (NAS) there are a number of technologies, processes, and procedures which together ensure that the risk of collision for manned aircraft is consistent with an acceptable Target Level of Safety (TLOS). These capabilities effectively function in a layered approach (see Figure 1). Similar to defense in-depth and layered information security architectures, it would take failures at multiple layers to cause a system failure, resulting in a collision.

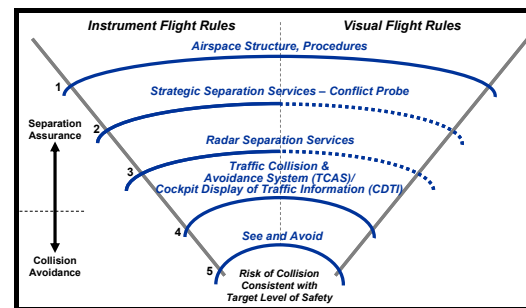


Figure 1 – A Layered Approach to Avoiding Collisions

Layer one is different from layers two through five, in that it is not specifically focused on mitigating the risk of collision between two airborne objects. Airspace structures and procedures are defined in a manner that further reduces risk from pure random chance. A good example is ordinal altitudes, which separate traffic by direction, reducing the potential for head-on encounters.

Layers two through five all follow a similar five-stage process in ensuring safety among two or

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more aircraft (or other airborne objects). See Figure 2.

- **Surveillance:** Accurate surveillance of potential targets is a key step. Targets that are either missed or their position erroneously identified would reduce the overall effectiveness of a collision avoidance system. Radar, beacon transponders, Automatic Dependent Surveillance – Broadcast (ADS-B) and the pilot’s vision are just some of the potential sensors used to survey potential targets.
- **Identification of a Risk:** Using relative position information, rate of change of relative position, and/or the trajectory information (either derived or reported) for all aircraft, a determination is made as to whether a risk of collision (i.e., two aircraft are on a collision course) or a conflict (i.e., a violation of safe separation) exists and if an avoidance maneuver is required.
- **Determination of Appropriate Avoidance Maneuver:** Once a potential collision or conflict is identified, an appropriate avoidance maneuver is determined. In the case of an air traffic controller providing radar separation assurance in the third layer of Figure 1, this determination is made based controller training and operational experience. In the case of Traffic Alert and Collision Avoidance System (TCAS) at the fourth layer, this determination is made by the on-board automation system. Key to both the identification of the collision risk and the determination of the appropriate avoidance maneuver is the accuracy of the surveillance information. For TCAS, all avoidance maneuvers are vertical since the relative altitude information is most accurate (i.e., it is based on pressure altimeter information), in comparison to the accuracy of relative bearing information.
- **Maneuver:** Once the appropriate maneuver is determined, it must be executed by the pilot(s) in control of the aircraft. In the case of radar separation services, this includes communication by the controller to the pilot.
- **Return to Course:** After the risk of collision has been mitigated by the maneuver, the aircraft can return to its original course.

The outcome of this process is the maintenance of either safe separation or avoidance of a collision, depending upon which layer (two through five) is being considered. All of the layers work together to achieve a desired TLOS at the system level.

In the 1990s, an additional layer was added with the introduction of TCAS [9, 10], shown as layer four in Figure 1. To understand the value of

the TCAS collision avoidance capability, the community needed to know that the risk of collision was reduced by the addition of TCAS. MITRE was instrumental in using Monte Carlo simulation techniques to demonstrate from an overall system perspective that the risk of collision without TCAS was significantly greater than the risk with TCAS.

