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Assessment of Detect and Avoid Solutions for Use of Unmanned Aircraft Systems in Nonsegregated Airspace

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Executive summary

ASSESSMENT OF DETECT AND AVOID SOLUTIONS FOR USE OF UNMANNED AIRCRAFT SYSTEMS IN NONSEGREGATED AIRSPACE

Problem area
Unmanned Aircraft Systems (UASs) emerge as new possibility for civil and military aircraft applications, without having the need for a pilot onboard the aircraft. Although there is great potential, there is also the need to show that the introduction in nonsegregated airspace can be done without endangering other (manned) traffic. In this report the most promising candidate solutions for Detect and Avoid (DAA) for use of UAS in nonsegregated airspace are assessed against a set of DAA requirements. A DAA solution is the combination of the sensor suite, the avoidance algorithms, and the method of operation. The functions of a DAA solution are collision avoidance and, in uncontrolled airspace, separation provision. The focus of this report is the detection of conflicting traffic by the sensor suite. The sensor suite needs to be able to detect different classes of conflicting traffic in varying environments. Requirements for DAA solutions have to be set, and DAA systems must then be developed to meet these requirements.

Description of work
A common direction is visible in requirements drafted by different organizations on the use of UAS in nonsegregated airspace. In this report a set of EUROCONTROL requirements that are directly or indirectly of influence on the sensor suite used to Detect and Avoid other traffic is used as baseline for the establishment of DAA requirements. This set is expanded by the development of five additional generic requirements based on the main tasks of a DAA solution: (1) detection of other traffic, (2) tracking of other traffic and assessing if there is a conflict, (3) if there is a conflict, determining which evasive maneuver is to be executed, and (4) executing the selected maneuver. Five candidate solutions are assessed against the requirements: a noncooperative solution, a cooperative solution, and three

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solutions mixing cooperative and noncooperative sensors.

Results and conclusions
Overall it is concluded that it is a great challenge to develop a collision avoidance solution for UAS with a satisfactory level of safety. It is even more difficult to develop a DAA system that is capable of both collision avoidance and separation provision. Therefore, collision avoidance is considered a first step in developing DAA solutions for UAS, restricting the operations to flights in controlled airspace with ATC providing separation at all times. The conclusions of the assessment of the five candidate solutions are:

- A full non-cooperative concept with RADAR and Electro Optical / Infra-Red (EO/IR) sensors is flawed because cooperative traffic is harder to detect than when using cooperative concepts.
- A full cooperative concept seems not feasible because there is always a need to detect non cooperative traffic.
- DAA solutions combining a Traffic Collision Avoidance System (TCAS), EO/IR and Radar seem to be the most feasible ones in the near future if accommodation is not an issue. However, high performance is required from sensors to reliably detect non-cooperative traffic. Note that a replacement of the cooperative surveillance functionality of TCAS by Automatic Dependent Surveillance – Broadcast (ADS-B) is not foreseen in the near future.
- No practical DAA solutions are fully compliant with the requirement for independence between collision avoidance and separation assurance.
- No solutions are found that match all requirements if accommodation is an issue.

It is recommended to continue to develop suitable methods to perform the safety analysis for introduction of UAS equipped with DAA solutions in nonsegregated airspace.

Applicability
This study has evaluated several candidate SAA solutions against (likely) requirements for UAS Detect and Avoid. The identified capabilities of SAA solutions can be used in safety assessments. As such, this study contributes to development of standards for safe integration of UAS in non-segregated airspace.

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Assessment of Detect and Avoid Solutions for Use of Unmanned Aircraft Systems in Nonsegregated Airspace

70

Joram Verstraeten, Martijn Stuip, and Tom van Birgelen

Contents

Abstract

Unmanned Aircraft Systems (UASs) emerge as new possibility for civil and military aircraft applications, without having the need for a pilot onboard the aircraft. Although there is great potential, there is also the need to show that the introduction in nonsegregated airspace can be done without endangering other (manned) traffic. In this chapter the most promising candidate solutions for Detect and Avoid (DAA) for use of UAS in nonsegregated airspace are

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assessed against a set of DAA requirements. A DAA solution is the combination of the sensor suite, the avoidance algorithms, and the method of operation. The functions of a DAA solution are collision avoidance and, in uncontrolled airspace, separation provision. The focus of this chapter is the detection of conflicting traffic by the sensor suite. The sensor suite needs to be able to detect different classes of conflicting traffic in varying environments. Requirements for DAA solutions have to be set, and DAA systems must then be developed to meet these requirements.

ATM requirements for use of UAS in nonsegregated airspace have been drafted by EUROCONTROL (2007). This set includes a subset of requirements that are directly or indirectly of influence on the sensor suite used to Detect and Avoid other traffic. This subset is used as baseline for the establishment of DAA requirements and expanded by development of five additional generic requirements based on the main tasks of a DAA solution: (1) detection of other traffic, (2) tracking of other traffic and assessing if there is a conflict, (3) if there is a conflict, determining which evasive maneuver is to be executed, and (4) executing the selected maneuver. Five candidate solutions are assessed against the requirements: a noncooperative solution, a cooperative solution, and three solutions mixing cooperative and noncooperative sensors.

Overall it is concluded that it is a great challenge to develop a collision avoidance solution for UAS with a satisfactory level of safety. It is even more difficult to develop a DAA system that is capable of both collision avoidance and separation provision. Therefore, collision avoidance is considered a first step in developing DAA solutions for UAS, restricting the operations to flights in controlled airspace with ATC providing separation at all times. It is recommended to continue to develop suitable methods to perform the safety analysis for introduction of UAS equipped with DAA solutions in nonsegregated airspace.

70.1 Introduction

70.1.1 Background and Scope

Historically, pilots have to use their eyes as the sensors to detect other aircraft. It is commonly agreed that like manned aircraft, UAS should adhere to the general rules of the air. According to ICAO Annex 2 (ICAO 2005), all pilots need to exercise vigilance for the purpose of detecting potential collisions and are responsible for taking collision avoidance action when in flight, irrespective whether the flights is under instrument flight rules (IFR) or visual flight rules (VFR) and irrespective of Air Traffic Control (ATC) services. UAS also needs to adhere to the right-of-way rules, as can been found in ICAO Annex 2. For a UAS to adhere to the rules of the air and the right-of-way rules, a DAA solution is needed. The DAA solution should include a collision avoidance function at all times. A separation provision function is needed where this is not provided by ATC. The DAA solution must detect at a sufficient range to allow a timely maneuver to avoid a collision.

