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GUIDANCE ON SENSE AND AVOID FOR UNMANNED AIRCRAFT SYSTEMS

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NATO LETTER OF PROMULGATION

23 February 2018

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for

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CHAPTER 1 INTRODUCTION

1.1. GENERAL REFERENCES

References applicable to the entire document or used multiple times are listed here, and they are referenced within the text with the standard number or author. References applicable only to a specific section are defined in footnotes therein.

1.1.1. NATO Standards and Allied Publications

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SAE, Guidelines for Development of Civil Aircraft and Systems, ARP4754A, 2010.

1.2. TERMS AND DEFINITIONS

1.2.1. Definitions

Active Surveillance	Surveillance that requires signal transmission from the surveillance equipment.
Air Traffic Control Service	A service provided for the purpose of: a) preventing collisions: 1) between aircraft, and 2) on the manoeuvring area between aircraft and obstructions, and b) expediting and maintaining an orderly flow of air traffic (ICAO Annex 2/11)
Air Traffic Management	The dynamic, integrated management of air traffic and airspace — safely, economically and efficiently — through the provision of facilities and seamless services in collaboration with all parties. (ICAO Doc 9854)
Air Traffic Management System	A system that provides ATM through the collaborative integration of humans, information, technology, facilities and services, supported by air and ground- and/or space-based communications, navigation and surveillance. (ICAO Doc 9854)
Air Vehicle Control Station	The subsystem designed to plan and control a UAS mission, including sensor employment and connectivity with the appropriate airspace controlling authority. (ATP-3.3.8.1/STANAG 4670)
As Low as Reasonably Practicable	A risk is considered to be “As Low As Reasonably Practicable” when the cost of any further Risk Reduction is demonstrated grossly disproportionate to the benefit obtained from that risk reduction. This cost includes the loss of defense capability as well as financial or other resource costs. (AOP-15/STANAG 4297)
Command and Control Link	The data link between the remotely piloted aircraft and the remote pilot for the purposes of managing the flight (ICAO Annex 2)
Conflict	Any situation involving an aircraft and a hazard in which the applicable separation minima may be compromised. (ICAO Doc 9854)
Conflict Management	The function to limit, to an acceptable level, the risk of collision between aircraft and hazards. (ICAO Doc 9854)
Cooperative Aircraft	Aircraft that contain operable equipment for the purposes of identification—e.g., transponder, ADS-B.
Detect and Avoid	The capability to see, sense or detect conflicting traffic or other hazards and take the appropriate action. (ICAO Annex 2)
Field of Regard	The total angle where detections can be made by the system.

Noncooperative Aircraft	Aircraft that do not contain operable equipment for the purposes of identification.
Passive Surveillance	Surveillance that does not employ signal transmission from the surveillance equipment.
Remotely Piloted Aircraft	An unmanned aircraft that is controlled from a remote pilot station by a pilot who has been trained and certified to the same standards as a pilot of a manned aircraft. (AAP-06)
Separation Minima	The minimum displacements between an aircraft and a hazard which maintain the risk of collision at an acceptable level of safety. (ICAO Doc 9854)
Separator	The agent responsible for separation provision for a conflict and can be either the airspace user or a separation provision service provider. (ICAO Doc 9854)
Sense and Avoid	Detect and Avoid of other aircraft in flight for unmanned aircraft systems. Note: this document only addresses the sense and avoid of other aircraft in flight, rather than additional hazards, such as birds, terrain, obstacles, weather, and aircraft on the ground.
UAS Operator	The individual in the Air Vehicle Control Station tasked with overall responsibility for operation and safety of the UAS. Equivalent to the pilot in command of a manned aircraft. (ATP-3.3.8.1/STANAG 4670)
Unmanned Aircraft	An aircraft that does not carry a human operator and is operated remotely using varying levels of automated functions. Notes: 1. Unmanned aircraft can be expendable or recoverable. 2. Unmanned aircraft may carry a lethal or non-lethal payload. 3. Cruise missiles are not considered unmanned aircraft. (NATO)
Unmanned Aircraft System	A system whose components include the unmanned aircraft, the supporting network and all equipment and personnel necessary to control the unmanned aircraft. (AAP-06)

1.2.2. Acronyms

ABSAA	Airborne Sense and Avoid
ACAS	Airborne Collision Avoidance System
ADM	Aeronautical Decision Making
ADS-B	Automatic Dependent Surveillance-Broadcast
ALARP	As Low as Reasonably Practicable
ATC	Air Traffic Control
ATM	Air Traffic Management
C2	Command and Control

DAA	Detect and Avoid
DAL	Design Assurance Level
EO	Electro-Optical
FINAS	Flight in Non-Segregated Airspace Working Group
FOR	Field of Regard
GBSAA	Ground Based Sense and Avoid
HITL	Human in the Loop
HMI	Human Machine Interface
HSI	Human Systems Integration
ICAO	International Civil Aviation Organization
IMC	Instrument Meteorological Conditions
IFR	Instrument Flight Rules
IR	Infrared
JCGUAS	Joint Capability Group Unmanned Aircraft Systems
LOA	Level of Automation
M&S	Modelling and Simulation
MAA	Military Aviation/Airworthiness Authority
PIC	Pilot-in-Command
RA	Resolution Advisory (ACAS)
RF	Radio Frequency
RPA	Remotely Piloted Aircraft
RR	Risk Ratio
S&A	See and Avoid
SA	Situation Awareness
SAA	Sense and Avoid
SATCOM	Satellite Communications
SME	Subject Matter Expert
SSCI	Software Safety Criticality Index
STANAG	Standardization Agreement
STANREC	Standardization Recommendation
SWaP	Size, Weight, and Power
TA	Traffic Advisory (ACAS)
TLS	Target Level of Safety
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
VMC	Visual Meteorological Conditions
VFR	Visual Flight Rules
VV&A	Verification, Validation & Accreditation

1.3. BACKGROUND

Unmanned Aircraft Systems (UAS) are a key enabler for NATO missions. However, UAS operations without a pilot in the aircraft have faced operational restrictions due in part to the lack of a capability to see and avoid other aircraft. In order to achieve the NATO goal of unfettered UAS operations in non-segregated airspace on par with existing manned aircraft operations, a Sense and Avoid (SAA) capability will be needed that satisfies this See & Avoid responsibility. The NATO Flight in Non-Segregated Airspace Working Group (FINAS), under the auspices of the Joint Capability Group Unmanned Aircraft Systems (JCGUAS), commissioned consistent NATO-wide guidelines for the development of Sense and Avoid systems to enable NATO and member state cross-border operations. This document leverages the findings of two NATO Industrial Advisory Group (NIAG) studies regarding SAA (SG 134 and SG 205); therefore, the final reports of these studies are included as references.

1.4. PURPOSE AND SCOPE

1. This Allied Publication details comprehensive guidance and recommended practice for the development of Sense and Avoid systems, referencing and providing guidance regarding application of existing standards and best practice. It does not contain operational requirements nor equipment requirements; rather, it is intended the bridge the gap between operational requirements and equipment requirements—i.e., how to develop a system consistent with the operational requirements. A civil example of operational requirements is the ICAO RPAS Manual (Doc 10019) and of equipment requirements are Minimum Operational Performance Standards (MOPS) developed by EUROCAE and RTCA. The guidance and recommended practice herein is intended to be used by program managers and systems engineers to guide system development, and by others involved in system development and approval as a reference. This document is intended to apply to a wide diversity of potential system architectures, and is not intended to unnecessarily constrain implementations; therefore, it allows varying levels of automation and operator involvement. Additionally, it is intended to provide a common set of NATO terminology and concepts that are linked directly to operational requirements that can be used by system and standards developers. This guidance could be used in the future to develop common NATO SAA requirements approved within a STANAG.

2. This document references the civil internationally harmonized ICAO Convention on International Civil Aviation and associated Annexes. Contracting States to ICAO may deviate from the rules within their national regulations and practices, but the civil and military requirements pertaining to the avoidance of collision are fairly consistent across NATO Member States. According to the preamble to the Convention on International Civil Aviation, the convention is only applicable to civil, and not state, aircraft. Nevertheless, there is content, such as due regard, that is directly applicable to state aircraft. Additionally, NATO Member States routinely operate military aircraft under civil rules and procedures aligning with ICAO

standards and procedures during peace time. Furthermore, States may require coordination with or approval from their civil counterparts for operational approval. Therefore, the use of ICAO standards, procedures, and guidance provides a common understanding that will aid cross border operations. In this document, civil guidance is used to provide operational context, rather than to directly levy requirements on military state aircraft. Therefore, although this is a NATO document, the SAA guidance and recommended practice is likely to be useful to civil systems as well.

1.5. DOCUMENT OVERVIEW

1. This Allied Publication first describes the responsibilities of an airspace user for the avoidance of midair collisions to provide operational context, and it provides a generic system functional architecture. Next, the overarching development process is detailed including system safety assessment. Finally, each component of the system architecture is discussed in detail: human factors, alerting and guidance, and surveillance.

2. The guidance and recommended practice in this document is indicated by statements using the term *should*, or is otherwise indicated by explicit statements such as “it is recommended that”. Although this document does not contain binding requirements, that would be indicated using the term *shall*, assumed requirements, critical guidance, and existing standards are reinforced using the term *must*, or by statements such as “it is critical/important that”.

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CHAPTER 2 SYSTEM

2.1. BACKGROUND

1. Pilots have a regulatory responsibility to operate their aircraft in a safe manner. Early aviation regulations adhered almost exclusively to the “see and be seen” concept to reduce midair collision frequency and it provides a constant underpinning for midair collision prevention to this day. The “see and be seen” concept has led to regulations concerning aircraft lighting and equipage requirements, the regulatory requirement of an on-board pilot to see and avoid other airborne aircraft, and its limitations led to the development of the air traffic control system, ACAS, ADS-B, and other systems.

2. Unmanned aircraft do not have an on-board pilot to satisfy regulations concerning See & Avoid (S&A). Sense and Avoid (SAA) is a means for unmanned aircraft system (UAS) to satisfy the requirement of an on-board pilot to see and avoid other airborne aircraft. Detect and Avoid (DAA) has been broadly defined by the International Civil Aviation Organization (ICAO) in ICAO Annex 2 Rules of the Air and also the RPAS Manual:

> Detect and Avoid: The capability to see, sense or detect conflicting traffic or other hazards and take the appropriate action.

3. Detect and Avoid includes the avoidance of hazards other than aircraft, such as terrain and obstacles, while Sense and Avoid as defined here is specific to the detect and avoid of other aircraft in flight by the unmanned aircraft system and is the focus of this document[1]:

> Sense and Avoid: Detect and Avoid of other aircraft in flight for unmanned aircraft systems.

4. It is also important to note that SAA is not a replacement for, but rather compliments air traffic control (ATC) separation, the Airborne Collision Avoidance System (ACAS), or other systems and procedures. SAA is part of the Safety Management System and as such, SAA needs to be compatible and interoperate with these systems and procedures. Existing equipment, such as ACAS, could be used as part of an SAA capability.

2.2. OBJECTIVES AND RESPONSIBILITIES

Because Sense and Avoid will satisfy the See & Avoid requirement for unmanned aircraft, a description of See & Avoid and how it operates within the Air Traffic

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[1] Note that this does not prohibit the use of the same SAA equipment for the avoidance of other hazards such as birds, weather, and terrain.

Management (ATM) System is necessary to provide context for SAA system requirements, development, and operations. ICAO Annex 2, Rules of the Air, provides internationally harmonized and accepted standards regarding the operation of civil aircraft.

2.2.1. Objectives

1. The two objectives of See & Avoid are: 1) avoiding hazardous situations that could develop into a potential midair collision (collision hazards) by remaining well clear of other aircraft; and 2) the avoidance of midair collisions when a collision hazard exists with another aircraft. Well clear and collision hazard are defined to be mutually exclusive and exhaustive conditions—i.e., when a collision hazard exists, the aircraft are not well clear and vice versa. These objectives are codified in the ICAO Rules of the Air (ICAO Annex 2):

> 3.2 Avoidance of collisions
> Nothing in these rules shall relieve the pilot-in-command of an aircraft from the responsibility of taking such action, including collision avoidance manoeuvres based on resolution advisories provided by ACAS equipment, as will best avert collision.
>
> *Note 1.—It is important that vigilance for the purpose of detecting potential collisions be exercised on board an aircraft, regardless of the type of flight or the class of airspace in which the aircraft is operating, and while operating on the movement area of an aerodrome.*
>
> 3.2.1 Proximity
> An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard.

2. In order to accomplish See & Avoid effectively, pilots are required to follow right-of-way rules that are also encoded in the Rules of the Air. Right-of-way rules help to maintain safety by providing coordination and guidance on how to manoeuvre with respect to other airborne aircraft to ensure that conflicting manoeuvres are not selected by both aircraft. Right-of-way rules are used in advance of collision hazards in order to prevent a collision hazard from developing, and are also used to avoid midair collision with another aircraft when a collision hazard exists. However, deviations to the right-of-way rules are permitted when well clear.

2.2.2. Responsibilities

1. The responsibilities and constraints for See & Avoid in the existing ATM system, and thus SAA, depend on whether an air traffic control (ATC) service is being provided:

    a. When an ATC service is provided, it is the pilot’s responsibility to provide See & Avoid which acts to avert collision once the ATC service has been compromised. In this scenario, the prevention of collision hazards is a responsibility of the ATC service (ICAO Doc 9426 & 4444).

b. When an ATC service is not provided, it is the pilot's responsibility to provide See & Avoid including avoiding collisions and collision hazards. This situation has been called own or visual separation in ICAO Doc 9426 & 4444.

Manned See & Avoid does not consist of independent systems to satisfy the objectives of avoiding collisions and collision hazards (unless ACAS or equivalent is separately mandated), so independent systems are not required for SAA. Independent in this context means that a system is not dependent on the other for operation. It should be noted that the terms *collision avoidance* and *self separation* (*remain well clear* in the ICAO RPAS Manual) are explicitly avoided herein due to differing conceptual perspectives encountered with respect to SAA. Specifically, the terms *collision avoidance* and *self separation* can indicate serial actions/functions or independent defensive layers (as in ICAO Doc 9854)—the latter requires independence while the former does not. If a system developer chooses to use these terms, they should be clearly defined because this is a common source of confusion. The guidance described in this document can apply to either conceptual perspective. The term *conflict management* will be used in this document to encompass all ATM functions and components intended to prevent collisions between aircraft.

2. Separation minima are defined as the minimum displacements between aircraft which maintain the risk of collision and collision hazards at an acceptable level (definition derived from ICAO Doc 9854). Separation minima do not equate directly to what constitutes collision hazard due to uncertainties that require targeting an appropriately larger displacement. Detecting when the ATC service has been compromised may not be straightforward due to the diverse set of separation procedures and minima, and the compromise may only be detected once a collision hazard exists and action is necessary to avert collision. It is possible that the SAA system may be able to avoid a collision hazard after the ATC service separation mode has been compromised—e.g., if the SAA separation minima are much smaller than the ATC service separation minima. In any case, it is critical that the compatibility of the SAA system with an ATC service be fully considered under all operating modes.

3. The responsibility of See & Avoid pertaining to collision hazards is complicated when the airspace user operates in a mixed environment, defined as an environment where an ATC service may be provided for some aircraft but not all—for example, in ICAO Class D and E airspace for aircraft operated under Instrument Flight Rules (IFR) where the ATC service provides separation from other IFR aircraft but not from Visual Flight Rules (VFR) aircraft (ICAO Annex 11). In this mixed operation scenario, the responsible agent for separation may not always be obvious to the user and the user will be responsible for separation from some traffic, but not all. Various equipment indicators, including equipage and transponder code, could be used to decipher the responsible separation agent by the user in addition to coordination with the ATC service provider. In the worst case where there is user confusion regarding

who the separator is, the user may either manoeuvre to avoid collision hazards when the ATC service is responsible, or the user may wait until a collision hazard exists to avoid collision when the ATC service is not responsible for separation. In general, this situation can be avoided by the user coordinating with the ATC service as the potential conflict develops.

2.3. FUNCTIONAL ARCHITECTURE

1. A system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective (AOP-15). Functionally, an SAA system at its highest level consists of: the UAS itself, the operator, the human machine interface (HMI), surveillance, alerting and guidance, monitoring, and system support elements. The technical components developed and integrated for the specific SAA function will be termed the SAA *equipment*. Just as there is a diversity of UAS designs, there are many different potential SAA solutions that could be constructed. Major SAA subsystems can be on the ground as with Ground Based Sense and Avoid (GBSAA) or on the aircraft in the case of Airborne Based Sense and Avoid (ABSAA). Major subsystems can also be distributed on the ground and in the air with hybrid or integrated GBSAA-ABSAA solutions.

2. There is a diversity of SAA architectures and designs to support the wide range of UAS and flight operations. A common functional architecture framework for many SAA systems is shown in Figure 2-1, with the applicable section number shown.

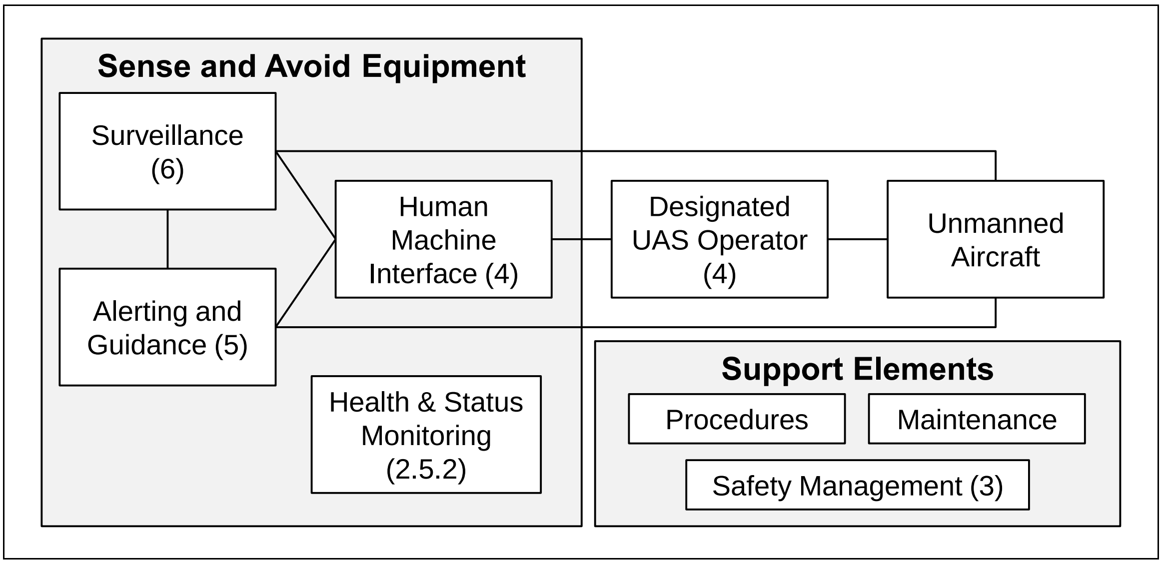

Figure 2-1: Sense and Avoid System Functional Architecture

2.3.1. External Components

1. Unmanned Aircraft System. A UAS enables flight operations for aircraft without an on-board pilot (unmanned aircraft). There is a diversity of UAS. UAS design architectures generally include one or more unmanned aircraft, one or more operators, and one or more control stations that provide a remote means of interacting with the unmanned aircraft.

2. Operator. The operator is a vital part of SAA systems. The role of the operator cannot be understated in SAA system design: the operator is always responsible for ensuring that the system is healthy, secure, and safe. This is true even when there is a high degree of automation. The SAA tasks assigned to the operator must be clearly defined, and the system must be designed and developed to support these tasks. The effectiveness of the operator in maintaining separation and avoiding collisions depends on many factors. Some of these include (see the Human Factors Chapter for additional discussion):

    a. Training and procedures

    b. Awareness of other aircraft operations in the airspace

    c. The quality, accuracy, and timeliness of the information conveyed through the HMI

    d. The effectiveness and utility of computer generated decision support aids

    e. The usability of the HMI

    f. The reliability of the system

Note that the general term *operator* is used in the following, unless referring to the specific responsibilities of the pilot-in-command, because some states may not define all personnel with pilot-in-command responsibility of UAS to be pilots, but rather operators. Additionally, some SAA architectures may employ personnel separate from the pilot-in-command to support the SAA function.