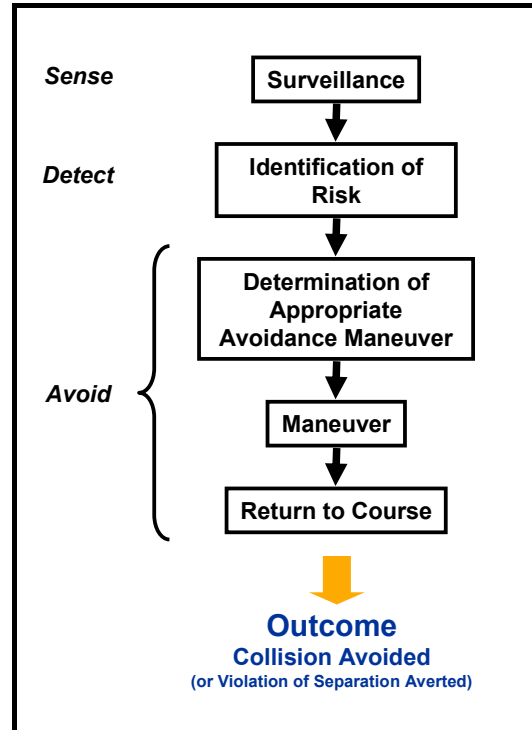


Figure 2 - Generic Process Model

Challenges Associated with UAS Collision Avoidance

With the introduction of a collision avoidance capability on unmanned systems, the challenges are much more complex. The key issue is: can we introduce a new aircraft type into the NAS while mitigating risks to an acceptable level (i.e., the defined TLOS)? The technology and processes associated with each layer in Figure 1 are likely to be affected by a shift to some of the aircraft operating in the system being unmanned. In today’s NAS, the pilot is central to the processes at each layer. Thus the impact of UAS is not just on the “see and avoid” (i.e., fifth layer). The community will need to address mechanisms at all five layers.

Some of the challenges are enumerated here.

- A community-accepted definition of the Target Level of Safety for UAS collision avoidance technology is lacking. Given that all the layers interact to produce a desired

collision risk, in order to evaluate system changes a target performance level is needed. Some in the aviation community point to the FAA's Safety Management System [11] and feel that since a mid-air collision is "catastrophic" that event should be "extremely improbable" and thus acceptable risk is 1×10^{-9} , which is one collision for every billion flight hours. Others are attempting to quantify a pilot's ability to "see and avoid" and develop TLOS performance at an equivalent level.

- Collision avoidance today relies upon human judgment, but with unmanned aircraft it is feasible that some sort of autonomous collision avoidance capability would prove most advantageous. This complicates testing and certification because in general the aviation community has difficulty testing, verifying, and certifying software-intensive autonomous flight critical systems, especially systems that have non-deterministic inputs and potentially an infinite number of system states.
- A complex set of requirements exists. UAS collision avoidance technology must be able to work in Instrument Meteorological and Visual Meteorological Conditions (IMC and VMC); day and night; work in the air and on the ground; detect aircraft and other airborne vehicles (e.g., balloons, gliders, parachutists); with transponding and non-transponding aircraft; be backwards compatible with TCAS; and be able to function on a range of aircraft, some of which have size/weight/power limitations and have a wide range of flight performance characteristics.
- There is a lack of community resources dedicated to the development of appropriate collision avoidance technology. By some estimates, TCAS took almost 20 years and expenditures of millions of dollars per year, just for the research and development. This estimate does not include the deployment cost of TCAS. In the opinion of the authors, the degree-of-difficulty of UAS collision avoidance is greater than that for TCAS due to the broader complexity of the requirements.
- Community agreement is needed on the methods for determining the effectiveness of the collision avoidance technologies and making the system safety case. [12]
- One major policy issue is whether a single, government-provided solution would be pursued or will multiple solutions be acceptable. In the case of TCAS, a single solution (i.e., a single algorithm) was

developed by the US Government, specified by RTCA [13], and provided to industry. Testing and FAA certification was to ensure that the product developed by industry adhered to the specifications.

Many of these challenges are further elaborated in the next several sections where we discuss sensor technology, collision avoidance algorithm features, and evaluation methodologies.