In the future both manned and unmanned traffic are expected to be integrated in nonsegregated airspace according to established procedures. This study investigates the current technological capabilities to support UAS with the detection and avoidance of potential traffic conflicts in nonsegregated airspace, thereby building on public references to studies on DAA solutions in Europe. A DAA solution is the combination of the sensor suite, the avoidance algorithms, and the method of operation of the UAS. The functions of a DAA solution are collision avoidance and, in uncontrolled airspace, separation provision. The sensor suite needs to be able to detect different classes of conflicting traffic in varying environments. The avoidance algorithms must assure that the conflicting traffic is avoided by taking appropriate avoidance action. The method of operation determines the autonomy of the DAA solution and is therefore of influence on the required performance of the systems. Requirements for DAA solutions have to be set, and technical systems must be provided to meet these requirements.

The mode of operation of the UAS considered for this study involves a designated UAS operator (DUO). It is assumed the detection of traffic and assessment of collision course is executed automatically, informing the DUO about the conflicting traffic. The focus is the detection of conflicting traffic by the sensor suite which is part of the DAA solution. This choice is made because most European research on detect and avoid focus on the needed sensors. It is assumed that avoidance will be executed automatically with human approval or veto. The type of UAS considered are those categorized as medium range or larger (i.e., a maximum take-off weight (MTOW) of 1,250 kg and up (van Blyenburgh 2011)). Due to this scope of UAS categories, it is believed the accommodation of sensors is not a major issue and is not further discussed in this chapter. The type of aircraft considered as traffic to be detected and avoided is UAS or manned aircraft with a take-off weight of 1,250 kg and up. The airspace classes considered are A–G. Airspace classes A–E are referred to as controlled airspace by ICAO, and subsequently airspace F and G are referred to as uncontrolled airspace. Only technologies to detect and avoid other airborne aircraft are considered. Technologies to avoid terrain, objects on the ground, and adverse weather are not considered. Legal aspects of UAS, DAA, and non-nominal events other than traffic on collision course are considered out of scope.

70.1.2 Objective

The objective of this study is to determine what the most promising candidate technological solutions are for detect and avoid solutions for UAS in nonsegregated airspace considering the requirements imposed.

70.1.3 Approach

The approach of this study is to match the most feasible DAA requirements with the most feasible DAA solutions. Therefore, the trend of requirement definition and the viability and feasibility of these requirements is determined. The key technical issues while developing these requirements and the research efforts to resolve these issues are identified. This leads to a final set of requirements that is deemed most likely. This set of requirements is then matched to five potential DAA solutions, so as to determine which candidate solution is most feasible and viable in terms of satisfying the requirements. The five solutions are determined considering the technologies available and European studies performed to assess these technologies. As Detect and Avoid is considered a "dual" technology that can be used for military and civil UAS, both civil and military initiatives will be considered in this study.

70.2 Detect and Avoid Requirements

This section discusses the requirements for the detect and avoid solution of UAS. It first discusses the generic requirement for the DAA solution to fulfill its primary functions. A set of generic requirements are drafted to be used in the assessment of DAA solutions as given in the final part of this chapter. Next, the requirements in development at by various European standardization and regulatory organizations are described and discussed. A relevant set of requirements is obtained to use for assessment of DAA solutions.

70.2.1 Generic Requirements of the DAA Solution

The two primary functions of a DAA solution are the provision of collision avoidance and, in uncontrolled airspace, separation provision. Table 70.1 lists the responsibilities regarding collision avoidance and separation provision per airspace class and flight rules for manned aviation. It is assumed these responsibilities are unaltered for UAS, where the pilot's role will be fulfilled by either a DUO with the help of a DAA solution or by the DAA solution itself. Therefore, collision avoidance will always be a function of the DAA solution. In case ATC is not responsible for

Table 70.1 Responsibilities related to airspace and flight rules

Flight rules	Airspace classes						
responsibility	A	B	C	D	E	F	G
IFR/IFR *Separation provision*	ATC	ATC	ATC	ATC	ATC	Pilot w/TA	Pilot
IFR/VFR *Separation provision*	–	ATC	ATC	Pilot w/TA	Pilot w/TA	Pilot	Pilot
VFR/VFR *Separation provision*	–	ATC	Pilot w/TA	Pilot w/TA	Pilot w/TA	Pilot	Pilot
All *Collision avoidance*	Pilot	Pilot	Pilot	Pilot	Pilot	Pilot	Pilot

TA ATC traffic advisory

separation provision, the DAA solution needs to fulfill both the separation provision and collision avoidance function. In the latter case ATC, if available, can aid the operator of the UAS (or the UAS itself) by giving traffic advisories, although it has not been established how to provide a UAS traffic advisories.

For both separation provision and collision avoidance, there are four generic tasks of a DAA solution. The requirements that arise from these tasks can be different for separation provision and collision avoidance. The four tasks are

1. Detect of other traffic.
2. Track other traffic and assess if there is a conflict.
3. If there is a conflict, determine which evasive maneuver is to be executed.
4. Execute the selected maneuver.

As indicated in the introduction, the focus of this study is the detection of conflicting traffic; task 1 and task 2 combined. Task 3 must be done by algorithms and communication between traffic. Task 4 is either executed by a DUO or UAS itself again using algorithms. For the purpose of drafting the requirements, task 1 and task 2 are modeled in an event tree, given in Fig. 70.1.

Traffic in proximity of the UAS needs to be detected. Each DAA solution can detect traffic in the volume of airspace that it scans, the surveillance volume. To be able to detect other traffic in time, the DAA solution needs to scan a sufficient large part of the airspace; in other words the surveillance volume needs to be sufficiently large. The surveillance volume is made up by two components: the field