2.3.2. Sense and Avoid Components

1. Human Machine Interface (HMI). The HMI is a key subsystem that provides the information and controls that the operator uses to perform SAA tasks. It connects the operator to the surveillance and guidance subsystems and provides control over these subsystems. The information and controls should be intuitive, easy to use, easy to train, simple, and clear to reduce confusion and errors. At a minimum, the HMI provides: information regarding other aircraft in the airspace, system status to include health and integrity, and system command and control. SAA HMI may or may not be integrated with UAS HMI and UAS command and control. SAA system

designs may provide additional information to include but not limited to: an assessment of threats which may be in the form of alerts, computer generated manoeuvre guidance, and information that may affect the SAA response including airspace boundaries and weather. HMI user controls are varied based on the level of operator training and qualifications, flight mission, specific unmanned aircraft system including operating environment, and SAA architecture. Refer to the Human Factors Chapter for specific guidance on HMI design.

2. Surveillance. The HMI traffic display and guidance require timely, complete, clean, and accurate surveillance data. The surveillance may interact with other subsystems to prioritize the surveillance of other aircraft in relation to the UAS to reduce HMI traffic clutter and communications link constraints. The surveillance consists of:

a. Sensor: provides detections of other airborne traffic. Sensors may detect cooperative or noncooperative aircraft, where an aircraft is cooperative if it contains operable equipment for the purposes of identification and tracking—e.g., transponder. Consistent with See & Avoid, a noncooperative sensor is required to account for all threats.[2] However, due to the superior detection performance and track accuracy with cooperative sensor technology when compared with noncooperative sensor technology, the concurrent use of cooperative sensing often results in a better performing system and should be used where practicable.

b. Tracker: integrates sensor detection information to create a track of other airborne traffic. When there is more than one sensor, the tracker creates a fused or integrated air picture; in this case, there may be trackers for each sensor in addition to an integration or fusion tracker.

c. Filter: separates aircraft tracks from non-aircraft tracks. Filtering functions may be integrated within sensors and trackers or be included as part of a separate subsystem such as a classifier. Examples of filtering include sensor detection filters designed to remove ground vehicles, tracking filters that exclude tracks moving faster than possible for aircraft, and classifiers that filter tracks based on track attributes. Filtering non-aircraft tracks is important to prevent unnecessary manoeuvres that may induce conflicts with other aircraft. However, it is important that tracks corresponding to actual aircraft are not removed: there is a necessary trade-off between correctly identifying non-aircraft tracks and falsely removing aircraft tracks. Non-aircraft tracks may

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[2] A noncooperative sensor may not be required in airspaces where cooperative equipment is required for all aircraft and the resulting safety is acceptable. However, the existing regulations governing See & Avoid do not include an exception in such an environment; therefore, operations without a noncooperative sensor may need approval from the appropriate authority.

result from false detections, and ground clutter, real airborne objects that are not aircraft such as birds and clouds, and ground vehicles.

3. Alerting and Guidance. Using the provided surveillance and own aircraft information, the alerting and guidance provides decision aids supporting the SAA function, and may consist of:

a. Alerts: used to highlight potential risks, and may include aural and visual means. Intruder alerting is used to prioritize other aircraft tracks based primarily on their collision risk. Alerting and prioritization criteria are context dependent. For example, the criteria must be considered for both structured operations in the terminal environment and unstructured en route operations. Computer generated alerts are recommended in order to aid the operator in prioritizing potential collision risks; alerting helps to decrease workload thereby improving overall system performance. The design of the alerting system must carefully weigh the balance between correct alerts and nuisance alerts—typically, a higher correct alert frequency will result in a larger number of nuisance alerts.

b. Guidance: it is ultimately the responsibility of the operator to provide for the safety of the aircraft and make safe manoeuvre decisions. Computer generated manoeuvre recommendations are useful for helping the operator make safe decisions. Automatic manoeuvre execution can be necessary in certain architectures, especially where response delays may degrade system efficacy. However, manoeuvre recommendations must be evaluated for their safety and their operational suitability: the operator acceptability and impact on the operational environment (including interactions with external systems, such as ATC). The effectiveness of manoeuvre decisions depends on the interactions between SAA subsystems, including the interaction of the operator and HMI, surveillance impact on manoeuvre recommendations, and the aircraft manoeuvre execution.

The guidance and alerts should be consistent if both are provided—e.g., convey the same level of urgency. The alerting and guidance may reside within the same algorithm, or be separate algorithms.

4. Support Elements. Supporting subsystems, documentation, procedures, and functions are required for realizing a complete, integrated, and functional SAA system. Some support elements are highlighted below and may include:

a. Program plans, budgets, schedules

b. System design, requirements, and supporting documentation

c. Health and integrity monitors that provide system status and alerts

d. Communication elements to include hardware, internal networking, and communication equipment

e. Software/hardware safety artefacts, development processes, test reports, approvals, and documentation to support airworthiness and operational approval

f. Certifications, processes, and procedures for operator, flight crew, and system maintainer

g. Logistics support, spares, prognostics, diagnostics

h. Operations monitoring tracking, reporting, and documentation, addressing system reliability, availability, and maintainability

i. Performance monitoring, tracking, and evaluation of how well the system avoids collision and collision hazards and interacts with external systems such as ATC and ACAS

2.4. ENVIRONMENT

The environment is broadly defined as all components and systems outside the boundary of the SAA system that will affect system behaviour and efficacy. It is therefore important that the SAA environment be comprehensively defined when developing, validating, and verifying the system. Furthermore, the environment over the operational lifetime of the system should be considered and not only the current environment. The environment consists of own and intruder characteristics such as type of operation (IFR/VFR), flight phase, equipage, and aircraft speed and manoeuvrability. Many of these attributes are linked to the ICAO airspace classification (ICAO Annex 11). There are other important environment attributes as well such as weather and clutter, but these other attributes primarily affect surveillance performance and are therefore discussed in the Surveillance Chapter.

2.4.1. Encounter and Airspace Environment

The encounter and airspace environment consists of environment attributes that are defined by the interaction of more than one aircraft, and include:

a. Services. The primary service that will affect the responsibility of the SAA system is whether an ATC service is provided for a given conflict, which is defined based on operation type (IFR/VFR) and airspace class (ICAO Annex 11). Regardless of whether the ATC service is responsible for separation for a given conflict, if an ATC service is being provided to the UAS or an ATC clearance is required, then coordination should occur when a conflict occurs and when possible. Other air traffic services include traffic information, traffic avoidance advice, and flight information (ICAO Annex 11).

b. Flight phase. At the highest level, there are terminal (arrival and departure) and en route operations, which are typically linked directly to airspace class (for the higher density terminal environments). Terminal area operations are controlled to a greater extent and consist of reduced aircraft separations: therefore, unanticipated deviations will have a larger impact on other users. Hence, nuisance SAA manoeuvres will be tolerated to a lesser extent and the system performance may need to be enhanced in the terminal environment or the automation level reduced. Additionally, unmanned aircraft operations may have flight paths that are not typical of existing manned military aircraft operations—e.g., not point-to-point, high or low altitude, significantly longer duration, runway independent launch and recovery.

c. Traffic density. The air traffic density is also typically correlated with airspace class, at least for controlled (IFR) operations. The traffic density will affect the required surveillance resources and the likelihood of multiple threat conflicts.

d. Structure. For SAA, the airspace structure considerations include standard separation between aircraft (vertical and horizontal): it is not advisable to have an SAA manoeuvre when aircraft are appropriately separated. The structure also consists of standard flight routes that may affect encounter geometry and the desirable SAA manoeuvre direction.

Note that there is some question to whether UAS can operate VFR, by the very nature of UAS operations being nonvisual (i.e., not by a human); it is outside the scope of this document to address this debate. In terms of SAA, the type of operation (IFR/VFR) affects only the responsible agent for separation, the procedures of which must be considered when obtaining operational approval from the appropriate entity.

2.4.2. Aircraft Environment

The aircraft environment consists of environment attributes that are specific to the own (UAS) or intruder aircraft: an intruder aircraft is one that poses a potential conflict risk such that it must be considered by the SAA system. The following are noteworthy SAA considerations in the aircraft environment.

a. Speed. The aircraft speeds will affect the required SAA tracking and manoeuvring ranges, which in turn influence the sensor requirements. Below 10,000 ft, aircraft are generally required to stay below 250 kt IAS to enable See & Avoid, although deviations exist (ICAO Annex 11). Aircraft are also typically required to be cooperative (have transponder equipment) above 10,000 ft. Thus, it can typically be assumed that noncooperative aircraft will have speeds below 250 kt IAS.[3] With air traffic analysis, it may be possible to reduce the required speed at which the SAA system must be effective—e.g., based on capturing a certain fraction of all aircraft (e.g., 95%). However, the future airspace environment should be considered when performing such an analysis.

b. Manoeuvrability. The ability to induce a separation with other aircraft will affect SAA requirements—e.g., if a separation can be induced more quickly, then the tracking range or accuracy requirements could be reduced. Manoeuvrability depends on own and intruder speed, vertical rates, turn rates, and other accelerations that could affect system efficacy—e.g., the ability to accurately track the intruder.

c. Equipage. Particularly the intruder transponder equipage will affect SAA system requirements: aircraft that are transponding are easier to detect (here transponders include standard Mode A/C/S transponder beacons as well as ADS-B). Furthermore, intruder aircraft may be equipped with radio or data link equipment which may enable some level of coordination in the event of a conflict. The SAA system will rely on the UAS communications link at some level, so the communications link performance must be characterized, including transaction time, continuity, availability, and integrity (terms defined in ICAO 9869). Lastly, intruder aircraft may themselves be equipped with ACAS, SAA systems, or have a pilot manoeuvring to avoid the UAS; it is important that compatibility with these systems is considered—i.e., that the SAA system does not defeat or interfere with the efficacy of the other systems.

2.5. DEVELOPMENT AND MONITORING

Ensuring an efficacious SAA system requires supporting processes throughout the system lifecycle, including during development and throughout operation. System monitoring includes tactical and strategic processes: tactical health and status monitoring ensures that the equipment is operating nominally, while strategic operational performance monitoring ensures that the system operates suitably in the operational environment over its lifetime.

2.5.1. System Development Process

A sound system development process aids development, deployment, and operation by linking disparate activities. AAP-48 provides NATO accepted system life cycle processes. Specific recommendations for SAA system development include:

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[3] Certain military operations are authorized to exceed 250 kt IAS below 10,000 ft (e.g., aircraft whose minimum safe maneuverability speed exceeds 250 kt IAS), but these are carefully controlled to ensure safety. Thus, an SAA system may not need to be designed to this situation.

a. Requirements traceability. Requirements traceability from the highest level performance objectives to the component level requirements is essential and enables trade-off assessment and optimization, as well as requirement validation and verification. Therefore, this process should be established on program initialization, and well documented throughout the lifecycle of the program. This may require several iterations during the program lifecycle from the top-down and bottoms-up. Top-down refers to decomposing top-level requirements to lower-level functions and components; however, in isolation this process can result in unrealistic or unachievable lower-level requirements. Hence, there is benefit of a complimentary bottoms-up approach that defines the range of performance considering available technology.

b. Safety centric. SAA is a safety system, so each component should be assessed for its safety contribution. Although some components may not have a significant safety contribution, no component should adversely affect the safety of the system.

c. Iterative development. Given the complex nature of SAA systems, it is likely that the system design and requirements may need to be revised as development progresses: this should be appropriately accounted for in the program schedule and budget.

d. Operational concept. The operational concept provides a clear overview of the system, key terms and definitions, assumptions, the operational environment, and the system's use (e.g., see ANSI/AIAA G-043A-2012). It is a key reference document that should be updated as system development progresses.

e. Risks. Program risks should be identified, mitigated, and tracked throughout system development and operation. The risks should include both safety and programmatic consequences.

f. Alternatives assessments and sensitivity analysis. Such analyses at the system through component level define the requirements trade space, and should be clearly documented.

g. Schedule. An integrated program schedule should be developed and kept current, incorporating supporting contractors as applicable. This is important to identify interdependencies and critical milestones while working through the development lifecycle.

h. Vulnerabilities. Interference and spoofing risks should be assessed and mitigated; this is especially important for systems employing high automation levels.

2.5.2. Health and Status Monitoring

The current equipment health and status should be clearly conveyed to the operator. This includes equipment degradation and failures and may include aural, visual, or other means of conveyance. Degradation or loss of SAA may require operational mitigations to ensure safety. Because SAA will likely rely on components outside the SAA equipment, degradation or failure of these other components should be monitored for their effect on SAA. For example, if the SAA function requires the communications link, then the resulting degradation or loss of SAA as appropriate should be conveyed to the operator and mitigations should be considered. Mitigations may include automatic SAA manoeuvres, but any SAA mitigations must be considered within the operational context to include interaction with the ATC service and other airspace users.

2.5.3. Operational Performance Monitoring

Operational monitoring ensures the safety and suitability of the system as the environment evolves, and also serves to validate the system in its environment. An operational monitoring mechanism should be designed into the system, enabling post-operation assessment of system safety and suitability. All data relevant to the SAA status should be captured if possible. The operational monitoring component should be designed to enable analysis of individual events, as well as aggregate monitoring in a given airspace or set of users. As an example, ACAS II provides an operational monitoring mechanism, downlinking resolution advisories (RAs) to ground air traffic control radars; this mechanism has proved valuable in identifying system deficiencies and providing data to validate system upgrades (ICAO Annex 10 Vol. IV). When the system is first deployed, it is advisable to collect and analyse a complete operational data set to fully validate system operation before full scale operation.

2.5.4. Certification, Airworthiness, and Operational Approval

Approvals by the appropriate authorities are necessary before the SAA capability achieves operational status. These approvals need to address the equipment itself, aircraft system installation, and operational considerations: the associated processes are often termed certification, airworthiness, and operational approval, respectively. It is anticipated that existing processes and approval mechanisms will support SAA with little or no modification. The approval processes are carried out by the appropriate authority, typically the military aviation or airworthiness authority (MAA). The airspace regulator, that may be a civil authority, may have some role in the operational approval process, while certification and airworthiness are usually left to the MAA. Certification, airworthiness, and operational approval may be addressed in a single formal approval by the appropriate authority, or separately. These processes are defined as:

a. Certification. “The process of officially recognizing that organizations, individuals, materiel or systems meet defined standards or criteria”

(AAP-06). For ATM systems, certification is typically focused on the equipment itself and ensures that the equipment meets the defined standards or criteria, which includes environmental criteria. A technical standard order (TSO) is a common civil certification means for specific equipment. If a TSO or equivalent is not used, then certification criteria would need to be developed, increasing the level of effort due to the required approvals and associated artefacts.

b. Airworthiness. “The ability of an aircraft or other airborne equipment or system to operate in flight or on the ground without significant hazard to aircrew, ground crew, passengers or other third parties” (AAP-06). For ATM systems, airworthiness may address equipment effects on aircraft airworthiness, or more generally on equipment installation to include installed system performance and other installation considerations—e.g., installation location, interference with other systems. Therefore, airworthiness is aircraft specific. The supplemental type certificate (STC) process is a common civil means for aircraft installation approval.

c. Operational approval. This final approval enables operation of the equipment under the specified conditions. This may entail approval or concurrence by the airspace regulator, and is therefore the domain of the State of the operation, whereas certification and airworthiness are the responsibility of the State of registry or the operator. Thus, the operational approval process may require review of certification and airworthiness artefacts, although it extends further by addressing operational considerations such as operator training, maintenance requirements, operating manuals, and operational procedures. Operational procedures may include procedures by phase of flight, emergency and failure conditions, flight planning, and those for components such as communications links and transponders. The operational approval may document operational limitations as identified through the certification, airworthiness, and operational approval processes.

The ICAO ACAS manual (ICAO Doc 9863) contains an overview of civil approval processes for a system similar to SAA. Since operational approval is a prerequisite for system operation, a certification, airworthiness, and operational approval plan should be established on program initialization. This plan should identify key stakeholders, to include the responsible authorities, as well as program milestones. These approval processes are not limited to initial operational approval, but continue throughout operation as the equipment, aircraft, and operational contexts evolve. The artefacts required to obtain the various approvals are likely based on executing the guidance and recommended practice in this document. Lastly, the approval processes, including acceptance by other States, are supported by standard criteria and interstate recognition agreements; therefore, these should be considered and developed to support SAA operation.

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CHAPTER 3 SAFETY

3.1. CRITERIA

The objective of Sense and Avoid is to provide a capability for unmanned aircraft that satisfies the See & Avoid requirement that exists in manned aviation. It is largely agreed by military and civil authorities that UAS operations must be at least as safe as manned operations to be integrated in non-segregated airspace: for example, the ICAO RPAS Manual states that UAS “will have to be as safe as, or safer than, present manned operations” (ICAO Doc 10019). However, there is some divergence in the safety criteria recommended to specify UAS operation and SAA system efficacy. This chapter clarifies the potential criteria and provides a recommended approach.

3.1.1. Safety Assessment Methods

1. There are two general approaches for ensuring the safety of integrating new equipment and systems into the ATM system: reference and threshold (ICAO Doc 9689). When replacing a sufficiently similar system, the reference approach can be used which ensures that the system attributes are no worse in the replacement than in the reference: system attributes may include accuracy, detection, availability, and reliability. Safety is assured because the system is no worse for all quantifiable attributes; however, this requires that the replacement system is sufficiently similar to the reference—i.e., it must be used in the same manner, including interaction with other components and external systems, and have the same general architecture. The only potential reference system for SAA is See & Avoid, but it is not a suitable reference because it is not feasible to quantify See & Avoid attributes at the component level required for an accurate comparison—e.g., tracking range and accuracy, and manoeuvre safety and operational suitability. Furthermore, it is not sufficiently similar because SAA uses a different architecture which typically requires fallible communications links.

2. The alternative to a reference system approach that must be used for SAA is the threshold approach where the integrated system effectiveness is evaluated in the operational environment. Unlike the reference approach, the threshold approach does not constrain the system architecture, but the threshold approach typically requires more complex and resource intensive analysis methodologies because the system impact on the external environment must be quantified. Additionally, the threshold approach provides an overall estimate of system efficacy in the environment, while the potentially improved safety evaluated through the reference approach is unknown—e.g., although the system may have improved accuracy, detection, availability, and reliability, these may not have a substantial or measurable impact on safety.

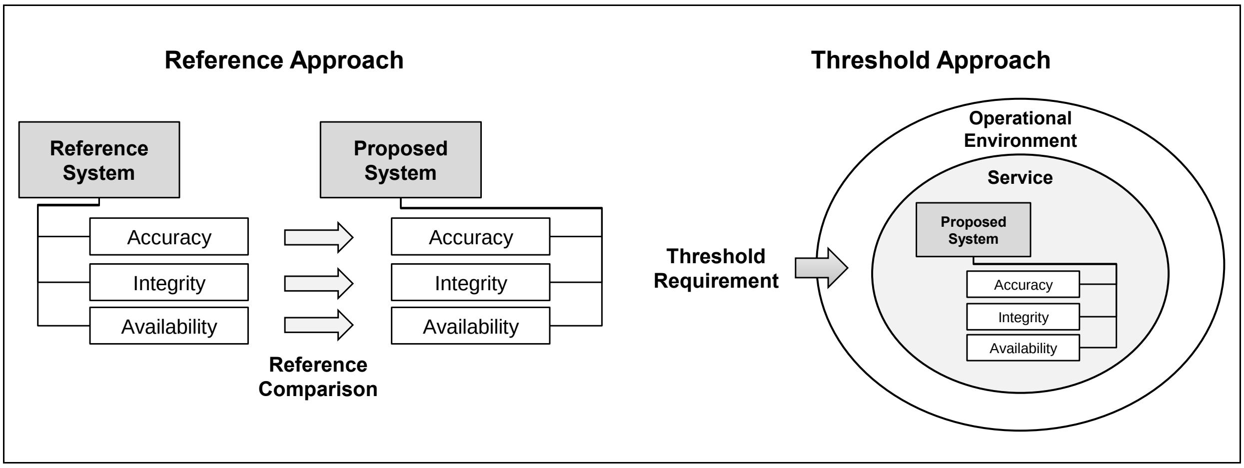

Figure 3-1: Safety Assessment Method Comparison

3.1.2. Threshold Criteria Alternatives

1. Absolute and relative criteria comprise the threshold safety criteria alternatives. Absolute criteria are expressed as an event per unit of exposure, such as fatal accidents per flight hour or operation, and such criteria are often used for the evaluation of en route separation systems. Commonly, absolute criteria are called target levels of safety (TLSs). Relative criteria evaluate the efficacy of the system relative to either the situation without the system or a separate, perhaps existing, system. An example of relative criteria is a risk ratio used for the assessment of ACAS Resolution Advisories that evaluates the degree to which ACAS reduces midair collisions compared to the status quo: it represents the fraction of midair collisions remaining after the system is employed. Absolute and relative criteria can typically be linked: for example, a risk ratio is the ratio of two levels of safety.