Parsing the Collision Avoidance Problem

In order to scope the Collision Avoidance problem, there are a number of factors and requirements to consider. Significant attention in the community is placed on developing technologies that would enable a UAS to satisfy the requirement for a pilot to "see and avoid" other aircraft consistent with the right of way rules. [14] Sense, Detect and Avoid (Figure 2) for all layers have to operate in a widely varying environment of different UAS types, different airspaces, different operating conditions, and different obstacles to avoid.

The UAS types, for which collision avoidance is being investigated, vary widely in size from the palm sized aircraft to the airliner sized aircraft like the Global Hawk. The environments in which these UAS will be expected to fly will vary widely as well, from daylight to darkness, and from clear weather to cloudy, foggy, rainy, or even stormy conditions, plus in a variety of FAA designated airspace types, from uncontrolled to fully controlled, with the associated capability performance requirements.

As with manned aircraft, it is anticipated that an unmanned aircraft must be properly equipped for the conditions and airspace in which it is intended to operate. To fly in controlled airspace or under Instrument Flight Rules (IFR), an aircraft must be equipped with specific navigation and surveillance functions. It is not expected that all manned aircraft be able to fly in all airspace and in all conditions; therefore, given the large range of UAS types, it is reasonable to assume that unmanned missions and equipage requirements will vary as well. The operating environment and mission will drive the need and requirement for degree and type of Collision Avoidance – no one method should be expected to cover all conditions.

Sensor Technology

Determining the type of sensor that is appropriate for the UAS and environment is a challenging, multidimensional problem.

The task of sensing obstacles in the environment can be performed by different kinds of sensors, most of which are limited to one degree or another. The fundamental information that a sensor needs to acquire is the range, azimuth and elevation of all targets of interest (Figure 3).

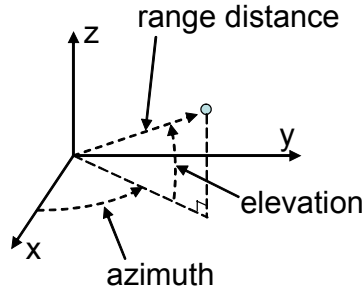


Figure 3 – Fundamental Sense Information

This information can be acquired directly or indirectly, depending on the type of sensor. If, over several scans of the sensor, the target angles do not change and the range is decreasing, then a collision is possible. It is the task of the “detect” part of the process in Figure 2 to make this determination, based on the sensor data over time. Modeling aircraft trajectories is another method used to determine the potential for a collision.

Surveillance for collision avoidance can be performed through two fundamental methods: 1) cooperative sensors, wherein a target transponds information about its position, and 2) non-cooperative sensors, which sense a target indirectly, through either passively sensing an attribute of the target, or by actively deploying energy to seek out the target. A brief summary of each sensor type follows.

Cooperative Sensors

Surveillance methods that sense a cooperative target will usually employ a transponding method by which the target transmits information about its position. TCAS relies on this method to discover other aircraft. This works well for aircraft (and eventually UAS) that fly in controlled airspace where all aircraft are required to carry a Mode A/C altitude-encoding transponder by FAA regulation. This does not permit sensing of non-transponding targets, so such targets must be identified through other means.

Non-cooperative sensors

Surveillance methods that sense non-transponding targets indirectly are considered non-cooperative sensing methods. A target is sensed and tracked, either (1) through passively acquiring information about the target (e.g., optical camera

recording the reflected light, or acoustic sensor perceiving the target by passively listening); or (2) by actively deploying energy to seek out the target (e.g., radar which emits an electronic pulse and determine range and bearing by the angle of sensor and timing of the response, or laser range finder which emits infrared coherent light and detects reflections).

There are attributes of each type that make each type appropriate for selected applications. Some of these attributes are summarized in Table 1 with the tendency of active vs. passive sensors based upon what we are observing through field data collection.