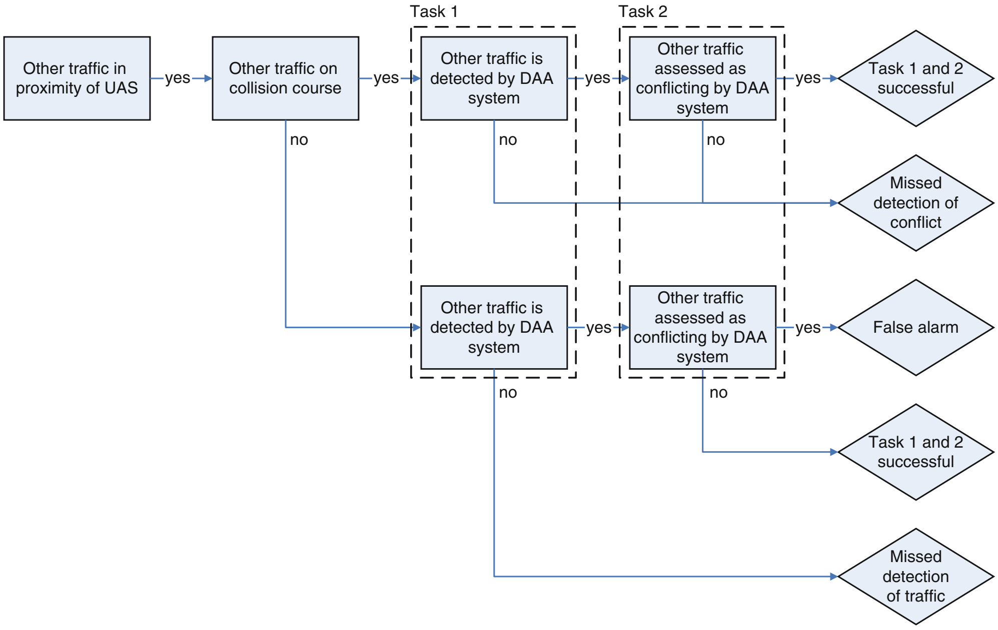

Fig. 70.1 An event tree including task 1 and task 2 of a DAA solution

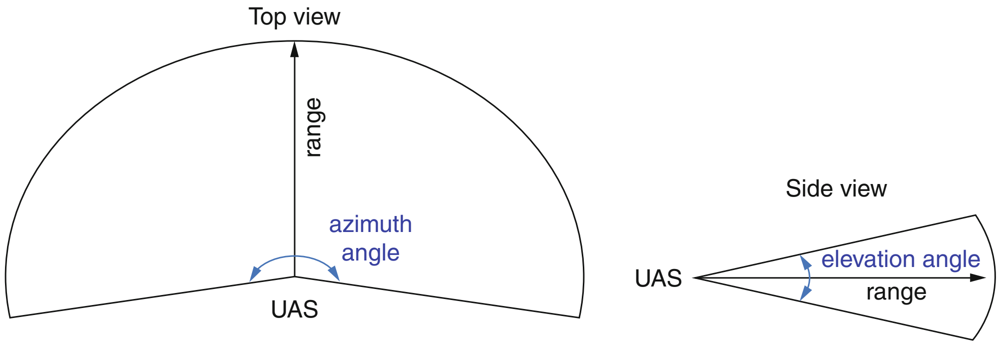

Fig. 70.2 Field of regard and range

of regard (the combination of azimuth and elevation) and the detection range; see Fig. 70.2.

This results in the following two, of five, generic requirements (GR):

GR01: *The DAA system must provide a sufficient surveillance volume by having a sufficient field of regard.*

GR02: *The DAA system must provide a sufficient surveillance volume by having a sufficient detection range.*

If these two requirements are met, the performance of the sensor suite is determined by its success rate (the ratio of detected traffic to total traffic in the surveillance volume). This ratio needs to be sufficiently high. An implicit resultant of this requirement is the need to detect both cooperative and noncooperative traffic. A failure of task 1 results in a missed detection of traffic, which can result in the missed detection of a conflict. The latter is of course unwanted since it can result in an actual collision. The failure to detect traffic that is not conflicting is also unwanted since one cannot depend on providence in designing a DAA solution. Summarizing, the third requirement is

GR03: *The success rate of traffic detection must be sufficient.*

If task 1 is fulfilled, the sensor suite will detect (nearly) all traffic in its surveillance volume. However, not all traffic will be conflicting. The system needs to assess if traffic is conflicting and needs to include a classification of traffic in case the traffic mix includes balloons, gliders, and powered aircraft. The classification is needed to be able to comply with right-of-way rules. Erroneous assessments can be caused by inaccurate sensor information of the other traffic's range, bearing, altitude, and lateral, and vertical speed. Also incorrect assessment of traffic that is not conflicting is unwanted, since it leads to false alarms and can possibly lead to a maneuver that induces a conflict. Summarizing, the fourth requirement is

GR04: *When traffic has been detected, the rate of correct assessments if a situation is a conflict or not must be sufficient.*

Since the function of a DAA solution is to provide collision avoidance and in some instances separation provision, the solution must be able to detect traffic conflicts. Any missed conflict can lead to a loss of separation or, worse, a collision. To emphasize this need the third and fourth requirement are combined into a fifth requirement:

GR05: *The DAA system missed conflict detection rate must be kept at an acceptable level.*

70.2.2 Requirements Under Development by European Organizations

A DAA solution has to fulfill the generic requirements as defined in the previous section. Complimentary to those requirements are those requirements that have to be met if a UAS is operated in nonsegregated airspace. For the analysis of those requirements, four European organizations drafting requirements are considered. The organizations considered are the European Aviation Safety Agency (EASA), EUROCONTROL, the European Organization for Civil Aviation Equipment (EUROCAE), and the Flight in Non-Segregated Airspace (FINAS) group of the North Atlantic Treaty Organization (NATO).

EASA develops the regulatory framework for civil UAS with a maximum takeoff weight larger than 150 kg. In 2008, EASA stated the following on DAA:

> Airworthiness certification is considered to address the intrinsic safety of the UAS. "Sense and Avoid" falls outside this area as its sole purpose is for anti-collision. The operating criteria on which it relies to adequately perform its function are dependent on the airspace being used and the aircraft flying into it. Such criteria should be defined by the authorities responsible for the safety regulation of air navigation services. (EASA 2008)

In Europe, the organization that usually dealt with harmonized safety regulation of air navigation services was EUROCONTROL. However, EASA will gradually take over this responsibility in the coming years.

EUROCONTROL distinguishes two types of air traffic: Operational Air Traffic (OAT) and General Air Traffic (GAT). GAT flights are all movements of civil aircraft, as well as all movements of State aircraft, when these movements are carried out in accordance with the procedures of ICAO. OAT flights are all flights which do not comply with the provisions stated for GAT and for which rules and procedures have been specified by appropriate national authorities. The EUROCONTROL UAV OAT Task Force has drafted Air Traffic Management (ATM) specifications for the use of military UAS as OAT outside segregated airspace (EUROCONTROL 2007). This set includes a subset of requirements that are directly or indirectly of influence on the sensor suite used to Detect and Avoid other traffic. These requirements are independent of the chosen solutions and are based on three main principles:

- UAS operations should not increase the risk to other airspace users.
- ATM procedures should mirror those applicable to manned aircraft.
- The provision of air traffic services to UAS should be transparent to ATC controllers.

It is considered likely that for the use of UAS as GAT in nonsegregated airspace, similar specifications will be developed. The EUROCONTROL Collision Avoidance Requirements for UAS (CAUSE) study confirm this (EUROCONTROL 2010).