2. From a regulator and operator perspective, it is desirable to define an absolute measure for the acceptability of the total UAS operation. However, SAA is only one contributor to the overall safety of an operation, so in order to specify the SAA performance measure, the SAA contribution to the absolute measure would need to be derived. This is quite difficult in practice due to the many contributors to the safety of an operation, their inherent variability, and uncertainty in their estimation: contributors include airspace traffic density, equipage, and provided services that depend on time of day and weather, airspace class, UAS operational attributes, among other factors (see Section 2.4.1 for a broader description). Furthermore, to have assurance that the absolute measure is achieved, the other contributions must be assessed considering UAS operations: this is a complex undertaking that has not been accomplished with confidence. In order to compensate for uncertainty in this derivation, conservative assumptions are typically made. However, these assumptions compound, resulting in significantly better performance requirements than that which See & Avoid achieves, and in some cases to the point of being unachievable by available technology. Lastly, although it is critical that overall safety should be assured, it is not the role of the SAA system to compensate for

deficiencies in other safety contributors (e.g., ATC service), and depending on the environment, it could appear that SAA is not necessary while this is contrary to manned aircraft operational rules. A summary of this discussion is given in Table 3-1.

Table 3-1: Threshold Safety Criteria Alternative Comparison

	Threshold Alternative	
Criteria	***Absolute*** *(Target Level of Safety)*	***Relative*** *(Risk Ratio)*
Definition	$\frac{\text{event}}{\text{unit of exposure}}$	$\frac{\text{risk with system}}{\text{risk without system}}$
Example Applications	• Reduced Vertical Separation Minima • Oceanic tracks • Precision Runway Monitor	• Airborne Collision Avoidance System (ACAS)
Advantages	• Provides total operation performance estimate	• Provides direct measure of SAA system efficacy
Disadvantages	• Includes external contributions outside of SAA that must be precisely quantified • Must assess and forecast diverse unmanned and manned operations • Prone to misleading conclusions about equipage requirements	• Must incorporate failures that occur as a frequency (e.g., reliability)

3. Given these considerations, the relative threshold safety criterion is recommended for the development and evaluation of SAA systems, and is the focus of the remaining discussion.[4] Although a total operation safety estimate will not be provided with this approach, analysing the independent conflict management functions separately with independent safety criteria agrees with existing safety assessment practice for manned aircraft—analysing independent capabilities with a single criterion may introduce a common mode failure condition.

4. It should be noted that there are two types of risk ratios commonly applied to ACAS safety assessment: logic and system (ICAO Doc 9863). The logic risk ratio evaluates the system as specified, without failures and operational effects such as inaccurate, delayed, or no response. The system risk ratio includes these contributors to SAA efficacy including equipment and operational failures, and therefore, the system risk ratio is preferred for the evaluation of SAA system, while the logic risk ratio may be used for evaluation and tuning of SAA technical components, such as guidance algorithms (see Section 3.2.1 for the mathematical

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[4] The absolute threshold approach may be appropriate for situations where the collision risk mitigation interactions are less complex, and where the airspace user is responsible for more than SAA. One such situation is Due Regard operations, wherein a state aircraft user in international airspace assumes responsibility for separation where an ATC service would normally be required.

risk ratio formulation). Note that there may be a continuum between logic and system risk ratio as described here based on the analysis requirement—i.e., including various failure conditions.

3.1.3. Relative Safety Criteria Precept

Given that SAA replaces manned See & Avoid, acceptable SAA performance requirements should be traced directly to the current performance of manned See & Avoid. It is therefore recommended that the minimum SAA system performance should be to resolve midair collisions at least as well as the average pilot using See & Avoid. Additionally, safety should be optimized within the constraints of operational effectiveness and suitability, time and cost, throughout all phases of the life cycle; this cost includes the loss of defence capability as well as financial or other resource costs (AOP-15). All SAA failure conditions and intersystem dependences should be accounted for during the system evaluation.

3.1.4. Relative Safety Criteria Derivation

1. Several methods, either solely or in combination, are recommended to be used to establish manned See & Avoid efficacy in order to baseline SAA system performance, although other methods are possible:

   a. Visual acquisition models. This approach provides a conservative estimate of See & Avoid performance in that total See & Avoid collision risk will be higher than visual acquisition efficacy. The use of visual acquisition models enables comparison across a wide variety of aircraft, in terms of both speeds and size; this comparison may be valuable because the efficacy of noncooperative surveillance is typically dependent on these parameters. Visual acquisition models have been developed based on pilot simulations and flight tests.[5] Additionally, estimates of escape manoeuvre performance once visual acquisition occurs can be included; these estimates may similarly be based on simulations or flight tests or by characterizing reported near or actual midair collisions.[6] However, See & Avoid performance has been found to be limited primarily by visual acquisition performance, so the addition of manoeuvre efficacy may not be necessary.

   b. Observed collision rates. Although it was previously discussed that it is difficult to decompose See & Avoid effectiveness from an overall collision rate (level of safety), there are scenarios where this approach is tractable in determining existing See & Avoid efficacy. Specifically,

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[5] For example, Andrews, J. W., "Modeling of Air-to-Air Visual Acqusition," *Lincoln Laboratory Journal ,* vol. 2, no. 3, 1989.

[6] Graham, W. and Orr, R. H., “Separation of Air Traffic by Visual Means: An Estimate of the Effectiveness of the See-and-Avoid Doctrine,” Proceedings of the IEEE, vol. 58, no. 3, 1970.

the interaction between General Aviation aircraft allows for an accurate estimate of the existing collision rate. The challenging calculation is extracting See & Avoid performance by estimating the midair collision rate had See & Avoid not been in effect: this is the so-called unmitigated collision rate. Methods for estimating the unmitigated collision rate include, for example, a blundering or gas model approximation[7] or through brute force simulation of virtual unmanned aircraft traffic over existing traffic[8].[9]

2. Whereas the use of visual acquisition models permits comparison over a range of aircraft speeds and sizes, the See & Avoid estimate extracted from observed collision rates represents the average aircraft speed and size for the population used in the estimate. Therefore, the use of this observed collision rate approach may require consideration of the SAA equipped aircraft size and speed—e.g., the use of the extracted See & Avoid performance for especially higher speed unmanned aircraft than the observed collision rate population may result in performance requirements exceeding that for a similarly operated manned aircraft (the reverse is true for lower speed unmanned aircraft).

3.1.5. Additional Safety Criteria Considerations

1. In addition to the precept recommendations, the following may also be considered during system development and certification:

a. A system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective. Safety throughout the SAA system should be a high priority. System safety processes should address CONOPS, procedures, training, currency requirements, flight records, hardware maintenance schedules and records, a system performance monitoring plan, and other common safety practices and procedures common with aviation systems.

b. Minimum SAA system performance in non-segregated airspace should lead to fewer midair collisions than if operations were conducted by a manned aircraft. Midair collisions are a result of failed interactions

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[7] May, G. T. A. "A Method for Predicting the Number of Near Mid-air Collisions in a Defined Airspace." Journal of Navigation vol. 24, no. 2, 1971, pp. 204-218.

[8] Maki, E., Weinert, A., Kochenderfer, M., “Efficiently Estimating Ambient Near Mid-Air Collision Risk for Unmanned Aircraft", in AIAA Aviation Technology, Integration, and Operations Conference, no. AIAA 2010-9373, Fort Worth, Texas, 2010.

[9] It should be noted that existing absolute (TLS) approaches applied to SAA effectively use this approach to decompose the TLS into the SAA performance criterion—i.e., use the status quo collision risk as the TLS (perhaps with an improvement factor) and derive the SAA contribution removing all other contributors. However, these existing approaches typically fail to consider the impact of the UAS on non-SAA contributions to the level of safety, such as the ATC service. Therefore, these existing approaches cannot be considered a TLS approach in the truest sense because they do not provide confidence that the total TLS is achieved—i.e., they are effectively risk ratio approaches.

between two or more aircraft; therefore, the ability of other pilots to see and avoid the UAS could be accounted for in establishing minimum SAA performance requirements.

c. Although the See & Avoid derived risk ratio might be satisfied with a significantly smaller surveillance field of regard (FOR) than for manned aircraft, it is recommended that the system have an equivalent FOR to noncooperative aircraft: either explicitly matching that of cockpit visibility requirements or ensuring that the proportion of aircraft that can be detected exceeds that for manned aircraft in the operational environment. This is important so that the SAA system is not considered deficient as compared to See & Avoid for the type of encounter geometries that can be resolved. Although a 110 degree azimuth is required to satisfy the right-of-way rules (ICAO Annex 2), it is recommended that the FOR is optimized within system development constraints.

d. System effectiveness in avoiding midair collisions should be a high system development priority. Rather than simply developing the system to meet a minimum performance requirement for system effectiveness, system development should plan to improve the system further when possible. This is consistent with the as low as reasonably practicable (ALARP) guideline (AOP-15). An analysis of alternatives based on quantitative measures to optimize performance early in the program can often result in performance that exceeds minimum requirements without a significant increase in system lifecycle cost.

e. For fully integrated operations with manned aviation, it is recommended that SAA systems be designed with high reliability and to fail safely when a failure occurs. Design architectures that reduce single points of failure throughout the design are recommended so that a complete loss of SAA capability is avoided. Health and integrity monitoring is also necessary for detecting problems early and switching to redundant subsystems when necessary.

f. Although See & Avoid efficacy is recommended as the benchmark for evaluating the suitability of SAA systems, comparing against existing operational systems such as ACAS II can provide additional confidence in SAA system performance.

2. SAA compatibility with other applicable systems should be demonstrated. Compatibility and interoperability assessment is important to show that collision risk does not increase for UAS operations as compared to the situation where a manned aircraft was performing the UAS mission. System performance requirements and design should also be assessed for compatibility with other systems. Specifically, compatibility with the following systems should be considered:

a. See & Avoid. SAA systems should follow right-of-way rules and the system efficacy for SAA/S&A interactions should be assessed against the system efficacy for S&A/S&A interactions with two manned aircraft. There may be situations where it is safer to not comply with the right-of-way rules; this must be carefully considered during system development. A standard method for conducting such an assessment does not yet exist; one option is to assess the SAA system in simulation against an intruder that complies with the right-of-way rules.

b. Airborne Collision Avoidance Systems. SAA systems should be compatible with ACAS so that ACAS effectiveness in preventing collisions is not degraded.

c. Air Traffic Control Services. SAA systems should be compatible when receiving ATC services so that collision risk does not increase and airspace management efficiency is not degraded. Designing for compatibility with ATC services may affect certain performance requirements to allow for ATC interactions and remaining safely separated from other aircraft.

3. Beyond the efficacy at mitigating collision, there are other important metrics that are captured at the boundary between the system and the environment—i.e., metrics that are architecture independent. These metrics include:

a. Collision hazards (well clear violations). This metric is of primary importance when the UAS is responsible for avoiding collision hazards. Thus, when the system is operated in conjunction with an ATC service, this metric is of lesser importance. Once collision hazards are defined by the program, they can be objectively quantified. There may not be an obvious requirement for the mitigation of collision hazards, but See & Avoid efficacy can be used in a similar way as for the risk ratio requirement: for example, by analysis of near midair collisions or air proximity reports. Otherwise, the system developer should seek to minimize collision hazards in a way that is achievable.

b. Operational suitability. This class of metrics evaluates the negative impact of the system on the external environment, including other airspace users and ATC. An example is nuisance manoeuvres that may cause disruption to both the UAS mission and the external environment, such as the airspace structure, other airspace users, and the ATC service. In general, the balance between disruption to the external environment and safety must be carefully considered—e.g., larger manoeuvres may be safer but may cause undue impact to external systems.

3.1.6. Separation Criteria

1. When developing an SAA system, it is important to distinguish between the system objectives and the separation targets used to satisfy minimum performance requirements against the objectives. The primary SAA safety objectives with which criteria are established are the prevention of collisions and collision hazards. In order to satisfy these objectives given the various sources of uncertainty when determining and executing SAA manoeuvres, the SAA system must be designed to target a larger separation than the objective. For existing ATC services, this separation target is termed the separation minima. Given that aircraft may be separated to exactly the separation minima (although typically larger in operation where possible), it is likely that the separation minima are violated often but typically by a small amount. However, the separation minima are designed with associated procedures to satisfy the safety objectives within the appropriate criteria. For example, a standard vertical separation minima for an ATC service is 1000 ft: given that aircraft are normally separated to this minima, the actual aircraft separation is likely to be less than this amount due to flight path variability (height keeping performance) and surveillance uncertainty (altimetry system performance). Because the primary purpose of the ATC service is to prevent collisions between aircraft (ICAO Annex 11), the primary metric used to establish separation minima is the collision risk. Additionally, compatibility with other systems, including collision avoidance systems, is considered. The degree to which the separation minima are violated may also be considered: this metric is typically used during operations for operational performance monitoring to identify associated mitigations where collision events are too rare to provide for a statistically significant estimate of the collision risk, and not for the safety assessment itself.

2. Within the system, the separation minima may or may not be explicitly defined and the operator may or may not have visibility to the separation minima. The system, including the operator or the technical equipment, may employ separation minima determined based on the dynamic scenario, resulting in variable and not explicitly defined minima. On the contrary, existing ATC service separation minima are explicitly defined in general. Although there may be explicit, predefined separation minima, the operator may not have visibility of the separation minima being applied if there is manoeuvre selection automation. One example is ACAS II Resolution Advisories (RAs) where a minima is defined within the algorithm to provide adequate collision risk mitigation and used to select the RA, but it is not communicated to the operator. It is recommended that an SAA system that requires the operator to interpret the situation and determine a course of action, without a specific automated manoeuvre recommendation, explicitly define the separation minima to ensure safety and provide for a consistent response. Additionally, the system objectives—collision and collision hazards—should be clear to the operator.

3. Although it is straightforward to identify and measure when a collision or near collision occurs, it may not be straightforward to define what constitutes a collision

hazard, or conversely what constitutes well clear.[10] In practice, violations of the collision hazard provision as defined in the Rules of the Air are assessed based on the subjective judgement of the pilots involved in the conflict.[11] The following methods for identifying whether a collision hazard exists are recommended for the development and evaluation of SAA systems:

a. Collision avoidance alerts. Advisories from ACAS and the SAA system itself (that could incorporate ACAS) may be used to establish that a collision hazard exists.[12] Note however, that these existing systems may have nuisance alerts that may not constitute collision hazards.

b. VFR cloud minima. Cloud clearances were developed to ensure that aircraft could be avoided with See & Avoid once an aircraft exited a cloud.[13] Therefore, aircraft that are separated by the VFR cloud minima are not at imminent risk of collision. The use of VFR cloud minima here only applies to the definition of collision hazard, and not any responsibility of the UAS to remain clear of clouds.

c. Pilot and air traffic controller simulation and surveys. Although subjective, these measures provide an assessment regarding the acceptability of the collision hazard definition.[14]

d. Collision risk. The risk of collision given a collision hazard, either mitigated or unmitigated by the SAA system, can be used to define a collision hazard.[12] Use of the unmitigated risk by definition does not reflect the actual risk with mitigation systems such as See & Avoid and SAA. With both mitigated and unmitigated risk, it may be difficult to define the acceptable risk level.

4. Given the computational resources available, complex separation minima could be developed. The minima could be based on many different possible state variables, including time, distance, velocity, uncertainty estimates, among others. Although it may be possible to design and optimize such complex minima based on the system objectives, the minima must carefully be considered in terms of the

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[10] It should be noted that the term well clear has been used both as separation minima and as the system objective (what constitutes system failure). Therefore, the context should be understood when comparing well clear definitions.

[11] In the United States, the National Transportation Safety Board has ruled that “the fact that an experienced pilot feels compelled to take evasive action to avoid a collision is itself acceptable evidence of a potential collision hazard" (NTSB Order No. EA-4185).

[12] Cook, S. P., et al, “Defining Well Clear for Unmanned Aircraft Systems”, in AIAA SciTech, no. AIAA 2015-0481, Kissimmee, Florida, 2015.

[13] The United States Civil Air Regulations dated 15 May 1961 state that “the minimum weather conditions prescribed…are those within which a pilot is expected to be able to observe and avoid other air traffic.”

[14] Comstock, J. R., et al, “UAS Air Traffic Controller Acceptability Study 2: Evaluating Detect and Avoid Technology and Communication Delays in Simulation”, NASA, TM–2015-218989, 2015.

operator ability to interpret and appropriately determine actions, decreasing usability and increasing workload. Higher complexity in the separation minima may in turn, require greater levels of automation for the guidance to successfully satisfy the minima—e.g., necessitating additional alerts and manoeuvre guidance.

3.1.7. Software and Hardware Assurance

1. Assurance that the system hardware and software satisfies the design requirements is a key activity during system development. The required assurance level of rigor is based on the hazardous conditions that may result from failure of the hardware or software. For avionics, key hazardous conditions include known and unknown losses of function, and hazardously misleading information: unknown losses of function and hazardously misleading information typically establish the assurance level while known losses of function set the hardware reliability—e.g., mean time between failures. The required level of rigor is typically categorized for civil aviation systems by development assurance levels (DALs), and for military systems by the software safety criticality index (SSCI) (AOP-52).

2. One possible perspective is that SAA is the only mitigation for collision, and that a loss of SAA or hazardously misleading information provided by the SAA equipment would directly result in a catastrophic outcome, requiring the highest assurance level. However, this perspective does not consider the inherent redundant, fault tolerant design of the ATM conflict management system, and existing assurance levels assigned to ATM equipment, such as transponders and ATC service radars. In fact, it is quite unlikely that a catastrophic condition will occur given an SAA failure condition. However, a conclusion of the highest assurance level may be appropriate for intentional operations where equipment failure conditions may directly result in a catastrophic outcome, such as formation flight and aerial refuelling. The following aspects should be considered when making an assurance level assignment:

   a. The entire conflict management system, including function independence as applicable, should be considered during assurance level allocation.

   b. A collision should be considered an external event, such that the conflict management assurance level can be reduced one level before allocation to independent functions and items (consistent with SAE ARP 4754A). An external event is an event being mitigated by the system, where the origin of the event is outside the control of the system under consideration. When the external event is sufficiently infrequent before the system is employed, the design assurance level can be reduced.

c. The severity associated with a collision should be dependent upon the conflicting aircraft type of operation.[15] This approach aligns with existing, diverse assurance levels for civil aircraft and systems. Specifically, aircraft not receiving an ATC service should not be judged the same as those that do.

d. Dependences and common mode failure conditions between and within functions should be considered when allocating assurance levels to subsystems.

e. Higher levels of automation, where the operator may have limited control authority, may require higher assurance levels because the operator may not be used as mitigation for the failure conditions.

Although military guidance for establishing the assurance level could be used (e.g., AOP-52), use of SAE ARP 4754A processes may be more suitable due to civil regulator familiarity and explicit guidance pertaining to function independence and external events.

3.2. ASSESSMENT

1. Safety assessment is a key tool in the systems engineering process (AAP-48) that supports system requirements allocation, validation, and verification. Therefore, it should be established early during program initialization and continually refined as system development progresses. The safety assessment, and supporting activities, is the primary method by which the program can understand and evaluate system performance and key trade-offs.

a. Allocation. Early-on in the program, the safety assessment is used to define key performance parameters (requirements) and associated trades between parameters through requirements allocation. This includes the initial identification of system hazards and potential internal and external mitigation means.

b. Validation. Before and during hardware and software development, requirements are validated through various means including modelling and simulation, flight test, and analysis. This includes risk reduction technology development and evaluation to demonstrate that the requirements are correct and achievable.

c. Verification. After software and hardware development, verification is used to ensure that the system satisfies the requirements. Verification includes subsystem and system test, both pre- and post-installation as

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[15] Note that safety and assurance processes for manned aircraft typically focus on people onboard the aircraft containing the systems and equipment, whereas these processes for unmanned aircraft focus on people external to the aircraft.

necessary. Additionally, the safety assessment is updated to estimate the performance of the system as built to support operational approval.