Table 1 – Sensor Type and Attributes

	Active	Passive
Power Required	More	Less
Field of Regard of a single non-moving sensor	Less	More
Sensor Resolution	Less	More
Processing Requirement	Less	Much More
Targets	Moving	Stationary
Example Modes	Laser Radar Acoustic	Electro-optic Thermal

Passive sensors, such as optical cameras, can be smaller and lighter-weight, since they do not need the power to transmit energy. Most optical solutions provide a good field of regard, especially with the appropriate lensing, and can be high resolution. However, this also drives a very high processing requirement to reduce the high resolution field of view to the objects of concern. Techniques such as optic flow have been used to reduce the processing requirements [15]. Optical solutions do provide accurate information on azimuth and elevation angles, but most of them cannot provide range information directly, which must be inferred or sensed in other ways. Figure 4 illustrates a target of interest in a video image – angles are easily computed but range is not.

Active sensors, such as a laser range finder, require more energy, so they tend to be bigger and heavier. These sensors typically can provide more accurate range information, though they are not good at angle resolution because their field of regard is either very small (laser range finder point) or very large (radar or acoustic omni-directional

ping). Figure 5 documents distance measurements of a fixed obstacle in front of a UAS, as it approached and passed the obstacle. Azimuth and elevation angles were zero in this case. Methods such as mechanical scanning or steering, or processing can enhance these measurements, but these methods add weight. There are efforts underway to miniaturize these types of sensors [16].



Figure 4 – Optical Camera as a Passive Sensor

Most of the non-cooperative sensors operate over a much shorter range than cooperative sensors, usually only in line of sight. Thus, they are most applicable to the very short time frames of the “see and avoid” level of collision avoidance, which is layer five in Figure 1.

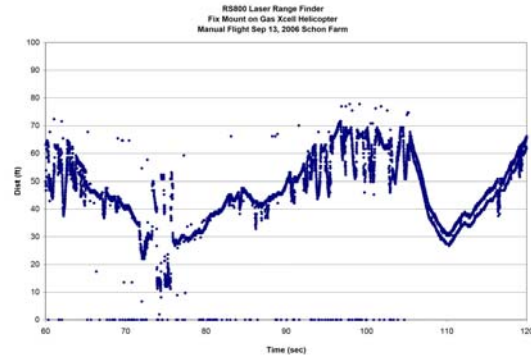


Figure 5 – Laser Range Finder as an Active Sensor

Not Just One Sensor?

There are several strategies to manage the shortfalls of the sensor types. One could employ multiple sensors to cover a larger area, or multiple sensor types. One could reduce the detection and tracking requirement from fine resolution object tracking to area sensing (i.e., if there is anything detected in this sector, avoid the sector). One could simplify the avoidance reaction maneuvers, so that the sensing requirement is limited (as in TCAS) Based upon our observations from field data collection and our experience with surveillance technologies, the trade-off of sensor types and attributes is shown in Table 2.

Table 2: Attributes of Selected Sensor Modes

	Modality	Range	Bearing (Azimuth)	Bearing (Elevation)	Trajectory
Mode A/C Transponder	Cooperative	Accurate; 10s of miles	Calculated	Calculated based on pressure altitude	Derived
ADS-B	Cooperative	Accurate; 10s of miles	Calculated based on GPS	Calculated based on pressure altitude	Provided
Optical	Non-Cooperative, Passive	Not sensed	Accurate	Accurate	Derived
Thermal	Non-Cooperative, Passive	Not sensed	Accurate	Accurate	Derived
Laser/LIDAR	Non-Cooperative, Active	Accurate; 1000 ft	Narrow	Narrow	Derived
Radar	Non-Cooperative, Active	Accurate; 1 mile	360 degrees	360 degrees (Depends upon antenna mounting)	Derived
Acoustic	Non-Cooperative, Active	Accurate; 100 ft	360 degrees	360 degrees	Derived

Because of the limitations in each sensing mode, there is a real sense that no one sensor would provide a “one size fits all” solution to the many dimensions of the collision avoidance problem. Thus, weakness in one sensor type can be compensated by strengths in other sensors. Sensor cuing can also be part of the algorithmic development. For very limited applications and environments, a single sensor might provide a sufficient solution; otherwise, multiple fused sensors would be required to provide a complete solution. To assess the solution coverage for sensors, we have begun to map the considerations of sensor attributes over the environment types; more research is needed to fully map the sensor appropriateness to the environment.