According to EUROCONTROL a DAA solution should achieve an equivalent level of safety to a manned aircraft (EUROCONTROL 2007). Since the first discussions on certification of UAS, many attempts have been undertaken to quantify this level of safety for manned aviation. Clearly, when it is not possible to quantify all the elements related to detect and avoid, it is not possible to define an equivalent level of safety. The alternative is to establish a target level of safety (TLS) for UAS. A safety assessment is then needed to prove the TLS can be met by a particular UAS operation. UAS proponents have to work closely with the authorities (e.g., FAA and EASA) to determine what the TLS should be or how it should be defined. Although not easy, the task focus can initially be on a comparison of UAS with manned aircraft.

The NATO FINAS group has also drafted DAA requirements, which are restricted to the situation where separation provision responsibility rests with the designated UAS operator (NATO 2007). The FINAS requirements have been evaluated by the NATO NIAG Steering Group 134. The steering group's conclusion was that the FINAS requirements are incomplete, not coherent in level of detail and often without proper rationale (NATO 2010). Their recommendation toward NATO is to use the EUROCONTROL subset of DAA requirements.

EUROCAE is a European body in which industries work on commonly accepted standards for specific implementations. Generally, showing compliance with these standards can serve industry as certification evidence to convince authorities that their system is safe to use and also increases interoperability between products of different manufacturers. EUROCAE Working Group 73 is tasked to develop a requirement framework that will support civilian UAS airworthiness certification and operational approvals (Hawkes et al. 2008; Kallevig 2011). EUROCAE WG73 has expressed that it is unlikely that a single company producing UAS will make the step as a certification applicant for a UAS to fly in nonsegregated airspace. Focusing on DAA only, WG73 expects that huge efforts, beyond the budget of most industry, are needed to show compliance for requirements such as equivalent level of safety with manned aviation and compliance of DAA solutions with existing ACAS equipment. Instead, a standard would collect the common requirements of potential users, share data for establishing safety, performance and interoperability criteria, and validate the result. This should simplify the process for each applicant who can conform and for the approving authority. WG73 proposes a stepwise UAS integration process:

1. To develop initial standards offering significant additional flight capabilities in nonsegregated airspace compared to flight in segregated airspace, in a reasonable timeframe and with an affordable effort (i.e., UAS nominally flying under IFR with ATC providing separation from other airspace users at all times and UAS flight within Visual Line Of Sight (VLOS) of the DUO)

2. To benefit from the experience of initial standards to develop more complex steps to follow

As a consequence, the result will be a number of EUROCAE standards (e.g., Minimum Aviation System Performance Standards (MASPS) and Minimum Operational Performance Standards (MOPS)) that express system requirements for a specific system or solution. By complying with this standard, the industry is then better able to develop a DAA solution that becomes certifiable and accepted by aviation authorities. Hopefully, this approach will be better than trying to develop several independent and proprietary DAA solution. EUROCAE is currently drafting a framework for such UAS standards. At this stage, no concrete DAA requirements have been published by EUROCAE WG-73 in the public domain.

A continuing discussion is the separation minima; a DAA solution should accomplish if no ATC separation is provided. There are no prescribed ICAO separation minima for manned aircraft where responsibility for separation rested with the onboard pilot. Instead, according to EUROCONTROL it is only necessary that aircraft should not be operated in such proximity to other aircraft as to create a collision hazard (EUROCONTROL 2007). However, industry required something less vague. As a consequence, a practical minimum separation to be achieved by a UAS pilot-in-command is proposed. According to EUROCONTROL several organizations quote or imply that 500 ft is an appropriate and acceptable miss distance for UASs (EUROCONTROL 2007). In the USA, the FAA view of “well clear” (i.e., so as to not represent a collision hazard) is a minimum separation of 500 ft between aircraft. To a considerable degree, this figure is accepted by the Joint JAA/EUROCONTROL UAV Task Force as the basis for recommending work to identify minimum performance standards (MPS) for future DAA systems. Industry itself regards 500 ft as a minimum “worst-case separation” distance for DAA (EUROCONTROL 2007). Finally, in the context of maneuvering between aircraft to achieve safe separation, NATO defines 500 ft as “well clear” (NATO 2007). The use of 500 ft vertical separation is routine between manned aircraft and should therefore not cause undue concern to other airspace users; the application of 500 ft horizontal separation could generate a heightened sense of collision risk. An increase in horizontal separation to 0.5 nm would reduce this perception and also the collision risk and is therefore preferable.

According to EUROCONTROL, ATM regulations and procedures for UASs should mirror as closely as possible those applicable to manned aircraft. UAS-specific ATM procedures should therefore only be implemented where the absence of an onboard pilot – particularly in combination with loss of control data-link – generates a need for special arrangements. Otherwise, the provision of an air traffic service to a UAS should be transparent to the ATC controller and other airspace users. Due to the maturity of the requirements, they can be used in the assessment of DAA solutions and more specifically the sensor suite. A number of requirements are independent of the sensor suite of the DAA solution either because they are relevant for ATM only or for other operational aspects of the UAS. Some requirements are not deemed relevant for this study since they are part of the DAA solution but not dependent on the mix of sensors used; one such requirement is the requirement to notify the DUO in case of separation violation. For this study only those requirements that are directly or indirectly of influence on the sensor suite are considered. These requirements are given below (EUROCONTROL 2007) (note that the numbering from EUROCONTROL is adopted here as well).

Specification UAV4 UAVs should comply with the right-of-way rules as they apply to other airspace users.

Specification UAV6 For VFR flight by UAVs, the UAV pilot-in-command should utilize available surveillance information to assist with separation provision and collision avoidance. In addition, technical assistance should be available to the pilot-in-command to enable him to maintain VMC and to detect and avoid conflicting traffic. An automatic system should provide collision avoidance in the event of failure of separation provision.

Specification UAV7 A UAV DAA system should enable a UAV pilot-in-command to perform those separation provision and collision avoidance functions normally undertaken by a pilot in a manned aircraft, and it should perform a collision avoidance function autonomously if separation provision has failed for whatever reason. The DAA system should achieve an equivalent level of safety to a manned aircraft.

Specification UAV9 Implementation of separation provision and collision avoidance functions in a DAA system should as far as is reasonably practicable be independent of each other. In execution, they should avoid compromising each other.

Specification UAV10 Within controlled airspace where separation is provided by ATC, the separation minima between UAVs operating IFR and other traffic in receipt of a separation service should be the same as for manned aircraft in the same class of airspace.

Specification UAV11 Where a UAV pilot-in-command is responsible for separation, he should, except for aerodrome operations, maintain a minimum distance of 0.5 NM horizontally or 500 ft vertically between his UAV and other airspace users, regardless of how the conflicting traffic was detected and irrespective of whether or not he was prompted by a DAA system.