2. The safety or assurance case purpose "is to provide convincing justification to stakeholders that critical system assurance requirements are met in the system's expected environment" (AEP-67). The safety case provides a coherent, structured argument that if satisfied provides the basis for approval. It documents the system development and safety assessment process, with the associated rationale and evidence. Therefore, the safety case is a valuable tool throughout system development.[16]

3. The purpose of this section is not to define a safety assessment process since there are many accepted processes and each organization may have a preferred process, but rather to provide guidance on how these processes may be applied to SAA including key lessons learned. It is recommended that safety assessment methodologies specific to avionics and other ATM equipment be evaluated to tailor the preferred processes. Examples include SAE Aerospace Recommended Practice 4754A (Guidelines for the Development of Civil Aircraft and Systems) and the Eurocontrol Safety Assessment Methodology. Additionally, previous system development and assessments, such as ACAS II, can be used to tailor the safety assessment process.[17]

3.2.1. Probabilistic Risk Assessment

1. Given the probabilistic nature of SAA and associated failure conditions, a probabilistic risk assessment is typically necessary to fully evaluate the risks. Ideally, the uncertainties contributing to the risks could be modelled and evaluated analytically—i.e., using solvable equations. However, the complexities and dynamics of the SAA problem, including alerting and manoeuvre recommendations, require the use of Monte Carlo (probabilistic sampling) methodologies to fully evaluate the risk. For example, oceanic procedural separation is typically evaluated through analytic means due to the slowly evolving and constrained dynamics, while ACAS resolution advisories are assessed through Monte Carlo simulation.

2. Although Monte Carlo simulation must be used for SAA, there are failure conditions that may not lend themselves to incorporation within a Monte Carlo simulation due to the frequency or confidence associated with the failure condition—e.g., hardware reliability is infrequent compared to other failure conditions, and operator contributions may not be characterized with adequate confidence to be incorporated within Monte Carlo methods. Furthermore, outcomes from several distinct Monte Carlo simulation scenarios may need to be combined externally. Thus, a probabilistic method is required to combine the various risk contributors, including

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[16] See also NATO AEP-67/AOP-52, as well as the Eurocontrol Safety Case Development Manual (DAP/SSH/091, Edition 2.1, 2006).

[17] For example: Eurocontrol, "ACAS II Post-implementation Safety Case", Edition 2.3, 2011.

dependences. The typical method to account for the logical dependences between failure conditions is through probabilistic trees. Various references may call these fault, event, or contingency trees; the term *tree* is derived from the resemblance of the multilevel logical decomposition. These trees are decomposed to individual events or faults that can then be estimated through various methods, including modelling and simulation, analysis, test, and even subject matter expert (SME) judgement. This document will call these *ratio trees* to reinforce that the metric of interest is a risk ratio, or the fraction of collisions remaining after the system is deployed, formalized as:

$$\begin{aligned}\text{Risk Ratio} &= \frac{\text{Collision Risk with SAA}}{\text{Collision Risk without SAA}} \\ &\approx \frac{\text{P(NMAC|encounter with SAA)}}{\text{P(NMAC|encounter without SAA)}},\end{aligned}$$

where the collision risk is the frequency of collisions, and the risk ratio computation is typically approximated conservatively using near midair collisions (NMACs) as a modelling convenience so as not to model the complex geometry of aircraft. NMAC for ACAS is defined as a loss of separation less than 500 ft horizontally and 100 ft vertically (ICAO Annex 10 Vol. IV), although this definition may not be appropriate for all unmanned aircraft, especially smaller airframes. Recall that there are two types of risk ratio: logic and system. The logic risk ratio evaluates the system under specified conditions (without failures and operational effects such as inaccurate, delayed, or no response), and is typically used to evaluate manoeuvre advisories and surveillance performance, while the system risk ratio extends the logic risk ratio by considering all other failure conditions including operator response and hardware integrity. A similar ratio can be formed for failures to prevent collision hazards. The risk ratio as defined here evaluates the risk relative to the situation without any tactical SAA or See & Avoid capability; depending on the analysis objectives, the risk can also be evaluated relative to other risks, including alternative capabilities such as See & Avoid. The total risk ratio is the summation of the unresolved and induced risk ratios, where induced risk is that caused by the system and unresolved is that which cannot be overcome: induced risk is typically considered less acceptable than unresolved risk because it is a risk that did not exist without the system.

3. There are many potential ways to organize and decompose the ratio tree. Considerations and lessons learned for the development of the ratio tree include:

a. Extensive decomposition of the logical tree may provide greater understanding of the SAA hazards and contributing factors but it may be increasingly difficult to estimate lower level hazards with confidence. Thus, the additional detail must be weighed against uncertainty in the resulting risk ratio that is compounded as multiple events are combined.

b. Where there is a large degree of uncertainty, the event estimates should be conservative in the sense that it degrades the top level risk ratio estimate. This uncertainty, and thus conservatism, can be reduced through further analysis and in some cases decomposition of the ratio tree. Therefore, there is a trade between the simplification of the ratio tree and the amount of simulation and analysis needed to justify performance and reduce system performance requirements.

c. The estimates in the ratio tree assume that prior conflict management layers have failed. Therefore, it is important that the events are conditioned on the other layers failing to ensure that the risk reduction provided by the SAA system is accurately estimated. For example, if other layers use the same surveillance information as SAA, hazardously misleading information (e.g., gross altimetry system errors) may cause both layers to fail: that is, the probability of hazardously misleading information given the failure of the other systems may be different than the marginal, or unconditioned, probability. Another example is that the encounter geometries resulting from an ATC service failure will likely be different than those had ATC not been involved.

d. Conflict dependent events, such as the efficacy of escape manoeuvres, lend themselves naturally to risk ratios. Time dependent events, such as communications system availability and hardware reliability, can be considered by assuming loss or degradation of the SAA function during the event. For example, if the SAA function is dependent on a communications link, then the function is effectively lost. To convert to ratios, the likelihood of a communications link, or lack thereof, given a conflict needs to be estimated. As a notional example, consider the mean time between loss of link events is 500 flight minutes and the mean duration until link is reestablished is 5 minutes; this results in 1% of the flight time without a link. If it is further assumed that a conflict can result at any time during this period, then the risk ratio contribution from the communications link is 1% because of a loss of function.

e. The ratio tree may mask deficient performance under certain conditions due to the combination of disparate events, so key events need to be assessed separately. For example, if noncooperative conflicts are relatively rare, the top level risk ratio could be satisfied with only cooperative surveillance—i.e., without any means to avoid noncooperative aircraft. This is contrary to the existing See & Avoid system. For this particular example, it is recommended that the risk ratio requirement derived from See & Avoid efficacy be satisfied for noncooperative aircraft, independent of cooperative surveillance.

f. The ratio tree should be used as the basis to define the analysis activities that are required. Otherwise, the analysis activities may not have a clear foundation.

3.2.2. Modelling and Simulation

1. The necessity of modelling and simulation (M&S) throughout the system lifecycle for decision making has already been introduced: simply, it is not possible to demonstrate system safety analytically due to the problem complexities or through flight test due to the expense, infrequency, and diversity of encounters that contribute to collision risk. Thus, large scale, faster than real time (Monte Carlo) simulation is typically the foundation of SAA program system-level analysis. Methodologies and lessons learned can be leveraged from ACAS development, where Monte Carlo simulation is required to prove system efficacy (ICAO Annex 10 Vol. IV).[18] However, many other analysis tools may be used, especially when assessing subsystems—e.g., sensors, HMI. Generically, there are three distinct types of simulation:

   a. Constructive simulation consists only of simulated agents, and is typically accomplished in fast time to accumulate a large number of statistics.

   b. Virtual simulation includes at least one operator with simulated agents, and is often used to evaluate operator performance. This simulation type is also called human-in-the-loop (HITL) simulation.

   c. Live simulation includes at least one real component and may include an operator (hardware or software), but in a nonmission environment—e.g., flight test.

Table 3-2 shows several primary simulation purposes by system development phase and simulation type.

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[18] This reference provides an overview of the fast-time simulation process based on ACAS: Zeitlin, A., Kuchar, J. et al, “Collision Avoidance for Unmanned Aircraft: Proving the Safety Case”, MITRE and MIT Lincoln Laboratory, 2006.

Table 3-2: Simulation Purposes by Type and System Development Phase

	System Development Phase		
Simulation Type	***Allocation & Validation***	***Design & Development***	***Verification***
Constructive	• Identify subsystem requirements and associated trade-offs • Evaluate alternatives	• Evaluate design trade-offs	• Safety assessment inputs
Virtual	• Evaluate HMI and automation alternatives • Determine, evaluate, and validate requirements that affect the end user	• Prototype and validate system usability and HMI designs and requirements	• Safety assessment inputs • Develop & validate constructive operator models
Live	• Validate operational concepts	• Validate designs and prototypes with live data • Integration experience	• Operational test and evaluation
	• Validate virtual & constructive models		

2. For SAA, each simulation type has unique benefits and drawbacks. Although constructive simulation is typically used to robustly provide estimates of the risk ratio, all are needed during system development. Benefits and drawbacks are summarized in Table 3-3.

Table 3-3: Simulation Type Benefits, Drawbacks, and Challenges

Simulation Type	*Benefits*	*Drawbacks & Challenges*
Constructive	• Provides logic risk ratio estimates • Relatively quick execution and low cost • Provides ability to evaluate alternatives and worst case scenarios without risking aircraft or humans	• Difficult to incorporate human behaviour (operator, ATC, intruder pilot) • Requires modelling environment and all system components and the environment • Extensive computational requirements
Virtual	• Enables targeted evaluation of operator behaviour and the HMI • Provides system and subsystem requirements usability validation	• Full-task, high-fidelity simulations can be costly and time consuming • Challenging to provide statistically significant and realistic risk estimates • Difficult to obtain enough qualified end users to provide statistically significant test results • Training is required and may present a risk to accurate and realistic results • Potentially misleading results with multiple encounters closely spaced in time
Live	• Provides end-to-end system realism • Provides an opportunity to test hardware and software	• Time consuming and costly to plan and execute • Limited test conditions due to required safety margins

3. There are several considerations that apply to all simulation types that are described here. General considerations are also documented in the NATO Modelling and Simulation Standards Profile (AMSP-01). The following sections have specific considerations for each simulation type.

a. Verification, validation, and accreditation. It is critical to establish the credibility of the modelling, simulation, and analysis tools. As the system progresses through the development phases, the impact of false or misleading analysis results increases, and must be weighed against the likelihood. A risk based approach to evaluating this impact should be considered.[19] A program verification, validation, and accreditation (VV&A) plan should be established upon program initialization. Independent subject matter expert (SME) reviews should be conducted as required to verify and validate the simulated environment and models.

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[19] Elele, J. and Smith, J., “Risk-based verification, validation, and accreditation process” in Modeling and Simulation for Defense Systems and Applications, SPIE, 2010.

b. Requirements. The M&S requirements and associated acceptability criteria are used to judge the suitability of the simulation, and are the basis for the V&V process. It is also important to clearly define the intended use of the simulation before suitability is judged.

c. Fidelity. Although higher fidelity models and simulated environments may be more representative, the higher fidelity may have higher computational costs, be more difficult to train or accredit, and may mask model deficiencies if employed by an untrained user. Therefore, the model fidelity must be carefully considered.

3.2.2.1. Constructive

1. Throughout the system lifecycle, constructive system level simulation is the primary method used to map subsystem attributes to system level metrics, such as the risk ratio and operational suitability metrics. This mapping enables decision making during requirements allocation, design, and verification. Although not discussed here in detail, constructive simulation may also be used at lower subsystem or component levels without linking back to the system level metrics—e.g., high fidelity sensor modelling to evaluate sensor design and trade-offs. One of the key challenges with system level constructive simulation is that every system component must be considered and modelled—for example, in order to evaluate the surveillance contribution to the risk ratio, an algorithm or operator response must be included in the simulation.

2. The main use of constructive simulation is to estimate the safety and suitability of the system in the anticipated, realistic environment. However, other system level constructive simulation uses include exhaustive stress testing to identify failure conditions, scenario or procedure specific analysis such as terminal operations, and analysis of observed operational events if such data are available. The basic simulation to support each of these objectives is typically the same, with the synthetic encounters used as inputs being the key difference. Typically, thousands to millions of synthetic encounters are generated and individually simulated to assess the outcome and produce statistically significant aggregate metrics. Key components of the SAA simulation include:

a. Surveillance. The sensor models can typically be high-level parametric models, considering detection and measurement accuracy. Tracker and sensor integration logic can be directly integrated into simulation. When allocating requirements, the surveillance models can be fairly high level, capturing the key requirements—e.g., tracking range and accuracy. Simulation used for design and verification may require higher fidelity than for requirements allocation—e.g., incorporating high-fidelity intruder signature representations.

b. Alerting and guidance. Alerting and manoeuvre recommendation algorithms are integrated directly into the simulation, if available. Before alerting and guidance algorithms are developed, subject matter expert defined responses can be defined, or a surrogate can be used if applicable—e.g., ACAS II.

c. Operator response. The required fidelity of the operator response model depends on the role of the operator in the system. Systems with automatic responses may require little to no operator response modelling, while systems with no manoeuvre recommendations may require significant understanding of the operator's response. Virtual and live simulations can be executed to obtain a statistically significant operator response for a limited set of encounters that can be translated into a constructive model. Before virtual simulations are executed to inform such a model, subject matter expertise may be used to define the anticipated or ideal operator response.

d. Aircraft dynamics. The fidelity of the aircraft dynamics model depends on whether the objective is to evaluate the system on a particular platform or a generic class of aircraft. For example, typical ACAS analyses use a fairly simple model to evaluate performance on the broad category of civil transport aircraft (ICAO Annex 10 Vol. IV). In any case, it is important that the dynamics are physically representative.

e. Encounters. An encounter model represents the realistic distribution of encounters expected in the operational environment, and is therefore a key component of constructive simulation intended to estimate collision risk. Such models are typically built from observational data: historically from air traffic control radars. However, because UAS operations are fairly infrequent and current operations may not be representative of future rule-compliant operations, observational data must typically be combined with other data sources (e.g., flight manual, telemetry, flight plans) and expert input for SAA assessment.[20] The level of effort required to develop such models is typically quite high due to extensive data collection and processing, model optimization, and validation. Recent encounter models have used country-wide radar data, but the model complexity is still limited by the relative infrequency of encounters that occur in the airspace.[21]

3.2.2.2. Virtual

1. Throughout the system lifecycle, virtual simulation is the primary method used to determine the usability of the system and to collect and analyse operator response. The operator is often overlooked when the sub-system requirements are

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[20] For example, see Griffith, J and Kuchar, J, "Evaluation of TCAS on Global Hawk with US Airspace Encounter Models" MIT Lincoln Laboratory, ATC-353, 2009.

[21] Kochenderfer, M. et al, "Airspace Encounter Models for Estimating Collision Risk" in Journal of Guidance, Control, and Dynamics, AIAA, 2010.

being developed. Including operators throughout the development process is crucial to a usable system. However, the level of virtual simulation required will depend on the tasks that are allocated in part or whole to the operator. The usability of system requirements can be determined through different types of user involvement, and not every requirement needs to be determined or validated through its own virtual simulation. High-fidelity full-task virtual simulations, where every effort is made to accurately represent all components and interactions, are costly and time-consuming so they are typically targeted at specific objectives and metrics, and require extensive planning of the involved facilities and personnel. Therefore, part-task virtual simulation, where specific components and interactions of interest are represented, is often used where appropriate given the analysis objectives. The simulation must also be carefully prepared and controlled to ensure that all data are ultimately usable. Virtual simulations have a limited data collection, but with proper planning and program support the data collected can be in the range of hundreds to thousands of encounters per analysis.

2. The fundamental trade-off for virtual simulation is between environmental validity and data quantity. Accurate, high fidelity facilities can be constructed, but they are typically limited in quantity and require significant schedule and cost resources to construct. Conversely, lower fidelity simulations can be distributed, and depending on data sensitivity and simulation architecture, can employ external participants. The required fidelity depends entirely on the simulation's intended use and the development phase. For example, early HMI prototyping and evaluation can typically employ a lower fidelity, while focused analysis of operator response to support certification will likely hinge on accurate, high fidelity environments.

3. Below is list of best practices to be considered when identifying requirements and planning for a virtual simulation (see also Section 4.5).[22]

a. Stakeholders. Identify the stakeholders in the process. Establish roles and responsibilities and determine a communication method and rhythm. Generate and compare the stakeholder's concerns, questions, and goals for the simulation.

b. Study requirements and simulation measures. Use the concerns, questions, and goals from the stakeholder feedback to establish the requirements for the study. Determine how each goal will be measured for successful data collection. Simulation measures may include objective (performance based) or subjective (questionnaire, feedback based) data. The goals and measures will determine the quantity of variables in a study, which leads to the number of subjects required for a scientifically balanced experiment.

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[22] Derived from Harvey, A., Buondonno, K., Kopardekar, P., Magyarits, S., and Racine, N., "Best Practices for Human-in-the-Loop Validation Exercises," Eurocontrol and FAA, 2003.

c. Determine and review concept of use. Meet with Subject Matter Experts (SMEs) to walk through the concept of use prior to an experiment. This will help to ensure a closest match as necessary to a realistic environment in regards to work load and cognitive tasks. Interviews, storyboarding and questionnaires can be used to determine a concept of use.

d. Communicate constraints. Common constraints for a virtual simulation include the duration of a study, availability and experience of the subjects, and operation environment being used.

e. Preparedness. The simulation results will be affected by any system behaviour or environmental conditions that are not representative. Thus, the simulation environment should be extensively tested before analysis data are collected, which should include a series of pre-experiment trials. A test readiness review (TRR) with stakeholders is recommended to review the requirements, test results, and back-up plan for system problems and failures prior to study execution.

f. Subject training. It is important that comprehensive and consistent training is provided to all subject operators to ensure consistent and valid results. Training may consist of a combination of classroom and pre-experiment simulation trials. Training is especially important when the subjects have no prior experience with the system. Participant’s attitude can greatly influence the results of a simulation. Insufficiently trained subjects can result in inaccurate objective measures and a poor attitude toward the usability of the system. Participants that are too involved to the experiment may have an overly positive or negative response to the study. It is accepted in most simulations that even with sufficient training, the subject’s performance will improve with time in the simulation. Therefore, blocking should be used to account for any training and learning effects on performance over time.

g. Define and maintain necessary levels of realism. A key challenge when performing SAA virtual simulations is that subjects may be exposed to higher encounter frequencies than would typically occur in order to collect the proper number of data points. Thus, response time, frequency, and compliance are typically quite high compared to operations.[23] Slower-manifesting problems are generally avoided since the practitioner wants to make the best use of valuable time. Prior simulation research has shown, however, that operational errors often occur in the beginning of troughs, or lower levels of traffic, immediately following very high levels of traffic activity. In order to better emulate the

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[23] Olson, W. et al, “Impact of Traffic Symbol Directional Cues on Pilot Performance During TCAS Events” in 28th Digital Avionics Systems Conference, IEEE, 2009.

operational environment and to capture all possible conditions for human effort, practitioners should script a range of traffic activity into their scenarios.

h. Operational objectives. To support the need for ecological validity in a full-task virtual simulation, the operator should be provided secondary tasks with similar loading to the operational environment and should have operational objectives—e.g., flight plans should be provided and flown. Early HMI prototyping where operational experts are used to evaluate HMI alternatives may not require such secondary tasking, but when measuring the response in a realistic environment, operational objectives should be included.

i. Statistical and operational significance of results. Ensure that the results of the simulation indicate relevance in terms of operational concepts. Early user involvement in part-task or low-fidelity HITLs are useful but are more descriptive in nature. Later simulations demand greater scientific rigor but can provide statistical analysis in terms of safety, capacity, delays, and manoeuvre decisions. It is rare to conduct one simulation exercise to solve complex operational issues. It is critical to trace the analysis and results to clear, high-level objectives that relate to operational feasibility, safety, benefits, etc. It is also important to note that statistical significance does not necessarily translate to operational significance. For example, users may prefer more information and automation and it could result in faster response times, but the operational need may not require the response times gleaned from the more computationally expensive design. Additionally, user preference may have no effect or even detriment operational efficacy, so user preference should be substantiated by analysis evidence.