Collision Avoidance Algorithms

Sensing a target is only the first step in performing collision avoidance. Many targets will become visible in the airspace. It is necessary to determine which targets may pose a collision risk, and then determine an effective avoidance maneuver. The algorithms that do these steps need to be matched to the sensor input, and to vehicle and environmental factors.

TCAS is a mature solution used by many manned aircraft, but analysis [17] uncovers areas of concern when applying it to UAS. If a remote pilot is to initiate the collision avoidance maneuver, any extra delay in doing so would markedly degrade its safety (e.g., adding 5 seconds approximately doubles the risk). Further problems could arise from limited vertical maneuverability. Whether UAS ultimately use an adapted TCAS algorithm or an entirely different one, a requirement will be to ensure no degradation of safety for TCAS-equipped manned aircraft, and to do so without imposing modifications to their TCAS.

It is enlightening to list differences between TCAS and requirements for UAS collision avoidance. See Table 3.

Table 3: Differences in Requirements

TCAS	UAS Requirement
Cooperative (transponding) targets	Cooperative and non-cooperative targets
Airborne targets	Airborne & surface targets
Vertical resolution	Maneuverability of some unmanned aircraft or rotorcraft may be much better in lateral plane
Explicit coordination of maneuver with another TCAS	Means of compatibility still to be determined

Sensor inputs vary in terms of their data content and coordinate systems, their fields of view, accuracies, and update rates (see Table 2). Where a suite of diverse sensors is used to detect different targets, the algorithms must deal with these data differences.

As with the previous section on sensor technology, discussion of collision avoidance issues is divided between cooperative and non-cooperative sensor types.

Cooperative Collision Avoidance

Traditionally, “cooperative” has equated to the ATC transponder, although recently ADS-B has begun to deploy across the aircraft population. With ADS-B an aircraft broadcasts its Global-Positioning System (GPS)-derived position¹ to ground automation and surrounding aircraft capable of receiving the information.[18] ADS-B is capable of serving the role of cooperative avionics, since it broadcasts the aircraft position, as well as its velocity, identity, type, and possibly its intent.

ADS-B could only play a part in collision avoidance if the UAS were equipped to receive the data. If that were the case, the same data could support both collision avoidance and an earlier-acting Conflict Detection (CD), the latter function giving advice that would not require such prompt maneuvering. CD is among the defined Airborne Separation Assistance System (ASAS) applications [19] that span several categories of airborne surveillance usage, ranging from situational awareness to airborne separation. TCAS is not suitable for CD because its lateral measurements are inaccurate; ADS-B overcomes this limitation.

A significant issue arises if ADS-B is to be considered for both collision avoidance and conflict detection. Using the same system for both functions makes the aircraft susceptible to a failure that would incapacitate the collision avoidance function (just when it would be needed) simultaneous with the failure of another function related to separation. This concern has led to general acceptance of the philosophy that these functions must remain independent, insofar as possible.

In considering algorithmic solutions for UAS collision avoidance, an attractive approach presents itself for addressing the dilemma. A UAS solution utilizing ADS-B would only be capable of surveilling suitably equipped traffic, so another sensing means would be required to detect non-cooperative traffic. Fortunately, such a sensor

¹ Other position sources are feasible, but GPS-derived position information is the preferred source. Other position information may be used especially during GPS outages.

would, in fact, detect any traffic, cooperative or not, albeit at different time horizons. It would provide the independent data that could validate ADS-B target data during normal operation, and also provide redundancy in the event of a failure of ADS-B. While the non-cooperative data alone might not provide an equally sophisticated surveillance source, it need only be capable of supporting the most basic avoidance of a collision.