Specification UAV12 Where a UAV system initiates collision avoidance autonomously, it should achieve miss distances similar to those designed into ACAS. The system should be compatible with ACAS.

70.3 Detect and Avoid Solutions

Detect and Avoid is the capability of a UAS to remain well clear from and avoid collision with other airborne traffic; therefore, it is a combination of self-separation and collision avoidance. In this research a DAA solution is defined as the combination of the sensor suite and the avoidance algorithms and the method of operation of the UAS in order to detect and avoid conflicting traffic. The method of operation is not further discussed; it is assumed a dedicated UAS operator will be in the loop. Many studies do, either briefly or more elaborately, consider operational issues of UAS as part of their work. The issues are related to UAS integration in an operational environment and not on detect and avoid specifically. In the short term, it is not expected that the UAS will fly completely autonomous. Only “last ditch” collision avoidance could be made autonomous. Avoidance algorithms are not widely discussed since the initial focus seems to be on the detect task and not on the avoid task. This is understandable because in order to be able to avoid air traffic, it has to be detected first. There is no detailed information available in the public domain regarding the avoidance algorithms used. One European research project does state that they aim at standardized avoidance logic, and as consequence the algorithms will be in the public domain (MIDCAS 2010a). The focus is on the sensor suite, being a combination of sensors used. A reason for the need for more than one sensor would be the ability to detect both cooperative and noncooperative traffic.

70.3.1 Sensor Suite

The European research projects and the sensors studied are shown in Table 70.2. The background of the projects discussed in this section is publicly available (USICO 2004a, b; EDA 2007; Hutchings et al. 2007; Korn and Edinger 2008; Selier et al. 2008; MIDCAS 2010a, b).

All studies except OUTCAST combine EO/IR sensors with radar technology. Cooperative traffic can be detected better using a cooperative technology such as TCAS (note that the concept is named ACAS). TCAS is equipment compliant with the ACAS concept. In this chapter the term TCAS is used (When referring to the specific equipment TCAS II is meant). Other types of sensors that have not been studied by the above research projects are active and passive acoustic systems, active millimeter wave systems, and collision avoidance systems such

Table 70.2 Type of sensors studied by different European research projects (Verstraeten and Selier 2011)

	TCAS	ADS-B	Radar	LIDAR LADAR	IR camera	Daylight (EO) camera	Passive millimeter wave
Type of sensor	*C*	*C*	*NC-A*	*NC-A*	*NC-P*	*NC-P*	*NC-P*
OUTCAST	▪				▪	▪	
WASLA-HALE			▪	▪	▪	▪	
USICO			▪	▪	▪	▪	▪
ASTRAEA		▪	▪		▪	▪	
DAA study EDA	▪		▪	▪[a]	▪	▪	
MIDCAS	▪[b]	▪	▪		▪	▪	

C cooperative, *NC* noncooperative, *A* active, *P* passive

[a] Only in medium-term solution

[b] The surveillance part of TCAS equipment (transponder interrogator) is considered as a candidate MIDCAS sensor (MIDCAS 2010a)

as FLARM (a commercially available active and cooperative traffic and collision warning system capable of giving traffic advisories) and TCAD (Traffic Collision Avoidance Device: a passive collision avoidance device capable of giving traffic advisories that is commercially available).

The most important ongoing projects with a focus on DAA technology are MIDCAS and ASTRAEA. The importance of these projects is due to the stakeholders involved and the budget available. MIDCAS is a project of the European Defense Agency (EDA) and 14 partners with a budget of 50 million euros. It started in 2009 and will finish in 2013. ASTRAEA is a research program of a UK consortium with a budget of 32 million pounds.

MIDCAS has as objective to demonstrate a DAA system for UAS able to fulfill the requirements for traffic separation and midair collision avoidance in nonsegregated airspace for both cooperative and noncooperative intruders. ASTRAEA aims to ensure that UAS operation is transparent to manned aviation. The behavior of the UAS in flight must be consistent with that expected by manned aviation. Within the ASTRAEA framework, there is a dedicated project focusing on collision avoidance systems. The project seeks to verify the merits of enabling technologies and system capabilities that could be used by UAS for collision avoidance.

70.3.2 Candidate Detect and Avoid Solutions

Five candidate solutions for DAA, representing a number of combinations of sensor technologies, are derived. The DAA solution should include a collision avoidance function at all times. A separation provision function is needed where this is not provided by ATC. For the five candidate solutions the following sensors are considered: TCAS, ADS-B, Radar, IR, and EO. Next, the five conceptual solutions are described, starting with a full noncooperative concept and a full cooperative concept:

1. *Full Noncooperative Concept* This concept combines Radar sensors with EO/IR. This concept is inspired by projects such as WASLA-HALE and USICO. Radar is capable of quickly scanning a large area, also in IMC, although it requires more energy to detect objects through clouds and rainy conditions (when more energy is absorbed) than in VMC. In general powerful Radar introduce more weight and require more power. Besides traffic detection Radar can also be used to detect terrain and weather phenomena. Although this is beyond the scope of DAA for air traffic, it may enhance UAS intrinsic safety. Once directed properly on the conflicting aircraft, EO/IR provides a highly accurate bearing toward the other aircraft and can be used to classify the object by visual inspection.
    a. Advantages: requires no cooperation from the object to be sensed and avoided.
    b. Disadvantages: Detection of objects highly depends on a single type of sensor (Radar) with limited bearing accuracy.
2. *Full Cooperative Concept* This concept combines two cooperative sensors: TCAS II and ADS-B. TCAS II is de facto system for collision avoidance and is

mandated in Europe for larger aircraft with a maximum take-off weight greater than 5,700 kg or authorized to carry more than 19 passengers. Beside detection TCAS II can also advise the pilot with an avoidance maneuver. A version of TCAS that is capable of automatically performing the resolution advisory maneuver has been certified (Airbus 2009). TCAS can therefore be considered the most mature collision avoidance system available. Detection and avoidance is based on information contained in the reply of an interrogated mode-S transponder in the other aircraft. If the conflicting aircraft is also equipped with TCAS II, the avoidance maneuvers of both aircraft are "negotiated" by the systems to maintain maximum safety. An ADS-B equipped aircraft automatically transmits the aircraft identity, position, altitude, and intent information (among others) to other airspace users. With this information other airspace users, but also Air Traffic Control, are able to construct a traffic picture. This way ADS-B can provide a basis for separation provision, which is especially useful when separation is not provided by ATC. The completeness of such a traffic picture depends on the population of nearby aircraft equipped with "ADS-B out," which at this moment is not yet the case in Europe.