3.2.2.3. Live

Although constructive and virtual simulation are the key analysis tools throughout development, live simulation is necessary to validate operational concepts, models, and assumptions, and ultimately to verify the integrated system. Live simulation can be especially valuable where technical or operational experience is limited and uncertainty is high; such risks can be mitigated by conducting early prototype testing. Such risk reduction live testing can occur at the component, subsystem, and end-to-end system levels. As a complex integrated system, SAA also benefits from end-to-end system testing to validate system integration, gain integration experience from stakeholders, and foster relationships between diverse stakeholders. As noted previously, live simulation cannot prove that the end-to-end system is safe, but can show that the system is unsafe. Live simulation data can be used to demonstrate the current state of the system, and if sufficient data are archived it can be used to demonstrate future system response. Encounters that are tested typically include a combination of encounters that stress the system (where an undesired outcome is likely) and where the outcome is assured. Key considerations for conducting live simulation include:

a. Integration. Live simulations require building and testing prototype hardware and software. Thus, the lead time for a flight test is on the order of months to years. It is critical that the hardware is extensively tested before the live simulation itself, including collecting and analysing all output data.

b. Coordination. A range of stakeholders are typically involved in live simulation activities, to include the testing range, operators/pilots (unmanned and manned), air traffic control, and the flight test team. Thus, pre-, during, and post-simulation coordination are central to ensuring success.

c. Expectation. Given the purposes of live simulation, the expected outcome of each simulation should be known: the other simulation tools are used to establish which encounters should be tested and the expected outcome.

d. Safety. System level live simulation includes a combination of real manned and unmanned aircraft. Thus, safety margins must be employed (horizontal and vertical separation), and the encounters must be comprehensively choreographed.

e. Collection. Due to the expense for live data collection, it is important that all data are collected and appropriately time stamped. Accurate positions and velocities of all elements should be collected, as well as any secondary independent sources—e.g., ground based air traffic control radar, ADS-B. Feedback from all stakeholders should also be solicited.

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CHAPTER 4 HUMAN FACTORS

4.1. SCOPE

1. This chapter addresses the aspects of the SAA system associated with the human component and identifies a number of recommendations and design considerations. Historically, many UAS mishaps are traced to human error. Additionally, system development within the aviation community has considered human factors and human-machine interfacing as superfluous modifications to a system whose primary goal is to perform a mission. In recent years, however, the advent of modern systems including UAS has led to more thorough attention to the human's role in the system. The importance of good Human Factors engineering, procedures, and user training cannot be understated for safe UAS operations. The operator is a central part of any SAA system and will continue to remain so until perhaps SAA systems are fully automated for all phases of flight and the operator has no SAA responsibility. The pilot-in-command always has the ultimate responsibility and decision authority for safety of flight. The intended function of an SAA system is therefore to support the operator in making safe manoeuvre decisions in order to maintain separation and avoid collision with other airborne traffic. Effective operation of the SAA system is reliant on the effective teaming of automation and the human operator as well as the design of the associated human-machine interface (HMI).

2. The following sections within this chapter provide an overview of the issues associated with the effective integration of the SAA human component by initially considering current best practice regarding how humans interact with different levels of automation (LOA) and how this relates to SAA integration. The chapter further addresses the issues associated with the evaluation of an SAA system through human-in-the-loop assessments. The chapter then identifies specific Human System Integration (HSI) issues associated with SAA and how these should be considered. Finally, the chapter discusses the UAS operator training aspects associated with the SAA operation. Further guidance on the general application of human factors (HF) on UAS can be found in the NATO HSI Guidebook.

4.2. HUMAN SYSTEM INTEGRATION DESIGN

There are a number of specific characteristics associated with the SAA system that have considerable impact on the integration of the system human component. These specific considerations are identified in this section and the specific HSI issues addressed.

4.2.1. Unmanned Aircraft System Characteristics

With respect to SAA system operation there are a number of UAS characteristics that impact the human system integration design.

4.2.1.1. Remote Operation

Being located remotely from the aircraft has a significant impact on how the operator interacts with the SAA system. All the information required must be presented to the operator at the control station. In a manned aircraft, detection of conflicting traffic is through systems such as TCAS in addition to the operator visually detecting the collision threat. In UAS, conflicting traffic will be detected only by the SAA system and therefore the HMI must enable the operator to interact intuitively and respond appropriately. However, there must be a balance when designing the interface with situation awareness versus information saturation. There may be a tendency to want to present all possible information to the operator as soon as possible. The information must be presented in an intuitive way that allows the operator to make safe manoeuvres in an appropriate amount of time.

4.2.1.2. Operation via Datalink

1. A consequence of the operation of the UAS via datalink is that there may be issues associated with the latency in the transmission and receipt of data. This may be minimal (<1 second) or under certain conditions far greater. Therefore, the potential impact of information latency to the operator must be taken into account in the HSI. Latency is a complex issue that needs to be addressed as an issue of C2 communication between the operator and UA, as an issue regarding the acceptable delay for ATC voice (caused by SATCOM), as well as a portion of time reserved for human reaction in both UAS control and ATC communication. Information on the datalink performance should be provided to the operator in real-time. Operations in certain types of airspace may require the datalink performance to be at a certain level. Depending on the airspace and type of operation, it should be ensured that the timeliness of data transmission and communication, including latency, is compatible with safe flight.

2. Depending on conditions, the SAA may operate under different LOA. These conditions may include loss of link as well as the range at which the conflicting traffic is detected and the associated closure rate which determine the time available for an avoidance manoeuver to be implemented. For example, conflicting traffic detected very late may require the platform to carry out the manoeuver automatically without input from the operator. Conversely, if the conflicting traffic is detected at greater ranges, the operator may be presented with an appropriate avoidance manoeuver and associated time window in which to approve or initiate an alternative manoeuver. Algorithm development, separation boundaries, and alerting guidelines must all consider delays in order to provide enough time for the operator to respond to an encounter in a safe manner.

4.2.2. Mission Considerations

The UAS mission(s) should be considered in the design of the system, the LOA, and the information presented to the operator. Currently, UAS perform a wide array of missions including cargo movement, Intelligence, Surveillance, and Reconnaissance (ISR), and even air-to-ground strike missions. For example, a high-altitude, heavy-lift rotary wing UAS may require a higher LOA for its SAA capability in a congested airspace than other rotary-wing UAS whose mission is to transport cargo over short distances at low altitude with little or no air traffic. The role of the human within these varying system requirements will be considered in the following section.

4.2.3. Human System Integration Considerations

1. The operator is ultimately responsible for maintaining separation and therefore is central to the Sense and Avoid system. The operator should be considered during all phases of flight for an SAA encounter. Human Systems Integration is not just about the operator's interface and controls. Rather, it should be included in the systems engineering process during requirements definition, design, training development and execution. Human Systems Integration will enforce the human as the central factor to the system and will aid in making trade-off decisions during systems development. Below are some important considerations and best practices to ensure proper human integration in the SAA design process.

2. Given the safety critical nature of SAA, it is vital that the required information is presented to the operator in an intuitive manner that supports the operator in the decision making process. This should make full use of HF research and guidance on the display of critical information—e.g., MIL-STD-1472, Def Stan 00-251. HSI should be considered throughout the requirements process when determining what information will be provided to the operator. For example, sensor requirements, track identification, alerting guidelines, separation boundaries, and safety metrics are requirements that should include a human factors expert and operator influence. Often the HSI process is limited to the interface after these requirements have been determined. This may easily lead to unnecessary system requirements, operator displays that are less intuitive, and higher levels of automation that may not be necessary.

   a. The HMI should inform the operator when a traffic encounter is happening or is about to happen. Proper information of ownship and intruder traffic state is necessary regardless of the LOA used.

   b. The system should support the operator in determining the consequences of any required avoidance action that is to be taken. The consequences must be transparent and be able to be quickly assessed by the operator. The HMI should provide sufficient information to enable effective operator manoeuvre decisions in the event that any available manoeuver selection automation fails or provides incorrect guidance. In addition to avoiding another aircraft, consequences may include restricted air zone violations, weather considerations, flight path or mission requirements, and terrain avoidance.

c. The HMI should provide guidance to the operator on how and when the planned flight path may be resumed. If an automated manoeuvre is used, the operator should be told when the manoeuvre is changing from avoidance to a return to path. Mission requirements should be taken into consideration when displaying or executing the return to flight path.

d. The HMI should support the operator in the operation of the SAA at the various levels of automation at which the SAA system will operate. For example, the system could provide the operator with alerting and situation awareness via information (informative display), a number of alternative options for an avoidance manoeuver (suggestive display) or a single, safest manoeuvre (directive display). If the system suggests a single manoeuver and requires the operator to approve in a given time, the operator must be clearly presented with the information required to approve or veto the manoeuver, including the time remaining. If, due to time constraints, the system undertakes the manoeuvre automatically, the operator must be informed immediately that the manoeuver has been executed, what the manoeuvre is, and when the manoeuvre is complete.

e. If the platform carries out an avoidance manoeuver when operating under lost link conditions, on resumption of the data link the interface must inform the operator that an avoidance manoeuver has been completed and details of the manoeuver presented to the operator including how the air vehicle returned to the planned course and route if the return was done automatically. The process for returning to the planned course and route is dependent on a number of factors such as deviation from the desired route and distance from the next waypoint; the process should be precoordinated with the ATC service and airspace regulator to ensure compatibility.

f. Minimum HSI requirements to ensure this communication should be elicited in requirements identification and analysis activity. It is expected there will be commonalities concerning flight controls and flight guidance between different UAS because they will be required to meet relevant military and civil standards (e.g., STANAG 4586), but some details of the HMI definition may be UAS specific.

4.3. TRAINING

The integration of an SAA system in the control station on a UAS has several consequences that take an effect on the training of UAS crew members. The integration of an SAA system most notably changes:

a. Control station lay out/configuration

b. Crew tasks and responsibilities

c. Standard working procedures

d. Emergency procedures

The integration of an SAA system relates to highly relevant safety critical aspects. Use of the system as well as second level, indirect relationships, should therefore be sufficiently trained (see also STANAG 4670). Because SAA system operation may influence other airspace users and ATC, training should also be considered for these external individuals; however, this section focuses on SAA operator training.

4.3.1. Sense and Avoid System Training

1. SAA system training should be provided to all personnel that are directly involved with the control of the UAS—e.g., the flight crew consisting of the UAS operator and the Sensor Operator. Training considerations are as follows:

a. Flight crews that are currently operating non-SAA equipped UAS need to be provided conversion training to obtain SAA system operation qualifications.

b. Whole task training of the SAA system, and interrelated dependencies of the system, need to be integrated in the formal training programs, at a minimum in the UAS qualification training. SAA training should include both UAS and Sensor Operator to accommodate for the effects of crew Human Factors.

c. UAS flight crews should stay current on the use of the SAA system. Therefore, regular theoretical principles and awareness training should be provided to the UAS flight crew. Regular (simulator) SAA emergency flight training should also be provided to the UAS flight crew.

d. Training should include understanding of automation and awareness of potential pitfalls such as dynamic external requirements and conditions that the algorithms may not consider.

e. Flight crews should be trained on applicable internal and external organization incident reporting, to include reporting of system deficiencies.

2. The SAA system is an automated, safety critical component. System components that feature a high level of automation demand a high level of understanding of the system architecture and system behaviour. When circumstances do not necessitate regular use of the system, loss of knowledge and skill is expected. This increases the risk of operator mistakes, therefore:

a. UAS flight crews should be provided sufficient training in use of the SAA system in contingency and emergency situations, such as lost link and loss of engine.

b. UAS flight crews should be trained specifically with respect to achieving flight safety and the effective management of automation.

   (1) UAS flight crews should be trained on aspects that are important in achieving resilience: leadership, problem solving/decision making, and communication.

   (2) UAS flight crews should be trained to deal with a variety of unexpected situations. Therefore, a varied set of realistic training scenarios should be used in the SAA system training.

   (3) UAS flight crews should be trained to maintain a high level of SA in a highly automated environment. Periodic review is necessary to understand the currency for automated systems.

4.3.2. Trainee Selection Criteria

The integration of an SAA system in the UAS control station environment changes several aspects of the UAS flight crews' tasks and responsibilities. The UAS operator organization should determine the effects of SAA system integration on the necessary competencies required for positions that are directly operating the SAA system. UAS flight crew selection criteria should be amended when necessary. This requires that:

a. Future potential UAS flight crews are selected on the capabilities required to operate the automated systems of the UAS effectively.

b. Current UAS flight crews should be reevaluated to determine if they still meet the revised criteria. UAS flight crews that do not meet revised criteria should:

   (1) Be trained to meet revised criteria, or

   (2) Be removed of task/responsibility to operate the SAA system

4.4. AUTOMATION DESIGN OVERVIEW

As automation technology has matured, it has augmented or replaced many of the functions that have been historically left to human operators to conduct. Examples of these functions include information analysis, communication, and decision making. Despite this shift towards automation, humans remain a key component in the UAS, and by extension the SAA. Therefore, SAA systems should be designed and based on human-automation interaction principles. It is critical to understand these principles in order to avoid many of the issues that result when humans and automation interact. The following sections provide a summary overview of these principles.

4.4.1. Scope of Human-Automation Interaction

1. Taxonomies provide guidance to understand the nature of human-automation interaction. Automation can be characterized in a number of different ways, which often makes it difficult to compare one system with another. A common method of classification is Sheridan and Verplank's ten levels of automation[24], which provides a useful taxonomy for classifying automated systems by considering the degree of authority a system possesses, or to what extent that system can operate independently of human input (Table 4-1).

Table 4-1: Levels of Automation (Adapted[24])

Levels of Automation		Description
High	10	Fully autonomous: the system decides everything; acts autonomously, yet collaborating with other autonomous systems, and ignores the human.
	9	The system informs the human only if it decides to.
	8	The system informs the human only if asked.
	7	The system executes an action automatically and then necessarily informs the human.
	6	The system allows the human supervisor a restricted time to veto before automatic execution.
	5	The system executes that suggestion if the human supervisor approves.
	4	The system suggests one decision action alternative.
	3	The system narrows the decision choice selection down to a few.
	2	The system offers a complete set of decision/action alternatives.
	1	The system acquires the data from the process and registers them without analysis.
Low	0	Fully manual: the system offers no assistance: the human decides and acts.

2. Another method of automation classification is according to its general function. For example, some automated systems merely collect information and display it to the user, but do not provide any interpretation of that data. Other systems take that information and interpret it or put it into some context—i.e., the engine temperature is above normal limits. Other systems provide users with options or decisions for action, and even more sophisticated systems execute those actions. In this sense, automation has been grouped according to functions that align with the

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[24] Sheridan, T., and Verplank, W. "Human and computer control of undersea teleoperators", MIT Man-Machine Systems Laboratory, 1978.

four stages of information processing.[25] For a brief description of these stages and examples of automated systems by each stage see Table 4-2.

Table 4-2: Simple Four-Stage Model of Human Information Processing[26]

	Sensation	Perception	Decision Making	Response
Automation Example	A basic sensor that detects, records, and displays readings	A system that provides meaning to data, alerting the user to instances that are out of bounds	A system that provides the user a list of suggested actions the user can take in response to some event	A system that executes an action automatically, with or without human input

3. The discussion on automation taxonomy is useful because research has illustrated that highly automatic systems can create vulnerabilities relating to safety. This is primarily because the high reliability and near-perfect performance of most computer systems vastly exceed the limitations of human concentration,[27] but humans employed in the task of monitoring an automated function frequently demonstrate a drop in awareness and vigilance.[28,29,30,31] If humans who have not been mentally engaged in the prior operation of automation encounter an anomaly or failure of that system or process, they frequently lack the necessary awareness of the system state or the state of the world with which the automation is interacting. The resulting decisions and responses to these rare automation failures are often incorrect or inappropriate, which in certain cases can be disastrous. This relationship between humans and high levels of automation has been found to be exacerbated by conditions of high concurrent cognitive workload (i.e., multitasking)[26,32] and time

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[25] Atkinson, R., & Shiffrin, R. "Human memory: A proposed system and its control processes." In K. W. Spence & J. T. Spence (Eds.), The Psychology of learning and motivation, Vol II (pp. 85–195). New York, 1968.

[26] Parasuraman, R., Sheridan, T., and Wickens, C., "A model for types and levels of human interaction with automation" IEEE Transactions on systems, man, and cybernetics-Part A: Systems and Humans, 30(3), 286-297, 2000.

[27] Mackworth, N. "Researches on the measurement of human performance" In Selected Papers on Human Factors in the Design and Use of Control Systems (pp. 174–331). New York, NY, 1961.

[28] Adams, M., Tenney, Y., and Pew, R. "Situation Awareness and the Cognitive Management of Complex Systems" Human Factors, 37(1), 85–104, 1995.

[29] Endsley, M., "Automation and Situation Awareness" In M. Mouloua (Ed.), Automation and human performance Theory and applications. Mahwah, NJ, 1996.

[30] Parasuraman, R., Sheridan, T. and Wickens, C., "Situation Awareness, Mental Workload, and Trust in Automation: Viable, Empirically Supported Cognitive Engineering Constructs" Journal of Cognitive Engineering and Decision Making, 2(2), 140–160, 2008.

[31] Smith, A. and Jamieson, G., "Level of Automation Effects on Situation Awareness and Functional Specificity in Automation Reliance" Proceedings of the Human Factors and Ergonomics Society 59th Annual Meeting, 56, 2113–2117, 2012.

[32] Wickens, C. , Goh, J., Helleberg, J., Horrey, W. , & Talleur, D., "Attentional Models of Multitask Pilot Performance Using Advanced Display Technology" Human Factors, 45(3), 360–380, 2003.

pressure[33]. Attempts to mitigate this type of automation-induced complacency have included approaches in training[34], enhanced alerting strategies[35], and integrated displays.[36,37,38] Despite these attempts, this phenomenon persists as a potential vulnerability whenever humans are tasked to monitor high levels of automation. This relationship has been implicated in numerous aviation mishaps, both manned[39] and unmanned[40,41]. The decision of what type of automation a function should employ and to what extent should be made by fully considering the possible negative consequences on human performance.

4. An implication of these taxonomies is that a task can be decomposed into subtasks so that a single automation level can be appropriately assigned. However, the decomposition of a parent task into any number of information processing stages or action monitoring and selection functions represents only a single level of subdivision into abstract task categories. Practically, a parent task is not accomplished by abstract functions but by many levels of subtasks, which are hierarchically decomposable sequences of specific activities. Thus, the relationships between automation level and task decomposition is still more complex, though there are many analytical techniques in human factors to perform task decompositions in a hierarchical fashion.[42,43] When tasks are assigned to the components of the system (e.g., automation, human), the automation taxonomy needs to address the question of which component(s) of the system performs each task. It should be noted, however, that some tasks may be dynamic in their assignment to human or automation depending on the demands on the human component of the system. Ideally, for tasks that can be done by both human and automation, the tasks and

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[33] Trapsilawati, F., Qu, X., Wickens, C., and Chen, C.-H., “Human factors assessment of conflict resolution aid reliability and time pressure in future air traffic control” Ergonomics, 58(6), 897–908, 2015.

[34] Patterson, R., et al “Training robust decision making in immersive environments” Journal of Cognitive Engineering and Decision Making, 3(4), 331-361, 2009.

[35] Pritchett, A. and Vándor, B. “Designing situation displays to promote conformance to automatic alerts.” In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2001.

[36] Dal Vernon, C. and Sanderson, P. “Designing displays under ecological interface design: Towards operationalizing semantic mapping.” In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1998.

[37] Rovira, E., et al “Displaying Contextual Information Reduces the Costs of Imperfect Decision Automation in Rapid Retasking of ISR Assets” Human Factors, 56(6), 1036–1049, 2014.

[38] Wickens, C. et al “The Influences of Display Highlighting and Size and Event Eccentricity for Aviation Surveillance” Proceedings of the Human Factors and Ergonomics Society, 2003.

[39] Jones, D. and Endsley, M. Sources of situation awareness errors in aviation. Aviation, space, and environmental medicine, 1996.

[40] Tvaryanas, A., Thompson, B., and Constable, S. “U.S. Military Unmanned Aerial Vehicle Mishaps: Assessment of the Role of Human Factors using Human Factors Analysis and Classification System”, HSW-PE-BR-TR-2005-0001, 2005.

[41] Williams, K.. “Human factors implications of unmanned aircraft accidents: Flight-control problems” In Human Factors of Remotely Operated Vehicles, 2006.

[42] Hart, S. and Staveland, L. “Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research” Advances in psychology, 52, 139-183, 1988.

[43] Salvendy, G. Handbook of human factors and ergonomics. John Wiley & Sons, 2012.

levels of automation should be assigned to the human-automation partnership, where the task allocation is intelligently selected so as to optimize overall system performance.[44] This intelligent assignment of tasks is termed *intelligent automation*.