Moreover, this philosophy, if proven successful for UAS usage, could migrate to manned aircraft, and thus allow the larger aircraft to replace their current TCAS equipment with a presumably more capable ADS-B collision avoidance system, again backed up by a non-cooperative surveillance sensor.

Non-cooperative Collision Avoidance

As mentioned above, the collision avoidance algorithm must perform properly with the data coming from the sensor. In the arena of non-cooperative sensors, several technologies exhibit different strengths and weaknesses, as introduced in the previous section. Those that enable measurement of bearing (azimuth) should support the evaluation of a collision threat and the selection of a lateral escape maneuver. However, further research is required to determine the needed angular accuracy and update interval, as well as to determine the accuracy requirements for range information. The importance of range and derived range rate would surface when the two aircraft tracks were projected to cross, enabling a determination of a safe lateral sense for the resolution.

Other technologies provide a range measurement without accurate angle information (azimuth or elevation). The range could support a time-based and distance-based threat declaration, as is done in TCAS. Additional information likely would be needed to minimize nuisance alerting. TCAS uses both the vertical dimension, supported by transponder-based altitude measurements, and a horizontal miss-distance estimate derived from the second derivative of the changing range measurement. Some technologies may use an elevation angle measurement, rather than cooperative data exchange, in estimating vertical separation. As in the horizontal case, a vertical rate estimate would be needed to safely estimate the resolution when converging or crossing vertical profiles are observed.

An example of the required analysis was performed for TCAS III when that system was still undergoing development [20]. Its surveillance system proved inadequate for safe collision avoidance, but the analysis provides good insight

regarding the contributions of bearing and bearing rate errors as well as the correlation between successive measurements.

A separate issue of great importance to non-cooperative technologies concerns techniques for reliably distinguishing true targets from noise. This topic has been well-treated for radar, but details of the processing and decision threshold could vary for different technologies. Finally, if several technologies are to be combined for the purpose of using their various strengths, a sensor fusion process must be developed that matches the sensor characteristics to the requirements discussed above.

Evaluation Methodologies

A comprehensive set of methods is needed to evaluate, verify, and certify that these collision avoidance capabilities perform as expected. Ultimately, Collision Avoidance system performance will need to be verified end-to-end. As part of the end-to-end verification, each step in the process will need to be evaluated:

- Sensor measurements and target tracking
- Algorithms that determine threats and (optionally) provide resolution advice
- Communication link latency and accuracy, when a remote pilot is in the loop for collision avoidance
- Pilot latency and accuracy in avoiding the hazard, when in the loop
- Aircraft maneuverability (e.g., latency, acceleration, maximum bank or vertical speed)

Given that it is sometimes difficult to conduct the required number of trials, simulation methods are often employed. Simulation is used to correctly model the environment, i.e., geometries that represent conflicts between the UAS and other aircraft. These will need to build upon the existing encounter models used for TCAS evaluation, because the UAS will fly in different manner (e.g., loitering, patrolling), have different speed and maneuverability characteristics, and will be deployed over geographies and altitudes that generally do not correspond to the distributions of manned aircraft. Therefore, it is to be expected that their close encounter characteristics will differ in distribution from the manned aircraft data. A major task will be to construct the appropriate model. It will require estimating mission profiles and locations, and developing the statistics to consider the diverse types of aircraft combinations.

Flight testing also plays a role, but this methodology is not sufficient. Safety cannot be determined simply by testing a pair of aircraft.

Performance must be evaluated using the range of realistic flight mission profiles in the context of air traffic composition and density, ATM procedures and separation techniques.