- Advantages: Once detected good tracks may be obtained of nearby traffic, and ADS-B may provide information useful for classification.
- Disadvantages: With this system it is not possible to detect noncooperative traffic.

The next three concepts mix both cooperative and noncooperative sensors. These concepts are described below:

3. *Mixed Concept 1* This concept combines one cooperative sensor TCAS II with the noncooperative sensor EO/IR. It is based on the work performed in the project OUTCAST that had the objective to investigate a DAA solution with equipment readily available on the market. The use of operation is thought to be as follows: detect other traffic with TCAS and estimate if there is a reasonable chance of collision course. If that is the case, use EO/IR to classify the intruder (for separation provision) and obtain a better bearing toward the intruder. With this information an evasive maneuver can be calculated.
   - Advantages: simple concept.
   - Disadvantages: limitations of TCAS sensing accuracies (bearing), detection of noncooperative traffic only by EO/IR, difficult to keep track of multiple intruders by EO/IR.
4. *Mixed Concept 2* This concept extends Mixed Concept 1 (TCAS and EO/IR) with Radar. It is based on the work performed in the DAA study by EDA. The use of operation is thought to be as follows: detect other traffic with TCAS and Radar and, estimate if there is a reasonable chance of collision course. If that is the case, use EO/IR to classify the intruder (for separation provision). With this information calculate an evasive maneuver and obtain a better bearing toward the intruder.
   - Advantages: In addition to Mixed Concept 1, detection of noncooperative traffic can primarily be done by Radar.
   - Disadvantages: Use of Radar adds more weight to the UAS and requires more power.

Table 70.3 Summary of five candidate detect and avoid solutions

	1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
EO/IR	▪		▪	▪	▪
Radar	▪			▪	▪
TCAS		▪	▪	▪	
ADS-B		▪			▪

5. *Mixed Concept 3* This concept combines one cooperative sensor (ADS-B) and two noncooperative sensors (Radar and EO/IR) and only differs from Mixed Concept 2 in the sense that TCAS is replaced by ADS-B as the cooperative sensor. It is based on the work performed in the ASTRAEA project. The rationale for the replacement of TCAS is that through ADS-B more accurate information about air traffic can be obtained, compared to TCAS. In that case, for the collision avoidance function another solution must be in place (not necessarily performed by ADS-B only, but likely a combination of all sensors). ADS-B may provide information useful for classification.
    - Advantages: Mix of sensors gives a high probability of detecting all nearby traffic.
    - Disadvantages: ADS-B not mandated.

The five concepts are summarized in Table 70.3.

70.4 Assessment of Detect and Avoid Solutions

Tables 70.4 and 70.5 provide an assessment of the 5 DAA conceptual solutions (in columns) against the identified UAS requirements (in rows). The table is filled using the information available and NLR expert judgment. In Table 70.4 the situation is considered where ATC is responsible for separation provision and the DUO/UAS for collision avoidance. In Table 70.5 the situation is considered where the DUO/UAS is responsible for separation provision and collision avoidance. For each conceptual solution, the feasibility of compliance with the requirement is discussed; to what extent is the DAA conceptual solution compliant with the UAS requirement? Specific issues that are still in the way of compliance are indicated.

Using the full noncooperative concept with Radar and EO/IR sensors, it is harder to detect cooperative traffic than when using cooperative concepts. Using only a cooperative system is not feasible however, because there is always a need to detect noncooperative traffic. Even if transponders are mandated, transponder system failures are possible, resulting in de facto noncooperative traffic. The most feasible solution in the near future is combining TCAS, EO/IR, and Radar. Such a system is only possible in fairly large UAS where accommodation is not an issue. To reliably detect noncooperative traffic, high performance is required from sensors. Replacement of the cooperative surveillance functionality of TCAS by ADS-B (as in mixed concept III) is not foreseen in the near future. No practical DAA solutions are fully compliant with the requirement for independence between collision avoidance and separation assurance.

70.5 Conclusions and Recommendations

Overall it is concluded that it is a great challenge to develop a *collision avoidance* solution for UAS with a satisfactory level of safety. It is even more difficult to develop a Detect and Avoid (DAA) system that is capable of *both collision avoidance and separation provision*. Many consider therefore collision avoidance as the first step in developing DAA solutions for UAS, restricting the operations to flights in controlled airspace with ATC providing separation at all times.

There is no consensus that the requirement for equivalent level of safety (ELOS) compared to manned aircraft is feasible to work with. The level of safety for manned aviation is difficult to adequately quantify. As an alternative quantified Target Levels of Safety (TLS) for UAS operations could be set.

There is general consensus that DAA solutions require multiple sensors to detect and avoid both cooperative and non cooperative air traffic. Therefore, in this study, five conceptual solutions combining different types of sensors are assessed against UAS. The conclusions are:

- The full noncooperative concept with Radar and electro-optical/infrared (EO/IR) sensors is flawed because cooperative traffic is harder to detect than when using cooperative concepts.
- The full cooperative concept seems not feasible because there is always a need to detect noncooperative traffic.
- DAA solutions combining a Traffic Collision Avoidance System (TCAS), EO/IR and Radar, seem to be the most feasible ones in the near future if accommodation is not an issue. However, high performance is required from sensors to reliably detect noncooperative traffic. Replacement of the cooperative surveillance functionality of TCAS by Automatic Dependent Surveillance-Broadcast (ADS-B) (as in mixed concept III) is not foreseen in the near future.
- No practical DAA solutions are fully compliant with the requirement for independence between collision avoidance and separation assurance.

The following recommendations are made:

- Existing passive and active sensors capable of detecting noncooperative traffic need to be further developed such that the performance is sufficient to reliably detect noncooperative traffic.
- DAA solutions for small UAS where accommodation is an issue need further study.
- It should be assessed if it is possible to develop a practical DAA solution that is fully compliant with the requirement for independence between collision avoidance and separation assurance.