4.4.2. Functional Integration

1. Conventionally, automation design took a technology-centred approach and focused on maximizing technological performance.[45] The design of automation within an SAA system includes both adaptive (system initiated) and adaptable (human initiated) automation and aims to reduce the negative effects of static automation by dynamically shifting tasks between human and automation. Its goal is to keep the operator in the loop and maintain situation awareness. The nature in which this flexible automation handles changes in task allocation, however, results in the separation of system (e.g., SAA) functions. In other words, flexible automation must treat each function of the system independently and in isolation of other functions because changes in automation capabilities for one function would likely be inappropriate or not technologically possible for all components of the system. It invites issues regarding operator loss of authority and situation awareness in adaptive automation, and high workload and potential system failure in response to abnormal events in adaptable automation. Additionally, the validity of applying the concept of functional separation of tasks between human and automation is questionable when tasks can be carried out by either the human or automation component. This is especially true when an SAA design is based strictly on the considerations of human capabilities and limitations rather than overall system performance and efficiency, considering the integrated human and automation system performance. Automation needs to be designed in such a way that it not only keeps humans on the loop but also in the loop when necessary. Automation should not only provide feedback to the operator but also intelligently assist in maintaining situation awareness and making timely decisions by knowing when and how to assist the operator.

2. Intelligent automation is necessary as functional integration, rather than function allocation. It is a key characteristic of automation design for SAA systems. With functional integration, the behaviours required by the domain are shared across multiple functional components, including the operator and automation. Thus, the same behaviour can be performed by one of several components. Functional integration creates robust or resilient systems that are better able to handle unexpected events. For example, safety redundancies are built into aircraft control systems to allow an alternate course of action if a key component fails—e.g., redundant navigation systems such as inertial navigation system, GPS, and other simple systems for navigation via radio. In the same manner, intelligent automation should enable the operator to support or carry out an automated function if, for some reason, automation is unable to complete the function. SAA system design should

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[44] The Role of Autonomy in DoD Systems, U.S. Defense Science Board, 2012.
[45] Hou, M., Banbury, S., and Burns, C. Intelligent adaptive systems. New York, NY: CRC Press, 2014.

seek to restore the operator to the role of the decision maker. SAA systems should also provide safeguards for situations where time constraints or problem complexity restrict operator problem solving ability: an example is undertaking time and safety critical functions if the operator does not respond within the required period of time, although the safety and operational implications of such a response must be fully considered.

4.5. HUMAN COMPONENT EVALUATION

1. Varying levels of human involvement are expected when operating UAS, and more specifically, SAA decision and manoeuvre processes. Although evaluation methods vary in their approach to assess human involvement in these processes, the goal of this section is to outline common practices and provide guidance for the evaluation of human behaviour when integrated into the SAA system. This section focuses on human behaviour evaluation, while recommendations for conducting the associated modelling and simulation are contained in the Safety Chapter.

2. A key component of human behaviour that requires evaluation during the assessment of human capability in the SAA system is the decision-making process. The U.S. Federal Aviation Administration (FAA) has identified several aeronautical decision-making (ADM) models: 5-P, 3-P, CARE, TEAM, OODA, and DECIDE.[46] Although each model provides strengths and weaknesses in their recommendations for ADM, some components of these models are easier to evaluate than others. Five common components of these models for the ADM process that should be considered when developing a method for human component evaluation are detect, evaluate, prioritize, decide, and execute. This process component decomposition enables a discussion of associated potential levels of automation which is provided for reference.

3. For the purposes of this chapter, two types of measurements will be discussed in regards to ADM: timing and accuracy. Timing measures indicate the amount of time elapsed from the beginning of an intruder aircraft encounter event until the point in time that is of interest (i.e., the event timeline) or the time from the end of one phase in the ADM process to the end of a subsequent phase. Accuracy measures borrow concepts and terminology from signal detection theory[47] in that each component of ADM should be evaluated in regard to the successful or unsuccessful mitigation of an intruder aircraft event—i.e., high hit rate (correct detection) and low false-alarm rate.

4. The human component should be evaluated within a simulated environment that is of sufficient fidelity to ensure that the evaluation is valid. During evaluation activities, appropriate measures of performance, such as timing and accuracy,

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[46] “Aeronautical Decision-Making” in Pilot’s Handbook of Aeronautical Knowledge, Federal Aviation Administration, FAA-H-8083-25B, 2016.

[47] Green, D. and Swets, J. Signal Detection Theory and Psychophysics. New York, 1966.

should be used determine the ability of the operator to sense and avoid intruder aircraft and ambient air traffic.

4.5.1. Detect/Perceive

1. Intruder aircraft detection is the ability of the UAS operator to detect/perceive intruder aircraft on their displays or hear audible alerts to draw their attention to potential intruder aircraft. Detection should be evaluated using timing and accuracy measures. The display should not be subject to high levels of clutter so that the operator can quickly and intuitively assess the level of threat caused by the intruder aircraft. Consideration should be given to the provision of a declutter facility that enables the operator to remove ancillary information from the display to assist in the assessment of the threat.

2. Sufficient timing requires a sensor to relay intruder aircraft information to the control station with adequate time remaining for the operator to complete their ADM process. Accuracy assessment results in the successful or unsuccessful detection of an intruder aircraft due to the stimuli used on the ground station—e.g., visual tracks or auditory alerts.

3. Automation during the detection phase can range from low to high in terms of levels of automation, similar to that shown in Table 4-1. An example on the lower end of the automation spectrum is all or nearly all track information being provided to the operator. An example of a high automation level for the detection phase is when a system utilizes multiple sensors but, without human intervention, decides the most reliable track and presents it to the operator.

4.5.2. Evaluate

1. After the operator has detected the intruder aircraft, UAS operators must evaluate whether the intruder aircraft is a threat. Assessing the evaluation process of the UAS operator is not as simple as measuring the operator's ability to detect, but timing and accuracy measures can be derived from the verbal behaviour of the operator.

2. To assess the evaluation process, an observer should monitor how the operator evaluates their airspace upon contact with an intruder aircraft. The time from intruder detection until the operator completes their evaluation should be considered the evaluation phase of the ADM process. It is recommended that the operator verbalize their evaluation process with concise aviation vernacular, such as "intruder aircraft at 3 o'clock, no factor" or similar phraseology as determined by independent country training protocol. These utterances can be measured for timing, as previously mentioned, and accuracy. Whether the operator's evaluation is correct or not determines the accuracy of their evaluation.

3. During the evaluation phase, automation can again range from low to high LOA, similar to the detection phase. Comparable to low LOA in the detection phase, low LOA in the evaluation phase would provide little or no information regarding the likelihood that a detected track is a factor for SAA. Alternatively, a high LOA during the evaluation phase could asymptote as high as an evaluation of an impending threat to ownship being kept undisclosed within the system.

4.5.3. Prioritize

1. The most difficult phase to quantify by means of timing and accuracy is the prioritization phase. It can be assumed that, at times, a UAS operator will encounter multiple intruder aircraft or individual intruder threat aircraft with background traffic. In the prioritization phase, the operator should identify the most imperative encounter to resolve and to appropriately rank subsequent encounters. Similar to the evaluation phase, observers can use verbal behaviour of the operators to assess the timing and accuracy of their prioritization process.

2. During the evaluation of the ADM process, the operator should “talk through” their reasoning for choosing one manoeuvre over another, or why one intruder is more imperative to resolve over another. This information will allow the observer to calculate a timing measure and whether the operator accurately prioritizes intruder aircraft based on the information available to them through the sensor displays.

3. Similar to the evaluation phase, automation for the prioritization phase can range from low to high. Prioritization of ambient air traffic could be at the lowest level of automation that is fully manual: the operator makes all prioritizations based on information provided from the sensors. A higher automation level system could provide information regarding prioritization to the operator or higher yet the system could covertly develop its own prioritization list for its own decision making processes.

4.5.4. Decide

1. Unless a training program specifies the exact manoeuvre an operator should execute for all types of encounters, the operator will have some flexibility in their manoeuvring decision. Similar to the evaluate and prioritize phases of the ADM process, the operator should verbalize their manoeuvre decision for timing and accuracy measurement.

2. The decision phase is the period of time where the operator chooses an avoidance manoeuvre or to maintain their current course. For example, if an operator evaluates an intruder aircraft as a potential threat, during the decision phase the operator will verbalize the avoidance manoeuvre they intend to execute. Alternatively, if an operator evaluates a potential intruder aircraft as no factor in their safety of flight, during the decision phase the operator should verbalize that they will maintain the current flight path.

3. When considering automation levels, the decision and execution phases of the ADM process are typically considered rather than the previously discussed phases (as in Table 4-1). These final two phases are the most deliberated because they are the most overt and likely have the largest implications in operational automation. Additionally, it is worth noting that the LOA taxonomy previously discussed is focused on these two phases.

4. During the decision making phase, LOA can range from fully manual to fully autonomous (see Table 4-1). A low LOA system is when the automation conducts no decision making processes; whereas, a high LOA system could assimilate information from the previous three phases and decide what manoeuver, if any, is required to maintain a safe distance from other aircraft—the human operator could or could not be informed of the decision making process.

4.5.5. Execute

1. The execution phase is similarly easy to quantify as the detection phase of the ADM process. Currently, most UAS do not execute a manoeuver unless an execute command is issued by the operator. The culmination of the previous four phases is exhibited in the execute phase when the operator: a) inputs the manoeuver and executes the manoeuver by their own volition in a low LOA system, b) accepts, rejects, or overrides a system derived manoeuver in a medium LOA system, or c) observes the UAS execute a manoeuver in a high LOA system.

2. The timing of the execution phase could be measured in a number of ways. First, the execution timeline could be considered from the point of detection until the aircraft begins diverting from its current flight path. Second, the timeline could encompass the time from detection until the operator inputs a manoeuver or accepts a suggested manoeuver from the system. Finally, the execution timeline could only entail the time from the end of the decision phase to the time a manoeuver is executed. With the intent of the highest fidelity of human performance analyses, it is recommended that the last option is employed. Accuracy of the execution phase can be assessed with metrics indicating how well the operator maintained a safe distance from intruder aircraft (e.g., closest point of approach), if the operator followed suggestive/directive guidance provided by the system, if the operator induced a conflict based on the manoeuvre choice, and if the operator manoeuvres in time to avoid a higher alert or conflict.

3. To reiterate, automation can range from low LOA to high LOA for the execution phase similar to the decision phase. In a low LOA system, manoeuver execution does not occur via the automation, but rather the human operator executes all manoeuvers. Alternatively, in a high LOA system, manoeuvers can be executed with or without human operator input.

CHAPTER 5 ALERTING AND GUIDANCE

In order to enable avoidance of collisions and collision hazards, it is prudent to provide alerts and guidance to the operator that aids operator decision making and ensures prompt and accurate action. Here, an alert is defined as an indication meant to attract the attention of and identify to the operator a potentially threatening encounter. Manoeuvre guidance, or simply *guidance* herein, is information that is intended to aid in the selection of a course of action. Alerting and guidance must be carefully designed to enable safe operations, including adequate situation awareness, while not causing an undue burden on UAS mission operations or systems external to the UAS, including air traffic control and other airspace users. This section describes alerting and guidance design, development, validation, and verification considerations.

5.1. ALERTING

1. The sensory modes and urgency levels for alerting are well established (STANAG 3370): urgency levels comprise advisory, caution, and warning, while sensory modes may include visual, auditory, or tactual. Advisory alerts require crew awareness but not immediate action, caution alerts require immediate attention but not immediate action, and warning alerts require immediate attention and action. There is extensive standard practice regarding implementation of these alert urgency levels and sensory modes that will not be repeated here (e.g., STANAG 3370). During the course of an encounter proceeding to a potential collision, the sequence of urgency levels is clear, transitioning from advisory to warning.[48] Warning level alerts should be reserved for situations where avoidance action must be taken immediately to mitigate the hazardous situation. The system designer should consider whether warning level alerts are reserved for avoidance of collisions, or also for avoidance of collision hazards (well clear).

2. As the requirements increase for attention and action with the urgency level, reducing nuisance alerts becomes more important: nuisance alerts are defined as situations where an alert is issued but the situation is otherwise safe, while false alerts are situations where the system alerts based on a false track—i.e., a track that is not of an aircraft. The trade between nuisance alerts and correct alerts is a fundamental challenge when developing collision alerting systems.[49] A high nuisance or false alert rate may cause the operator to distrust and potentially ignore the system, while a low correct alert rate (high missed alert rate) is a safety concern—i.e., the very presence of an alerting system may cause some level of reliance and as a result, inattention because the operator may assume that the system will identify all

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[48] There may be situations where the encounter urgency dictates an immediate warning level alert rather than transitioning through all levels, such as for late detections or a rapidly changing encounter.

[49] Kuchar, J. K., “Methodology for Alerting-System Performance Evaluation” in Journal of Guidance, Control, and Dynamics, AIAA, 1996.

threatening situations. Defining what constitutes a nuisance alert may be challenging because there is typically some level of subjectivity: it is clear when an alert is required, such as for a near collision, but it is not always clear when an alert should not be issued. As an example, ATC separation minima and the airspace structure have been used to establish when a nuisance alert occurs for ACAS II, given the notion that ACAS II should not issue Resolution Advisories unless other means of separation have failed (ICAO Annex 10 Vol. IV).

3. ACAS II provides a reference as an existing operational system. ACAS II provides advisory level proximate traffic indications, caution level traffic advisories (TAs), and warning level resolution advisories (RAs) (ICAO Doc 9863). The following provides a brief overview of each ACAS II alert type—note that this is not a recommendation for SAA use. Following a similar alerting scheme may be beneficial because ACAS II has been extensively evaluated and will be familiar to many programs and flight crews.

a. Proximate traffic. An advisory indication of nearby traffic that should be considered when manoeuvring. Proximate traffic is denoted with a visual cue (change in traffic symbology) and no aural indication.

b. Traffic advisories (TAs). Caution alert intended to draw the attention of the pilot so as to validate intruder location and prepare the pilot for warning level alerts. Traffic advisories consist of both an aural and visual (yellow symbol) indication.

c. Resolution advisories (RAs). A warning level alert indicating that immediate action is necessary to avert collision. ACAS II resolution advisories are provided visually (red symbol) and aurally, where a manoeuvre resolution is also provided—i.e., a vertical command such as climb or descend. Note that ACAS I does not include RAs.

d. Clear of conflict. An advisory indication that the conflict has been mitigated and the mission can be continued. An aural indication is given and the traffic symbology is returned to either a TA, proximate traffic, or nominal state.

4. When designing and developing an alerting scheme, the following lessons learned and recommendations should be considered:

a. Alerts should have a level of persistence. In addition to nuisance alert frequency, it is operationally unsuitable to have alerts that are of short duration and that switch repeatedly between alert levels. Alert levels should hold long enough to complete the accompanying sensory output—for example, hold a visual alert long enough for the aural warning to be heard. Alerts should not persist when increasing in urgency, but should persist when maintaining or decreasing alert levels. There needs to be a balance between nuisance and false information, meaning that if an alert persists too long it may lead to a false representation of the encounter. If a secondary sensory mode is used, only use the secondary mode when increasing in urgency.

b. The alerting system should be evaluated with actual system characteristics (e.g., surveillance measurement noise, latency) in the anticipated environment to validate alerting system design (see Section 5.4 for detail).

c. Operators should have the ability to acknowledge an alert and to inhibit alerts in a saturated environment. Inhibiting can be done automatically or manually through operator control. Caution should be used when inhibiting alerts because it may lead to a lack of situation awareness, and increases in urgency level should not also be inhibited.

d. Alerts should be integrated with the existing UAS alerting system in order to avoid both interfering alerts that cause confusion as well as operator cognitive overload. Additionally, there should be prioritization of SAA alerts such that higher urgency alerts clearly override lower urgency alerts, and there should be consistency with other UAS alerts.

e. Multiple sensory modes used to convey the alert can be beneficial in terms of decreasing recognition and response time—e.g., visual and auditory. However, the benefit must be weighed against saturating the operator with multiple alert types and modes.

5.2. GUIDANCE

Manoeuvre guidance can be provided in various ways and can improve response time and accuracy, which may be especially beneficial when encounter urgency is high or during complex situations such as multiple threat encounters. When considering whether guidance should be provided and the guidance type, the benefits of response accuracy, timeliness, and consistency must be balanced with operational suitability considerations, including operator situation awareness and over-reliance. On two ends of a continuum, no guidance may be provided or a system may provide a complex path for the aircraft to follow. Similar to alerting, it is important that manoeuvre guidance is correct and minimizes nuisances—e.g., such as unnecessary deviations from the mission. Guidance, like alerts, can be provided with various sensory models and urgency levels—e.g., increasing automation levels when higher urgency is required. It is emphasized that guidance may not be required, resulting in an informative display.

5.2.1. Types

Guidance can be classified as either suggestive or directive:

a. Suggestive guidance provides a range of possible manoeuvres to avoid conflict that can be positive or negative: positive guidance indicates a range of manoeuvres that could be followed to avoid conflict, while negative guidance is a range of manoeuvres that should be avoided. Suggestive guidance is useful when the guidance algorithms may not have all of the information that an operator has, enabling operators to gain insight from the guidance while making the final decision themselves. Suggestive guidance should not become saturated during the encounter—i.e., such that no guidance is available.

b. Directive guidance provides a singular positive manoeuvre—e.g., turn to a specific heading, climb/descend. For example, ACAS II RAs would be considered directive. Directive guidance typically results in reduced response latency, but reduces the operator role in the decision making process. Directive guidance is typically reserved for high urgency situations due to system limitations, such as nuisance alerts caused by incomplete knowledge of the situation; incomplete knowledge includes measurement or future path uncertainty—path uncertainty may be caused by the guidance not being fully aware of the flight plan or environment structure.

The level of guidance a system requires depends on many variables, and one system may switch from one level of guidance to another depending on the mission requirements and encounter urgency. Considerations when determining the level of guidance include safety requirements, environmental and mission needs, operator workload, and operational suitability.

5.2.2. Considerations

Key considerations and lessons learned when developing manoeuvre guidance algorithms include:

a. Guidance is typically more intensive to develop, validate, and verify than alerting because it is more complex and provides a higher information level that may cause a greater degree of negative effects. For example, the manoeuvre guidance may recommend a path that would induce a conflict. Although guidance in general requires more intensive validation than alerting, higher levels of guidance automation may require more validation than lower levels because the role of the automation increases and the resulting severity of the outcomes may increase. Verification and validation should be conducted throughout the design process when considering alternatives, developing requirements, and prototyping solutions. Both human-in-the-loop (virtual) studies as well as fast-time modelling and simulation (constructive) contribute to a successful alerting and guidance design.

b. Higher levels of automation should be weighed against any impact on operator effectiveness such as complacency and loss of situation awareness. In order to ensure usability of the system for higher levels of automation, human factors must be considered throughout the design and development of both alerting and manoeuvre guidance, beyond solely the interface design of the end product (see the Human Factors Chapter for additional discussion).

c. It is important to fully consider and evaluate situations where the guidance may cause a conflict that would not have otherwise occurred, often termed an induced conflict. Fast-time constructive simulation can be used to test many encounter geometries in a relatively short amount of time for characterization of induced conflicts.

d. Interoperability with other airspace user systems (e.g., ACAS II) and ATC must be ensured. This often entails extensive analysis of the manoeuvre guidance when encountering these existing systems in the environment (including right-of-way rules). It is important to note that interoperability of collision avoidance equipment (with directive manoeuvre guidance) may be assured through explicit manoeuvre coordination where compatible manoeuvres are arbitrated through a communications link between systems.[50]

e. A key challenge when developing alerting and guidance algorithms is that the system may not be fully aware of the external environment. For example, the UAS flight plan, level of ATC provided services, and airspace structure may be unknown to the guidance algorithms. This may cause a higher nuisance frequency, and in some cases may detriment safety. In challenging external environments—e.g., in the terminal environment with a high degree of airspace structure—the alerting and guidance algorithms may need restrictions or inhibits. Alerts and guidance may be desensitized or automated response may be deactivated. These restrictions may be encoded in the guidance with inhibits: reasons for inhibits include airspace that should not be impeded (e.g., terrain, restricted airspace), aircraft performance limits (e.g., climb ceiling), or airspace environment (e.g., terminal). Inhibits may be absolute in that no manoeuvre guidance can be issued that conflicts with the inhibit, or partial where a conflicting manoeuvre can

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[50] It would seem that two of the same systems interacting in an encounter would provide compatible advisories. However, small variations in surveillance information and algorithms can cause incompatibilities such that explicit manoeuvre coordination is required.

still be issued in certain cases—e.g., when collision is imminent and the alternative is not as hazardous.

f. Another consideration of note is the objective to prevent collision hazards where the responsible party (ATC or the UAS) may be unknown to the guidance algorithm; therefore, it may be prudent to reserve higher automation level guidance for when the separation mode has been compromised and the responsibility is clear.

g. Uncertainty pertaining to the manoeuvre planned by the guidance is a key challenge that reduces system performance, even when the uncertainty is considered in the guidance algorithms. Sources of uncertainty include surveillance measurement uncertainty and future encounter state uncertainty. Future encounter state uncertainty may be caused by system and operator induced latencies or unanticipated manoeuvres by an aircraft in the conflict (ownship or intruder).

h. Platform manoeuvrability must be considered in the guidance algorithms. In order to obtain wide applicability to diverse platforms there is a trade-off between approaches that use a single manoeuvrability assumption and those that are tailored to specific platforms. A single manoeuvrability assumption solution is simpler to develop and certify, but will result in differences between the assumed manoeuvrability used in the guidance and the actual response; additionally, the lowest platform manoeuvrability that can achieve minimum performance requirements is typically used. Specific, tailored solutions that more closely match actual platform manoeuvrability can result in improved system performance, at the expense of higher complexity and certification burden—i.e., each manoeuvrability input may need to be analysed and certified. Increased manoeuvrability employed by the guidance will result in a safer system, at the expense of operational suitability; some systems employ stronger manoeuvres later in the encounter timeline to balance this trade (such as ACAS II strengthening RAs).

i. During the system's operational life, it is likely that it will encounter situations with multiple threats, or a single threat with proximate aircraft that must be accounted for when planning the manoeuvre guidance. Thus, the guidance and alerting must be able to consider multiple threats simultaneously.

j. Manoeuvre guidance can be generated separate from alerts, but guidance should occur coincident with alerts to provide clarity regarding the system and situation state.

k. Guidance information can be conveyed in many ways, through multiple sensory modes. However, situations that require prompt action dictate a means of conveyance that is immediately understandable, and where compliance can be monitored. This can include integration with flight control displays—e.g., a typical ACAS II installation includes vertical speed guidance on the vertical speed indicator.