A Framework of Evaluation Methods

There are a number of operational and technical questions that must be explored as a basis for evaluating these capabilities. As an example, component testing is necessary but insufficient to provide the whole picture. System level testing is required to assure safety, ensuring that the collision avoidance levels that are being tested on the UAS will be safe in an operational setting. See Table 4.

A number of evaluation methods were examined for their applicability to answering relevant questions. These methods are scoped as follows:

- **Bench Test** – includes any functional test of a single technology, in controlled environment of the laboratory or static test ranges.
- **Bench Test (Integrated System)** – includes testing of end-to-end system in a controlled laboratory environment.
- **Field Data Collection** – includes component evaluation of a technology in the operational setting under controlled environmental conditions.

Table 4: Evaluation Methods, and the Questions That Can Be Addressed

	Bench Test (component-level)	Bench Test (integrated System)	Field Data Collection (component-level)	Flight Test (integrated system)	Fault-tree / Hazard Analysis	Monte Carlo Simulations	Human-in-the Loop Laboratory Sims	Operational Evaluation	Performance Monitoring
What does the sensor see? Range? Azimuth? Elevation? Speed?	✓		✓						
How large an object can it see? How far away?	✓		✓						
Are sensor specifications accurate?	✓		✓						
Does the system function together?		✓		✓					
Does collision avoidance capability provide safe separation from manned aircraft?		✓		✓	✓		✓		
Do collision avoidance algorithms react in an acceptable way for other pilots?				✓			✓	✓	✓
Does capability act in an acceptable way in the context of the operating environment (e.g., ATM)?				✓			✓	✓	✓
What are the limits of the capability? Conditions? Size or number of targets?	✓	✓	✓	✓		✓			
How does collision avoidance technology compare to "see and avoid"?				✓	✓	✓	✓	✓	✓
What is the overall system performance? i.e., resulting collision risk					✓	✓	✓	✓	✓

- **Flight Test** – consists of technology evaluation in a full system setting, so that the contribution of the technology to the TLOS can first be evaluated.
- **Fault Tree and Hazard Analysis** – Techniques used to ensure that a system behaves as needed when pieces fail.
- **Simulation (Monte Carlo)** – combines models for each technology, human and aircraft behavior to capture interactions of their separate statistical distributions. Permits extensive testing runs that may not be practical under real operating conditions; used to scope the performance bounds of the technology.
- **Human-In-The-Loop Laboratory Simulation** – provides operating capabilities in a simulated environment, to supplement field testing and as a precursor to operational evaluations; frequently done in parallel to advance the understanding of the technology.
- **Operational Evaluation** – provides a full range of testing to prove that a technology fulfills a specification or standard. Includes limited deployment in the operational environment.
- **Performance Monitoring** – adds to the technology experience data, by evaluating it in use, under standard operating conditions.

Table 4 maps evaluation methods to some of the potential research and development questions that exist in the aviation community. No one evaluation method can answer all the questions, thus a well constructed set of tests must be developed to sufficiently support evaluation, verification, and certification of collision avoidance capabilities.

Conclusions

The development of UAS collision avoidance capabilities must be conducted in a comprehensive systems approach and not look at just one layer of functionality (e.g., “sense and avoid”). The performance of the entire system (i.e., TLOS) needs to be evaluated using a variety of methods in the context of their operating environment. The diversity of UAS aircraft, missions and system architectures suggest that safety evaluations will need to address specific differences within these areas. No one evaluation method can answer all the questions, thus a well constructed set of tests must be developed to sufficiently support evaluation, verification, and certification of collision avoidance capabilities.

It is likely that no single sensor will be sufficient to address all UAS collision avoidance requirements. Thus two or more fused sensors will

be needed to provide the needed surveillance accuracy and the necessary system integrity. Algorithms for sensor fusion, collision detection, and maneuver determination need to be developed and certified to reliably contribute to the TLOS for collision avoidance. Transponder-based collision avoidance must work in conjunction with non-cooperative collision avoidance. UAS collision avoidance must co-exist with present collision avoidance capabilities for manned aircraft, implying that it must also be backwards compatible with TCAS. Collision avoidance technology for UAS could also be used by manned aircraft to increase the safety of their operations.