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Table 70.4 Assessment of five DAA sensor suites. Case: ATC is responsible for separation

t9.1		1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
t9.2 t9.3		Radar, EO/IR	TCAS, ADS-B	TCAS, EO/IR	TCAS, EO/IR, Radar	ADS-B, EO/IR, Radar
	Generic Requirements					
	GR01: field of regard (azimuth, elevation)	Note: assessed for noncooperative (NC) and cooperative (C) traffic separately. Cooperative traffic is assessed considering the means available to exchange state information				
t9.4	+ = Large − = Small 0 = None	NC: +/− C: 0 Both EO/IR and Radar suffer more from masking by aircraft structure when increased field of regard is required	NC: 0 C: + TCAS and ADS-B have a full sphere field of view; reception does not suffer from masking by aircraft structure	NC: − C: + EO/IR suffer from masking by aircraft structure; compensated by TCAS for cooperative traffic only	NC: +/− C: + EO/IR and Radar suffer from masking by aircraft structure; compensated by TCAS for cooperative traffic	NC: +/− C: + EO/IR and Radar suffers from masking by aircraft structure; compensated by ADS-B for cooperative traffic
	GR02: detection range	Note: assessed for noncooperative (NC) and cooperative (C) traffic separately. Cooperative traffic is assessed considering the means available to exchange state information				
t9.5	+ = Long range − = Short range 0 = None	NC: +/− C: +/− EO/IR detection range is limited and unable to detect airspace users through clouds; Radar has longer detection range	NC: 0 C: + ADS-B detection range is high, and TCAS detection range is medium; both are hardly influenced by weather	NC: − C: +/− TCAS detection range is medium and hardly influenced by weather	NC: +/− C: +/− TCAS detection range is medium and hardly influenced by weather. For noncooperative traffic equal to concept 1	NC: +/− C: + ADS-B detection range is high and hardly influenced by weather. For noncooperative traffic equal to concept 1

Table 70.4 (continued)

t10.1		1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
t10.2 t10.3		Radar, EO/IR	TCAS, ADS-B	TCAS, EO/IR	TCAS, EO/IR, Radar	ADS-B, EO/IR, Radar
	Generic Requirements					
	GR03: success rate of traffic detection + = High success rate − = Low success rate	+/− DAA potentially capable to detect all nearby traffic capability to detect cooperative traffic is less than mixed concepts	− Detection of all traffic is poor, as DAA is only capable to detect cooperative traffic	+/− Both DAA sensors needed for detection of traffic (TCAS for distance EO/IR for accurate bearing)	+ DAA in potential capable to detect all nearby traffic	+ DAA in potential capable to detect all nearby traffic
	GR04: rate of correctly assessed conflicts + = High success rate − = Low success rate	Note: the correctness of an assessment of a whether a situation is a conflict or not depends on accuracies of bearing/range estimations and tracking errors. For the rating it is assumed traffic has been detected				
t10.4		− Radar has good range accuracy but poor bearing accuracy, partly compensated by EO/IR, depending on weather conditions	+ ADS-B provides accurate position of conflicting aircraft; hence tracking accuracy is high, improved by TCAS	− TCAS has good range accuracy but poor bearing accuracy, partly compensated by EO/IR, depending on weather conditions	+/− TCAS and Radar have good range accuracy but poor bearing accuracy, partly compensated by EO/IR, depending on weather conditions	+ ADS-B provides accurate position of conflicting aircraft; hence tracking accuracy is high, improved by Radar and EO/IR

	GR05: missed conflict detection rate + Low missed conflict detection rate – High missed conflict detection rate	Note: this is a combination of GR03 (success rate of traffic detection) and GR04 (rate of correctly assessed conflicts)				
t11.1		– Medium detection success rate, but low tracking performance	– Poor detection success rate of all traffic	– Medium detection success rate, but low tracking performance	+/– High detection success rate and capable of accurate tracking	+ High detection success rate and well capable of accurate tracking
	Eurocontrol Requirements					
	UAV04: comply with the right-of-way rules	Derived requirement: bearing of intruders must be determined				
t11.2		Feasible	Feasible	Feasible	Feasible	Feasible
	UAV06: VFR flight: system to assist DUO in separation provision. An automatic system should provide collision avoidance in the event of failure of separation provision	Note: in the assessment it is assumed that SSR transponders are mandated, but may fail during flight, therefore collision avoidance with noncooperative traffic must be included				
t11.3		Challenging The challenge is to detect all nearby traffic with noncooperative sensors only. The performance of the sensors must be very high to estimate distance, bearing, and altitude difference with the intruder aircraft	Not possible Detection of noncooperative traffic is not possible with cooperative sensors only	Challenging The challenge is to detect all nearby noncooperative traffic only by visual detection	Likely solution Cooperative traffic is handled by TCAS. Detection of remaining noncooperative traffic would be possible by combining Radar and EO/IR	Likely solution Cooperative traffic is handled by ADS-B as a TCAS replacement. Detection of remaining noncooperative traffic would possible by combining Radar and EO/IR

Table 70.4 (continued)

	1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
	Radar, EO/IR	TCAS, ADS-B	TCAS, EO/IR	TCAS, EO/IR, Radar	ADS-B, EO/IR, Radar
Eurocontrol Requirements					
UAV07: equivalent level of safety (for collision avoidance) with manned aviation	Note: quantification of equivalent level of safety (ELOS) is a challenge in itself, and there is no consensus that ELOS should be posed as a requirement for certification. Alternatively a target level of safety could be agreed upon. When ELOS is interpreted as having a type of sensor equivalent to the human eye, concept 2 fails, because it lacks an E/O sensor				
	Collision avoidance risk containment using DAA to be shown	Collision avoidance risk containment using DAA to be shown but expected to be highly challenging	Collision avoidance risk containment using DAA to be shown	Collision avoidance risk containment using DAA to be shown	Collision avoidance risk containment using DAA to be shown
UAV09: independence of separation provision and collision avoidance as far as reasonably practicable	Compliance with requirement is implicitly met because in this case ATC is responsible for separation provision and the DUO for collision avoidance				
UAV10: separation minima UAV in IFR equal to traffic with manned aircraft	Compliance with requirement is implicitly met because in this case ATC is responsible for separation provision				
UAV11: separation minima 0.5 nm horizontal or 500 ft vertical	Compliance with requirement is implicitly met because in this case ATC is responsible for separation provision				
UAV12: DAA compatible with ACAS (in terms of miss distances)	Compliance with this performance requirement does not only depend on the sensor performance but also on the UAS maneuverability. Focusing on the sensors only all concepts could comply with the requirement, provided the sensors have enough performance				