5.3. TECHNOLOGY TAXONOMY

1. This section provides an overview of existing and anticipated alerting and guidance technology, introducing benefits and drawbacks of the primary approaches. It is not intended to be comprehensive, and it is likely that a full accounting of existing technology will be inaccurate in a few years. Thus, this section will provide a high level overview of the different technological approaches and associated considerations, where details are left to other documents. As noted previously, the alerting and guidance may be combined into a single algorithm or separate algorithms may be used where the guidance computation will initiate when prompted by the alerting—ACAS II is an example of the latter where a threat is first identified, then a course of action selected.

2. Alerting and guidance technology can be classified in variety of ways[51], but there are predominately two approaches in current use and development: online open-loop path planning and offline closed-loop decision theoretic. Additionally, there are deterministic and nondeterministic approaches for guidance generation.

a. Online and offline define whether the algorithm propagates the future state in real time in the equipment as the encounter progresses (online) or before being loaded into the equipment and prior to an encounter (offline). Online algorithms typically have greater computational processing requirements, but can be more flexible to current conditions—e.g., current flight envelope, flight plan. Thus, offline methods may still employ some level of online computation. Although offline methods may have reduced computational processing requirements, offline methods may have greater computational memory requirements because they must encode an action for each encounter state. Additionally, some online approaches may not guarantee a solution within the allocated computation time; this would also need to be addressed in the system design and through algorithm validation and certification.

b. Closed-loop and open-loop refer to whether the algorithm explicitly considers potential future actions (closed-loop) or only considers the current encounter state and immediate possible actions (open-loop). A closed-loop algorithm may provide a reduced alerting frequency

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[51] For example, Kuchar, J. K. and Yang, L. C., “A review of conflict detection and resolution modeling methods," in IEEE Transactions on Intelligent Transportation Systems, vol. 1, no. 4, pp. 179-189, Dec 2000.

because it may delay an alert, at the expense of computational requirements (online or offline).

c. Path planning and decision theoretic define two methods for determining the recommended trajectories. Path planning is typically accomplished online where multiple own trajectories representing the action space are propagated and then a selection mechanism is used to down select to a single or set of recommended trajectories. Decision theoretic approaches employ computation optimization techniques to explicitly weigh the costs of safety and operational suitability, and are usually executed offline due to the computational burden. Path planning allows for high fidelity projection (aircraft dynamic) models, but computational requirements typically dictate that only a few hundred trajectories can be explored in real-time, and the time horizon, or time in the future that the algorithm explores, is limited. Decision theoretic approaches, by virtue of being able to execute offline, can explore many more potential actions (more accurately representing potential uncertainties) with a large time horizon, but the aircraft dynamic models are typically simpler and not modifiable online. As computational capabilities improve, it is likely that the drawbacks for both approaches will be alleviated. It is also possible to combine approaches to address the limitations of each method.

d. Nondeterministic indicates that for the same set of inputs, the algorithm does not guarantee the same outputs for every instance that the algorithm is executed. This presents a validation and verification challenge that must be addressed if such an approach is pursued.

Current technology examples of online open-loop path planning include ACAS II, JOCA[52], and DAIDALUS[53]. ACAS X[54] uses offline closed-loop decision theoretic planning, as does the Army Assess Algorithm[55] that uses a similar technology.

3. Surveillance and future encounter state uncertainty are the key technical challenges for alerting and guidance algorithm design. The uncertainty can be accounted for implicitly in the logic through parameter thresholds (e.g., desired separation, manoeuvre time) or explicitly when propagating potential trajectories and

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[52] Chen, W.-Z., Wong, L., Kay J. and Raska, V. M.,"Autonomous Sense and Avoid (SAA) for Unmanned Air Systems (UAS)," NATO RTO, MP-SCI-202-28, 2009.

[53] Muñoz, C., Narkawicz, A., Hagen, G., Upchurch, J., Dutle, A. and Consiglio, M., "DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems," in 34th Digital Avionics Systems Conference, Prague, 2015.

[54] Kochenderfer, M. J., Holland, J. E. and Chryssanthacopoulos, J. P., "Next-Generation Airborne Collision Avoidance System," Lincoln Laboratory Journal, vol. 19, no. 1, 2012.

[55] Yenson, S. K., Cole, R. E., Jessee, M. S., Chris, C., and Innes, J.. "Ground-Based Sense and Avoid: Enabling Local Area Integration of Unmanned Aircraft Systems into the National Airspace System", Air Traffic Control Quarterly, Vol. 23, No. 2-3 (2015), pp. 157-182.

determining the recommended action. As an example of implicitly accounting for uncertainty, ACAS II accounts for barometric altimetry system error through the desired vertical separation (the altitude limit, or ALIM), which in turn defines the time required to alert (tau) given the assumed dynamic vertical response of the platform. Explicitly accounting for uncertainty can be addressed in multiple ways. For example, path planning methods may use additional trajectories to represent the uncertainty, but this is constrained by the computational resources available. Decision theoretic methods can consider a more complete representation of the uncertainty, although the representations may be simpler than for path planning methods due to the relatively limited fidelity that can be represented. The availability and uncertainty of the surveillance tracks may limit the alerting and guidance algorithm design. For example, ACAS II is limited to manoeuvring vertically due to the poor horizontal measurement accuracy, and must primarily use range and range rate (combined to estimate tau, a time parameter) to evaluate the horizontal threat level. This is not desirable because tau may indicate a threatening encounter when in fact the horizontal miss distance is sufficiently large. Similarly, radar with poor elevation error may be limited to horizontal manoeuvring.

5.4. VALIDATION AND VERIFICATION

1. Validation that the alerting and guidance are safe and operationally suitable and verification that the system is built as intended are critical support activities. The goal of validation is to evaluate all possible conditions to be experienced in operation to ensure acceptable algorithm behaviour, while the purpose of verification is to ensure that every algorithm component has been designed and integrated correctly.

2. Standard practice makes constructive and virtual modelling and simulation central to algorithm validation due to the extent and efficiency for which the algorithm can be evaluated. Human factors considerations should also be addressed through prototype review and focus groups (see the Human Factors Chapter for additional discussion). Flight test is necessary to validate the modelling and simulation, the usability of the system, as well as the hardware and software integration. In constructive simulation, there are several models of encounters used to evaluate alerting and guidance algorithms (see the Safety Chapter for a detailed simulation description):

a. Encounter model. An encounter model encodes the realistic distribution of encounters to be experienced in the operational environment and is intended to accurately estimate safety, and it can be used to estimate operational suitability (e.g., nuisance alert rate) if the model is appropriately designed to capture and accurately represent all encounters where an operational suitability event will occur. This model captures own and intruder aircraft states, such as speeds and accelerations, as well as the relative geometry of the encounter.

b. Stressing model. A stressing model is intended to robustly explore and evaluate all potential algorithm states. A stressing model is typically designed based on the algorithm and operational concept under consideration.[56]

c. Scenario specific. It may be necessary to evaluate specific operational scenarios for focused analysis, such as closely spaced parallel approaches, airport pattern operations, or for standard vertical separation. These may be derived as a subset of an encounter model, developed by operational subject matter experts, or identified from operational data as described next. This category may also include models for off-nominal conditions—e.g., a sensor is degraded or fails, the communications link is lost.

d. Operational data. If available, these data provide a basis for comparison to a reference operation and are typically used to evaluate operational suitability because they do not provide the statistical confidence required to evaluate safety (where an encounter model is used). Operational data are especially useful when evaluating system upgrades to compare to the existing system. However, it is important that the encounters encompass the alerting space for the system under consideration; else the operational suitability may be estimated incorrectly.

3. When conducting validation activities, metrics must be identified to summarize algorithm behaviour. At the top level, metrics may be categorized according to safety and operational suitability. Safety metrics include:

a. Conflicts. Collisions and collision hazards are the primary safety events that are evaluated. The logic risk ratio is the common metric used to evaluate algorithm safety efficacy, and evaluates the safety of the algorithm under the conditions for which it was specified—e.g., specified surveillance accuracy, operator response. For conflicts that do not result in collisions or near collisions, it may be helpful to evaluate the degree to which the conflict was violated; this is especially helpful when identifying scenarios for focused analysis.

b. Induced conflicts. Conflicts that the system causes that would not otherwise exist in the absence of the system are typically more concerning than unresolved conflicts. Thus, induced conflicts are typically analysed specifically.

c. Miss distance. In addition to the binary conflict event, the miss distance at closest point of approach provides a more complete picture of

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[56] Billmann, B. R., Spracklin, D. and Thomas, J., “Application of Fast-time Discrete Simulation Techniques in Evaluating Aircraft Collision Avoidance Algorithms” in Proceedings of the 14th Annual Symposium on Simulation, Tampa, 1981.

algorithm performance, including cases where miss distance was reduced with the SAA system but did not necessary result in conflict.

4. Operational suitability metrics describe algorithm behaviours that have an impact on the operator or operational environment (e.g., other users, ATC) and have an indirect impact on safety. For example, an operationally unsuitable alerting algorithm could cause higher operator workload which in turn could have a safety effect. Operational suitability metrics that specifically pertain to the SAA operator are sometimes termed pilot or operator acceptability metrics. The specific operational suitability metrics are operational concept specific: that is, the role of the operator and algorithm in the system will dictate the operational suitability metrics and their relative significance. Common metrics and metric categories include:

a. Nuisance alerts. Alerts during otherwise safe operations.

b. Late alerts. Alerts that occur too late to resolve the conflict.

c. Reversals and strengthens. If included in the algorithm design, direction reversals (e.g., climb to descend) and magnitude strengthens are undesirable (these are standard ACAS II metrics).

d. Split alerts. Alerts that are activated and deactivated several times during an encounter, including undesirable changes in alert urgency.

e. Deviation. Magnitude of the deviation from the nominal course, measured in time or distance.

Operational suitability considerations may have a higher level measurable effect on metrics such as operator response time and accuracy, including risk ratio, that could be used to identify operational suitability issues and validate mitigations. Total response time is the period of time required for the operator to implement a manoeuvre after the guidance is displayed, while accuracy represents the degree to which the implemented manoeuvre reflects the guidance and achieves the desired separation. See the Human Factors Chapter for a focused discussion of timeliness and accuracy metrics.

5. Once the algorithm is validated, it is important that it is implemented correctly in software and hardware, and into the UAS. Test cases should be generated that verify the implementation of the logic throughout integration. For example, test cases that evaluate each code branch and requirement are used for ACAS II verification (DO-185B). These test cases should include off nominal conditions, such as input loss or degradation, and multiple threat encounters.

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CHAPTER 6 SURVEILLANCE

1. As the initiating stage in the SAA process, the surveillance system affects the performance of downstream components, including guidance, HMI, the operator, and ultimately the efficacy of the resulting manoeuvres. Therefore, these components place requirements on the surveillance system. From the perspective of the other SAA components, the surveillance system must provide a complete, clean, timely, and accurate track of threat aircraft that is suitable for use by the operator and, if equipped, the alerting and guidance function. The system designer must translate the SAA system requirements into surveillance requirements and design.

2. The surveillance system generically consists of one or more sensors for acquisition and tracking, and a track integration function if more than one sensor or source of information exists. The tracking and track integration functions will typically include one or more filters to estimate unsensed states (e.g., velocity), and smooth the track over several individual measurements to reduce estimate noise. The surveillance system also typically incorporates various hardware and software mitigations for clutter.

3. The primary SAA system and UAS attributes that must be considered when developing surveillance requirements are depicted in Figure 6-1. During requirements analysis and decomposition, these attributes can be traded—for example, the requirements for one attribute may be relaxed at the expense of one or more other attributes. This figure illustrates the difficulty in establishing surveillance requirements because they interact with several other system attributes that may also need to be specified simultaneously.

a. Safety and Operational Suitability. These metrics are defined at the system level in that they are defined at the boundary between the system and environment, and include the collision and collision hazard risk, manoeuvre rate, course deviation, and manoeuvre reversals (reversing from one manoeuvre decision to another). Surveillance has an indirect impact on safety and operational suitability because a decision must be made and executed by the human or automation based on the surveillance information. Poorer surveillance can typically be overcome with greater manoeuvring, at the expense of operational suitability—e.g., manoeuvring more frequently or to a greater extent.

b. Latency. This key system attribute represents the delay in executing a manoeuvre based upon the current encounter state, and may have contributions from the surveillance itself, interconnects and links, decision, and execution. A system with higher latency may require a more accurate track and earlier tracking to achieve the same resulting effectiveness. Not shown here is the time required to accomplish a task that does not impart latency, but may impact surveillance requirements, such as required tracking range. For example, an operator will take an amount of time to determine a manoeuvre decision; however, the operator will use surveillance information up to the point that the decision is determined. If this decision duration only consisted of latency, then this would indicate that the decision was based on the surveillance information before the decision duration which is not realistic.

c. Manoeuvrability. This attribute captures the degree to which separation can be achieved by the SAA aircraft and the time required to do so. A more manoeuvrable aircraft can tolerate poorer surveillance (accuracy and detection). However, there are typically constraints placed on the system due to operational suitability concerns, such as nuisance manoeuvres and course deviation. These constraints will limit the trade space for manoeuvrability and accuracy/detection.

d. Decision efficacy. The accuracy with which decisions are made and executed may have a residual impact on the surveillance requirements. For example, a larger detection range may be required when the operator is less accurate at making a decision to allow time for later correction.

e. Accuracy. This surveillance attribute captures the error in the track. Accuracy may be represented by time dependent (jitter) and independent (bias) components.

f. Detection. In the context of surveillance, detection refers to attributes that may impact successful detection of intruder aircraft. Detection encompasses tracking range, time to establish a track, field of regard, and external elements that impact detection, such as noise and clutter—e.g., objects that are not of interest to SAA, such as birds, ground clutter, and weather.[57] For example, smaller tracking ranges may require higher track accuracy, additional manoeuvrability, or more accurate and timely actions (e.g., with higher levels of autonomy) to obtain the same safety and operational suitability.

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[57] Although these nonaircraft objects may not be of direct interest for SAA, the UAS may need to detect and avoid these other objects. When developing a Detect and Avoid capability for these other hazards, the suitability of the SAA operational concept, including requirements and attributes, must be reconsidered.

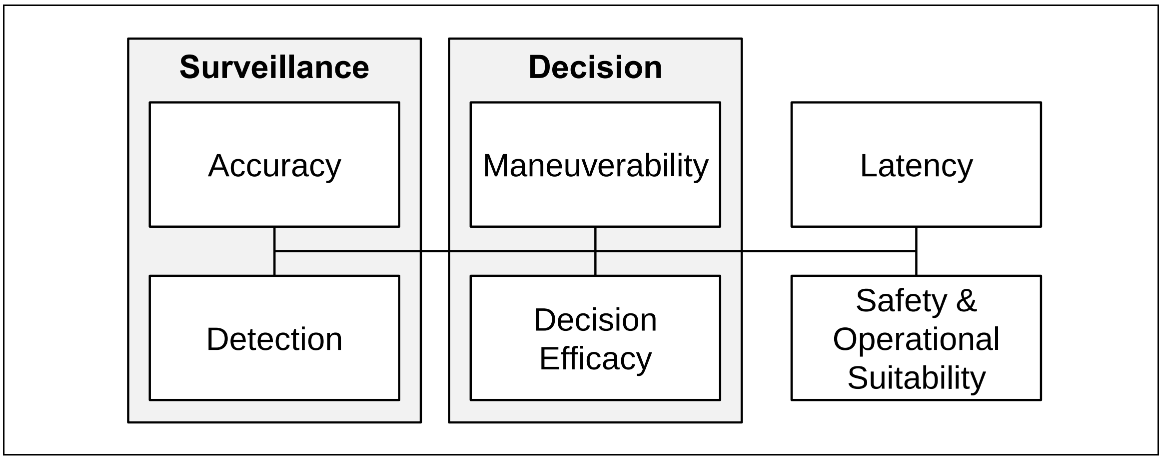

Figure 6-1: Primary Attributes Affecting Surveillance Requirements

6.1. GENERAL CONSIDERATIONS

Given the high level surveillance requirements defined in the context of the SAA system, sensor technology can be identified with associated requirements. General SAA surveillance considerations and recommendations that apply to all sensor types are described here, while considerations that are specific to a given technology are discussed in the following section.

6.1.1. Environment

The environment is broadly defined here as the conditions outside the UAS that affect SAA surveillance performance. All surveillance requires the detection of a signal that is spread across a portion of the frequency spectra. Therefore, the ability of the sensor to detect the signal will be affected by several components of the external environment that must be considered during design and evaluation, including:

a. Spectrum. Depending on the operating frequency, there may be other spectrum users that may adversely impact the ability to detect intruder aircraft. Further, regulations may limit the SAA sensor’s use of spectrum.

b. Weather and atmospherics. Clouds, rain, air density, and humidity, among others, may affect sensor detection. Typically, sensors are impacted to a greater extent at higher frequencies. These conditions may attenuate the signal, but also may contribute false detections (clutter).

c. Clutter. Broadly defined as potential sources of detections that are not the target of interest, clutter mitigation is a critical activity during system development. Clutter can be caused by signals from actual aircraft that are reflected off of the ground and other surfaces (multipath), or from nonaircraft such as terrain, ground vehicles, birds, and weather. Clutter mitigation must balance removal of clutter with the potential filtering of actual intruders if classified as clutter.

d. Target attributes. The intruder’s flight profile and signature will affect the ability to surveil. Ideally, all potential intruder types would be considered when defining requirements, but this is constrained by analysis resources and available intruder attribute data. Therefore, it is useful to define intruder categories based on these attributes to define surveillance requirements.

(1) Flight profile. Intruder speed and accelerations will affect the ability to acquire and track. Higher intruder speeds, resulting in higher closing speeds, will require greater detection and tracking ranges to achieve the same system efficacy. Intruder speed, such as measured range rate (Doppler), may be used to discriminate intruders from clutter (e.g., ground clutter, birds); however, intruder speeds and geometries that are near to that of the clutter may challenge successful detection and tracking, so such discrimination techniques must be carefully considered to ensure that intruders are successfully tracked. Depending on the tracking and estimation architecture, accelerations will result in the track estimate lagging the true state; in extreme cases, accelerations may induce a track drop if not properly accounted for.

(2) Signature. Because detection efficacy is dependent on the signal power received at the sensor, the power of the signal transmitted or reflected from the intruder is a key factor. Intruder aircraft that are equipped with avionics to enable detection (e.g., transponders) are straightforward to detect not only because of the high signal to noise ratio, but also due to the standardized, consistent signal. Detection of aircraft without such equipment (noncooperative aircraft) is more difficult, in part due to the variability in returned signal between different aircraft types and based on the geometry of the encounter (intruder aspect angle).