References

- [1] Statement of Nicholas A. Sabatini, Associate Administrator for Aviation Safety, Before the Committee on Commerce, Science and Transportation on Unmanned Aircraft Systems in Alaska and the Pacific Region: A Framework for the Nation, July 13, 2006.
- [2] Office of the Secretary of Defense, *Unmanned Aircraft Systems Roadmap 2005 – 2030*, Department of Defense, 4 August 2005.
- [3] Zaloga, Steven J., Dr. David Rockwell, and Philip Finnegan, *World Unmanned Aerial Vehicles Systems: Market Profile and Forecast – 2007*, Teal Group Corporation, October 2006.
- [4] Pitts, Michael J, *Presentation at FAA UAS Technology Conference*, Office of Customs and Border Protection Air and Marine, January 2007.
- [5] *Flight Demonstrations Evaluate UAV Collision-Avoidance Technology*, National Aeronautics and Space Administration News Release, <http://www.nasa.gov/centers/dryden/news/NewsReleases/2003/03-20.html>, 3 April 2003
- [6] McCalmont, John, James Utt, Michael Deschenes, *Detect and Avoid Technology Demonstration*, AIAA's 1st Technical Conference and Workshop on Unmanned Aerospace Vehicles, AIAA-2002-3419, May 2002.
- [7] *Northrop Grumman Helps Air Force Develop Collision-Avoidance System for Unmanned Vehicles*, Northrop Grumman News Release, http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=61490, 28 July 2004.
- [8] *DARPA Announces Award of Organic Air Vehicle – II Contracts*, Defense Advanced Research Projects Agency New Release, www.darpa.mil/body/news/2004/oavii.pdf, 29 November 2004.
- [9] *Introduction to TCAS Version 7*, Federal Aviation Administration, November 2000.

[10] Niedringhaus, William. P., and Andy D. Zeitlin, *Development of Airborne Collision Avoidance Algorithms Compatible with the National Airspace System*, American Control Conference, June 1982.

[11] *Safety Risk Management Guidance for System Acquisitions*, Federal Aviation Administration, 29 November 2006.

[12] Zeitlin, Andrew, Andrew Lacher, James Kuchar, and Ann Drumm, *Collision Avoidance for Unmanned Aircraft: Proving the Safety Case*, MITRE #: MP060219 Lincoln Laboratory #: 42-1017, October 2006.

[13] *Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System (TCAS II) Airborne Equipment*, DO-185A, RTCA, 1998.

[14] Code of Federal Regulations - Title 14 Aeronautics and Space; Part 91 General operating and flight rules; Section 113 Right-of-way rules: Except water operations.

[15] Utt, James; Dr. John McCalmont, and Michael Deschenes, *Development of a Sense and Avoid System*, AIAA Infotech @ Aerospace, AIAA-2005-7177, Arlington, VA September 2005.

[16] Long, David, *Compact, low-cost synthetic aperture radar*, 10,1117/2.1200610.0456, SPIE Newsroom, The International Society for Optical Engineering, 2006.

[17] Zeitlin, Andrew D., and Michael P. McLaughlin, *Safety of Cooperative Collision Avoidance for Unmanned Aircraft*, 25th Digital Avionics Systems Conference, Portland OR, October 2006.

[18] *Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B)*, DO-242A, RTCA, June 2002.

[19] *Minimum Aviation System Performance Standards for Aircraft Surveillance Applications (ASA)*, DO-289, RTCA, December 2003

[20] Neumeister, Kenneth E., *Effects of Bearing Errors on TCAS III Estimates of Miss Distances and Predicted Ranges With and Without Horizontal Maneuvers*, WP91W212, The MITRE Corp., July 1991.

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