Table 70.5 Assessment of five DAA sensor suites. Case: no ATC, DUO/UAS responsible for both collision avoidance and separation provision

t13.1		1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
t13.2 t13.3		Radar, EO/IR	TCAS, ADS-B	TCAS, EO/IR	TCAS, EO/IR, Radar	ADS-B, EO/IR, Radar
	Generic Requirements					
	GR01: field of regard (azimuth, elevation) + = Large − = Small 0 = None	Note: assessed for noncooperative (NC) and cooperative (C) traffic separately. Cooperative traffic is assessed considering the means available to exchange state information				
t13.4		NC: +/− C: 0 Both EO/IR and Radar suffer more from masking by aircraft structure when increased field of regard is required	NC: 0 C: + TCAS and ADS-B have a full sphere field of view; reception does not suffer from masking by aircraft structure	NC: − C: + EO/IR suffers from masking by aircraft structure, compensated by TCAS for cooperative traffic only	NC: +/− C: + EO/IR and Radar suffer from masking by aircraft structure, compensated by TCAS for cooperative traffic	NC: +/− C: + EO/IR and Radar suffer from masking by aircraft structure, compensated by ADS-B for cooperative traffic
	GR02: detection range + = Long range − = Short range 0 = None	Note: assessed for noncooperative (NC) and cooperative (C) traffic separately. Cooperative traffic is assessed considering the means available to exchange state information				
t13.5		NC: +/− C: +/− EO/IR detection range is limited and unable to detect airspace users through clouds; Radar has longer detection range	NC: 0 C: + ADS-B detection range is high, and TCAS detection range is medium; both are hardly influenced by weather	NC: − C: +/− TCAS detection range is medium and hardly influenced by weather	NC: +/− C: +/− TCAS detection range is medium and hardly influenced by weather. For noncooperative traffic equal to concept 1	NC: +/− C: + ADS-B detection range is high and hardly influenced by weather. For noncooperative traffic equal to concept 1

Table 70.5 (continued)

t14.1		1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
t14.2 t14.3		Radar, EO/IR	TCAS, ADS-B	TCAS, EO/IR	TCAS, EO/IR, Radar	ADS-B, EO/IR, Radar
	Generic Requirements					
	GR03: success rate of traffic detection + = High success rate − = Low success rate	+/− DAA potentially capable to detect all nearby traffic capability to detect cooperative traffic is less than mixed concepts	− Detection of all traffic is poor, as DAA is only capable to detect cooperative traffic	+/− Both DAA sensors needed for detection of traffic (TCAS for distance, EO/IR for accurate bearing)	+ DAA in potential capable to detect all nearby traffic	+ DAA in potential capable to detect all nearby traffic
	GR04: rate of correctly assessed conflicts (after traffic has been detected)	Note: the correctness of an assessment of a whether a situation is a conflict or not depends on accuracies of bearing/range estimations and tracking errors. For the rating it is assumed traffic has been detected				
t14.4	+ = High success rate − = Low success rate	− Radar has good range accuracy but poor bearing accuracy, partly compensated by EO/IR, depending on weather conditions	+ ADS-B provides accurate position of conflicting aircraft; hence, tracking accuracy is high, improved by TCAS	− TCAS has good range accuracy but poor bearing accuracy, partly compensated by EO/IR, depending on weather conditions	+/− TCAS and Radar have good range accuracy but poor bearing accuracy, partly compensated by EO/IR, depending on weather conditions	+ ADS-B provides accurate position of conflicting aircraft; hence, tracking accuracy is high, improved by Radar and EO/IR

	GR05: missed conflict detection rate + Low missed conflict detection rate – High missed conflict detection rate	Note: this is a combination of GR03 (success rate of traffic detection) and GR04 (rate of correctly assessed conflicts)				
t15.1		– Medium detection success rate but low tracking performance	– Poor detection success rate of all traffic	– Medium detection success rate but low tracking performance	+/– High detection success rate and capable of accurate tracking	+ High detection success rate and well capable of accurate tracking
	Eurocontrol Requirements					
	UAV04: comply with the right-of -way rules	Derived requirement: bearing of intruders must be determined				
t15.2		Feasible	Feasible	Feasible	Feasible	Feasible
	UAV06: VFR flight: system to assist DUO in separation provision. An automatic system should provide collision avoidance in the event of failure of separation provision	Challenging Detection only based on noncooperative sensors	Not feasible Detection of noncooperative traffic not possible with cooperative sensors only	Challenging Detection of noncooperative traffic based only on EO/IR	Likely solution Detection of noncooperative traffic possible with Radar and EO/IR	Likely solution Detection of noncooperative traffic possible with Radar and EO/IR
	UAV07: equivalent level of safety with manned aviation	Note: quantification of equivalent level of safety (ELOS) is a challenge in itself, and there is no consensus that ELOS should be posed as a requirement for certification. Alternatively a target level of safety could be agreed upon. When ELOS is interpreted as having a type of sensor equivalent to the human eye, concept 2 fails, because it lacks an E/O sensor				
t15.3		DAA risk containment to be shown	DAA risk containment to be shown but expected to be highly challenging	DAA risk containment to be shown	DAA risk containment to be shown	DAA risk containment to be shown

Table 70.5 (continued)

t16.1		1. Full non-cooperative concept	2. Full cooperative concept	3. Mixed concept 1	4. Mixed concept 2	5. Mixed concept 3
t16.2 t16.3		Radar, EO/IR	TCAS, ADS-B	TCAS, EO/IR	TCAS, EO/IR, Radar	ADS-B, EO/IR, Radar
	Eurocontrol Requirements					
	UAV09: independence of separation provision and collision avoidance as far as reasonably practicable. In execution, they should avoid compromising each other	Requirement interpreted as sensors used for collision avoidance should not be used for separation provision. Sensor types are allocated to fulfill SA and CA functions independently				
t16.4		Architectures possible in theory, but not practicable When two different radars are used (1 for SA function and 1 for CA function), EO/IR used to enhance each of them	Architectures possible in theory, but not practicable Not practicable, as noncooperative traffic cannot be detected. Assuming cooperative traffic only here: ADS-B could be used for SA function, and TCAS for CA functions, provided the UAV maneuverability is sufficient (i.e., compliant with ACAS II)	Not possible Both TCAS and EO/IR would be needed for CA function. This leaves no independent sensor for SA function	Possible, but without full compliance with requirement Full compliance with both TCAS and EO/IR would be needed for CA function. Radar could be used for the SA function. High sensor performance required (especially to detect difference in altitude). For best performance, all sensors would be needed for CA function, while Radar should also be used for the SA function	Possible, but without full compliance with requirement Full compliance with, e.g., Radar and EO/IR used for CA function and ADS-B for SA function. High sensor performance required (especially to detect difference in altitude). For best performance, all sensors would be needed for CA function, while ADS-B and Radar should also be used for the SA function

UAV10: separation minima UAV IFR same as for manned traffic	Not applicable for the case where DUO is both responsible for separation provision and collision avoidance				
UAV11: separation minima 0.5 nm hor or 500 ft vert	To be shown	To be shown	To be shown	To be shown	To be shown
UAV12: DAA compatible with ACAS (miss distances)	Compatibility to be shown	Compatibility to be shown	Compatibility to be shown	Compatibility to be shown	Compatibility to be shown

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