6.1.2. Field of Regard

The field of regard (FOR) is the volume of airspace surrounding the UAS that the sensor searches and tracks, and the reference frame is typically defined in that of the sensor—e.g., a common reference frame for an airborne sensor is aircraft body-fixed spherical where the components are range, azimuth, and elevation; relative altitude may sometimes be substituted for elevation if directly measuring altitude. Specific considerations and recommendations for establishing the FOR, which apply equally to ground-based and airborne surveillance, are:

a. Minimally, the FOR should be adequate to support the right-of-way responsibilities within the Rules of the Air—e.g., no less than 110° azimuth relative to aircraft plane of symmetry (ICAO Annex 2).

b. The FOR should be optimized to detect and track as many threatening aircraft as practicable, including consideration of geometries beyond that necessary to support the right-of-way responsibilities. This can be accomplished using simulation of realistic engagements using an encounter model.[58] Additionally, the range FOR can typically be reduced as azimuth is increased from head-on due to reduced closing speeds, assuming that a constant time to closest approach is required and that own and intruder speeds remain constant.

c. Unmanned aircraft attitude should be accounted for, including angle of attack, sideslip, and roll and pitch throughout the operating envelope. For example, best practice is to either stabilize the FOR during a turn or specify the elevation FOR sufficiently large to compensate.

6.1.3. Target Density

Once the FOR is determined, the number of aircraft that the sensor must track can be established. There are two target capacity values that should be specified:

a. Track capacity. The track capacity represents the number of tracks that the system must have the ability to keep track of in software.

b. Threat capacity. All tracks may not need to be acted upon, so they may not all require sufficient accuracy for an effective manoeuvre decision.

Both of these values can be determined by considering the maximum density in which the system will operate and the FOR, accounting for false tracks. The threat capacity is a subset of the total track capacity, and accounts for the likelihood of an alert or manoeuvre decision (RTCA DO-185B).

6.1.4. Tracking and Estimation

The ultimate objective of tracking and estimation is to provide intruder state estimates that can be accurately decided upon. Tracking and estimation may be comprised of several subfunctions, including acquisition and tracking, estimation and smoothing of own and intruder states, and multisensor track integration. These subfunctions may occur serially, could include feedback between subfunctions, or be tightly integrated. Practically, SAA will include some type of tracking and estimation, although it is

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[58] For example, Edwards, M. W. M., “Determining the Minimum Required Field of Regard for Sense and Avoid Surveillance Using Airspace Encounter Models,” in AUVSI Unmanned Systems North America, Denver, Colorado, 2010.

conceivable that an SAA system could operate without some or all of the tracking and estimation functions.

6.1.4.1. Search, Acquisition, and Tracking

The primary purpose of this subfunction is to acquire and update potential threats as the encounter evolves. This process requires the establishment and maintenance of tracks with measurement updates.

a. Search. The process of identifying the existence of potential intruders, search provides detections to acquisition and tracking.

b. Acquisition. If a detection is not associated with an existing track, candidate track hypotheses are created until tracks can be declared.

c. Tracking. Once a track is declared, it is updated with detections. New detections may occur solely with search timing, or may be scheduled independently, depending on the sensor technology and architecture. Additionally, detections may be intelligently scheduled so as optimize track accuracy for the intruders of interest.

Track continuity is an important tracking attribute; poor continuity, indicated with high rates of track drops, may cause split alerts, and ultimately may induce operator confusion and have safety effects.

6.1.4.2. Estimation and Smoothing

1. Typically, raw measurements from detections are not of suitable quality for making a manoeuvre decision because they may not be sufficiently accurate, have adequate update intervals, or contain the full required state—e.g., three-dimensional position and velocity. Estimation and smoothing is the process by which the additional required states are calculated and are time averaged to provide a usable estimate of the encounter state. A Kalman filter is a common approach for this process (with several variations), although other methods may be employed, including alpha-beta-gamma filters and particle filters. The prediction of the intruder state at the next scheduled detection may be derived from this process to inform acquisition and tracking. There is a fundamental trade between track accuracy and latency (or responsiveness): the more smoothing that is employed, the more accurate and stable a track may be; however, if the intruder manoeuvres, there will be a delay in identifying this manoeuvre in the output state estimate. Furthermore, if extensive smoothing is required before action, additional detection range may be required.

2. The alerting and guidance algorithm performance may be enhanced through knowledge of the state uncertainty—e.g., by modifying the targeted separation with the estimated state uncertainty. The state uncertainty estimate should consider all contributors to estimate error including uncompensated latency and track error. If

used, requirements should be placed on the accuracy of the uncertainty estimate, and both over and under estimating the uncertainty should be considered for the effect on system performance—e.g., under estimating the uncertainty may increase missed alerts, while over estimating the uncertainty may increase nuisance alerts. Because the alerting and guidance employs predictions of the future encounter state, the velocity estimate is typically more important than the position estimate. Thus, special attention should be given to ensuring velocity accuracy and stability over the course of an encounter.

6.1.4.3. Integration and Validation

1. If multiple disparate or similar sensors are employed, it is typically necessary to integrate the sensor outputs into a single track: although it is possible that a satisfactory SAA system could be developed that nominally operates on multiple tracks from the same intruder, this scheme will likely degrade safety and operational suitability performance. Furthermore, some sensors may be prone to erroneous or misleading data (e.g., ADS-B), that may require validation from other sensors before use.

2. There are several approaches to track integration. The simplest and most loosely coupled approach to track integration is best source selection where a track is produced for each individual sensor and the best is selected via a set of criteria for downstream processing.[59] On the other end of the spectrum is using individual measurements (or tracks) from each sensor and mathematically combining to form a track estimate[60,61]; this approach can include dynamic tasking of various sensors based on the current estimate. This latter approach of mathematical combination may be called sensor fusion, although there is broad disagreement regarding the terms associated with sensor integration. Although best source selection is easier to implement, the mathematical combination method is more robust to individual sensor drop-outs, can include sensors that may not be sufficient by themselves (owing to performance or measured states) and may initialize the track faster. However, care must be taken when employing mathematical combination so as not to degrade the integrated track accuracy with poor measurements—i.e., a poor sensor may degrade the track of a very accurate sensor.

3. Each approach to track integration requires association among the sensors outputs. Association can be accomplished track-to-track, measurement-to-track, or measurement-to-measurement (with increasing computational requirements, complexity, and potentially better performance). Best source selection typically uses

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[59] RTCA, “Minimum Operational Performance Standards for Aircraft Surveillance Applications System”, DO-317B, 2014.

[60] Chen, R., et al, “Multi-Sensor Data Integration for Autonomous Sense and Avoid” in AIAA Infotech@Aerospace, 2011.

[61] Bageshwar, V. and Euteneuer, E., “Multi-Intruder Aircraft, Multi-Sensor Tracking System” in 34th Digital Avionics Systems Conference, 2015.

track-to-track association, while mathematical combination may use any of the methods. Association requires that the reference frames for the different sensors are appropriately considered.

6.1.5. Platform Integration

Integration of the surveillance system on the platform must be considered in order to appropriately account for various forms of degradation on the surveillance from other aircraft components. Specific considerations include:

a. Platform capacity. The available size, weight, and power (SWaP) on the platform will influence not only the sensor selection and capability, but also the installation location, interfaces, and constraints. These should be identified early during system design, and tracked through installation and operation.

b. Multipath. Surveillance typically assumes a direct line of sight between the sensor and the intruder. Thus, any reflection of the signal of interest, or multipath, can corrupt the signal resulting in false tracks or degraded tracking performance—e.g., erroneous range or angle measurements.

c. Interference. Signals from UAS payloads and other systems (including ground systems) may degrade surveillance or these other systems may be degraded by the surveillance system itself. All potential sources of interference should be identified and appropriate mitigations put in place.

d. Thermal loading. Active sensors that require transmission of a signal require detailed consideration of the thermal environment due to the power consumed and heat produced. Furthermore, some receivers may be sensitive to the thermal environment. Therefore, the installed thermal loading needs to be analysed and mitigated.

e. Vibration and shock. The lifetime effects of vibration and shock must be considered, similar to other avionics.

f. Obstructions. Wings, rotors, and other platform features may obstruct the surveillance signal. Thus, the surveillance placement must be chosen to minimize such effects, and other mitigations considered if necessary.

6.1.6. Health and Integrity Monitoring

Like other SAA components, the surveillance system should include health and integrity monitoring to ensure effective operation. Surveillance system health can be monitored in a variety of ways including through power consumption, temperature, and received signals (digital or analog). At the surveillance system level, the sensor can be assessed against other similar or desperate sensors to ensure proper functioning. Performance out of spec should be reported to the operator, and hazardously misleading information should be identified and appropriate mitigations put in place—e.g., operator alerting, disuse in the downstream components.

6.1.7. Multifunction

Developing, validating, and verifying a sensor is a considerable expense. Therefore, it may be appealing to use the SAA sensor for other purposes, such as for weather and terrain avoidance, or for mission use. There are clear benefits in terms of size, weight, and typically power for a single integrated system versus two separate systems. However, the complexity of more than one function that must be interleaved may add cost, due to certification and verification. Specifically, interleaving a safety critical function (SAA) with a function that is not safety critical may require that the latter is certified to a higher level than required had it been separate. Higher certification levels typically result in higher cost and longer development timelines, limiting the agility of system updates.

6.1.8. Security

During system design, security considerations should be assessed for each mission phase. Depending on the environment, surveillance may be vulnerable to interference or spoofing, and measures should be taken to ensure that such vulnerabilities are detected and mitigated.

6.2. SENSOR TECHNOLOGY

Sensors can be classified according to whether intruder aircraft equipment is used or signals are emitted from the own aircraft sensor. When intruder aircraft equipment supports surveillance, such aircraft are termed cooperative, while other aircraft are termed noncooperative. The terms primary and secondary may be used to denote surveillance of noncooperative and cooperative aircraft, respectively. When a signal is transmitted from the sensor, such surveillance is termed active, while surveillance that only receives is termed passive. It is beyond the scope of this document to detail each sensor technology; rather, this section provides a brief description of each sensor, along with associated benefits, drawbacks, and other considerations specific to SAA.

6.2.1. Noncooperative

Noncooperative technology is the key SAA challenge when compared to existing technology for preventing aircraft collisions. Compared to cooperative technology, noncooperative sensing is prone to clutter from a variety of sources. Furthermore, many cooperative technologies provide a mechanism to exchange state data, such as position and velocity, whereas noncooperative sensors require measuring or estimating such data internal to the sensor, or elsewhere in the SAA system. The primary noncooperative technologies under consideration for UAS use either optical or radio frequencies—acoustic sensors have had relatively limited development for SAA. Optical technologies are generally smaller, require less power, and are less expensive, while radio frequency (RF) technologies are more robust to environment conditions. As for certain existing manned aircraft operations where the aircraft must remain clear of clouds, such as those conducted under VFR, similarly conducted UAS operations with optical SAA sensors are likely to be constrained to remain clear of clouds to enable SAA; it is conceivable that operations with RF sensors may not be so constrained. This section starts with a discussion of RF sensors and then optical.

6.2.1.1. Airborne Primary Active Radar

1. An airborne primary active radar consists of a single mechanically steered antenna or multiple fixed electronically scanned antennas (typically 2–3) to cover the necessary field of regard. Radars typically measure range and range rate (Doppler) well, but accurate estimates of angular position and derived velocity are relatively more challenging to achieve. Hence, monopulse techniques are typically employed to improve accuracy, and the array must be appropriately sized—larger apertures have better accuracy. Additionally, the radar beam must be scanned at a sufficiently high rate to ensure that a threatening intruder is detected and to provide an adequate number of measurement updates to achieve the required accuracy: this requirement has resulted in many designs employing electronically scanned arrays rather than mechanically scanned arrays.

2. The benefits of airborne primary active radar include reliable, relatively large detection ranges in many environmental conditions (clouds, weather, day/night), it is a fairly well established technology, and accurate range and Doppler measurements are typical. Drawbacks include the size, weight, power, and cost requirements: the sensor must transmit and receive over a large field of regard, and radio frequency (RF) technology is generally larger and more expensive than alternatives.

3. The key challenge for radar is clutter from the ground: mitigation techniques depend on whether the clutter is in the side or main lobes. Side lobe clutter can be mitigated through careful side lobe design as well as techniques such as an omnidirectional guard channel (also called a sidelobe blanker)[62]. Main lobe clutter mitigation is typically challenged by clutter aliased in range and Doppler, and mitigation techniques can include rejecting returns that have the same range and Doppler as the ground, or through intelligent waveform agility. Stationary and moving ground clutter will likely place a lower limit on the aircraft operating altitude: ground clutter presents a stronger return at lower altitudes. Clutter may also be present from airborne objects such as birds and weather that must be identified and mitigated;

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[62] Nickel, U., “Fundamentals of Signal Processing for Phased Array Radar”, in Advanced Radar Signal and Data Processing, NATO RTO-EN-SET-086-01, 2006.

weather attenuation and clutter is also present, but is more pronounced at higher frequencies. The radar frequency must be chosen to be within the spectrum approved for radio navigation[63], while providing for adequate accuracy, and considering on-board and off-board interference.

6.2.1.2. Ground Based Primary Active Radar

1. Ground based active radars are employed in a single or a multiple sensor configuration: multiple sensors are used to increase the operational volume or to improve tracking accuracy through track integration. Due to the geographically fixed operational volume, ground based radars are used to enable operations near the radar such as terminal operation training or transit to a nearby airspace where noncooperative SAA may not be needed—e.g., restricted airspace. Ground based radars may also augment airborne surveillance in the challenging low altitude environment.

2. The key benefits of ground based radar are two-fold: first, ground based radars are quite mature, largely available off the shelf, and in many cases may exist at the operational location, and second, provisions on-board the aircraft are not needed. This latter benefit is especially useful for smaller and existing unmanned aircraft, and to satisfy the airspace SAA requirements in a shorter timeframe compared to airborne solutions. Challenges include those similar to airborne radar, except that ground clutter can also be mitigated through clutter mapping which enables lower altitude operations. Additionally, ground infrastructure such as radar support equipment (power, towers) and communication links must be in place to support operations.

6.2.1.3. Multistatic Radar

1. Typical airborne and ground based radars are monostatic in that the transmitter and receiver are collocated. Bistatic radars have one transmitter and one receiver that are separated while multistatic radars may have multiple transmitters or receivers. Multistatic systems may employ a receiver on the aircraft or operate solely in a ground-based mode where all receivers and transmitters are on the ground.

2. The key advantage of multistatic radar is that it limits the equipment required on the aircraft, which would potentially only include the receiver; additionally, having only a receiver is less susceptible to jamming and identification.[64] However, the operational volume may be limited similarly to ground-based systems, unless transmitters have a wide geographical extent and the receiver is located on the aircraft. The architecture and processing for multistatic radar is more complex than

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[63] International Telecommunications Union, “Characteristics and spectrum considerations for sense and avoid systems use on unmanned aircraft systems,” ITU-R M.2204, 2010.

[64] Johnsen, T and Olsen, K. E., “Bi- and Multistatic Radar”, in Advanced Radar Signal and Data Processing, NATO RTO-EN-SET-086-04, 2006.

monostatic radar because synchronization is required between the transmitter and receiver.

6.2.1.4. Electro Optical and Infrared

1. Electro-optical (EO) and infrared (IR) sensors use optical wavelengths and are employed in a configuration of a handful of individual sensors to obtain the required FOR. These sensors are passive in that they receive signals present in the environment and do not transmit energy; thus, they are affected to a larger extent by the environment. EO and IR sensors employ a pixel array, and therefore are typically quite accurate in measuring angle; the derived angular velocity is therefore accurate as well. IR sensors may operate in the short to long-wavelength infrared regions, depending on the infrared energy to be detected: mid-wave for detecting hot components (e.g. engines), and long-wave for detecting skin thermal emissions. More sensitive IR sensors may require active cooling which adds to complexity, cost, power, and size.

2. The key benefit of EO/IR is that a passive sensor without transmission enables lower size, weight, and power, and therefore, typically lowers cost. Additionally, no transmissions may be attractive for sensitive operations. A key challenge is a lack of direct range measurements that are important for determining avoidance action including time to conflict: passive ranging (using several independent measurements over time) or the size of the intruder can be used to infer range or range rate, but the accuracy will not compare to that for radar. The clutter environment can be quite challenging, especially for EO sensors where clutter can include clouds, terrain, and ground objects; the same clutter sources exist for IR sensors, but the IR environment is typically more benign. Additionally, clouds, weather, and the sun will obstruct the ability to detect aircraft for both EO and IR. Hence, a UA operating under VFR would need to remain separated from these conditions if using EO or IR sensors for aircraft separation. Lastly, compared with radar, the detection ranges are small which may limit the efficacy at preventing collision hazards.

6.2.1.5. LIDAR

1. LIDAR uses a laser (typically infrared) to illuminate an intruder, and uses time of arrival to measure range and beam pointing to measure angle. Due to the wavelength of the LIDAR and typically small beam, the accuracy is superior or on par to radar and EO/IR. However, beamwidth makes scanning the full FOR challenging; thus, the LIDAR may be coupled with another sensor for scanning, and the LIDAR then is used for tracking.

2. Given that LIDAR illuminates the intruder, the detection can be enhanced compared to EO/IR; this is especially true for intruders that have a limited IR signature or may challenge EO such as gliders. Because LIDAR uses the same wavelengths as EO/IR, it is susceptible to the same environmental conditions, although the environment effects are lessened due to its active illumination.

6.2.2. Cooperative

Although SAA could be accomplished with only noncooperative sensors (as with human vision for See & Avoid), the enhanced detection range, accuracy, and maturity of cooperative surveillance enable more effective SAA manoeuvres. Cooperative technology relies on properly functioning equipment on intruder aircraft to enable detection; with a few exceptions, cooperative surveillance operates at the 1030 and 1090 MHz frequencies. Although some aircraft may not be equipped with the requisite transponder equipment, a majority of larger aircraft capable of carrying passengers are required to have transponders. Therefore, use of cooperative surveillance can enhance avoidance of collision against intruders where the severity of a collision is increased. Thus, use of cooperative surveillance is highly recommended if possible within size, weight, power, cost, and operational constraints.

6.2.1.1. Airborne Secondary Active Radar

1. Most notably used for ACAS II surveillance, airborne secondary active radar interrogates transponders originally intended for ATC purposes, in a method similar to ground based ATC radars. The reply is then used to estimate range using time of arrival and bearing using angle of arrival measurements. Precise altitude tracking is enabled through the barometric altitude encoded in Mode C transponder replies.

2. The key benefit of airborne secondary active radar is that it is highly reliable, and is effective against a large portion of existing aircraft. However, drawbacks include limitations on detection range due to spectrum considerations (the sensor is desensitized in higher density airspace), as well as poor angular accuracy due to the size and simplicity of the antenna used in existing ACAS II systems; hence, ACAS II issues only vertical avoidance manoeuvre guidance Additionally, the angular accuracy is highly dependent on the installation location, relative to aircraft structures and other antennas; this may be especially challenging for smaller unmanned aircraft. Lastly, because it is an active sensor, size, weight, and power requirements are relatively high.

6.2.1.2. Ground Based Secondary Active Radar

1. Ground based secondary active radar has been the surveillance backbone of the air traffic control system for decades. It provides long-range, reliable surveillance based on aircraft transponder equipment. Typical air traffic control radars rotate with a period of 5–12 s that dictates the measurement update rate, at a range of 60–250 NM: shorter periods and smaller ranges are intended for the terminal environment.

2. Although ground based secondary active radar is very reliable, a key consideration is that the same surveillance information may be used by air traffic control, potentially resulting in a single point of failure for the top-level function of preventing collisions between aircraft. Additionally, the surveillance lower altitude

floor will increase with range. Lastly, the surveillance quality may not be adequate at longer ranges for the avoidance of collision due to the low update rate and the absolute surveillance accuracy degrading proportional to the range.

6.2.1.3. Secondary Passive

1. In general, secondary passive surveillance transmits the aircraft state information without the need for the receiving sensor to make independent measurements. Most notably, ADS-B state information is transmitted that is derived from global navigation satellite system (GNSS) measurements or an inertial measurement unit (IMU). Therefore, ADS-B data is generally of superior accuracy compared to other cooperative technologies. Additionally, there are variants of ADS-B that include Traffic Information Surveillance – Broadcast (TIS-B) that uses ground-based radar surveillance transmitted similarly to ADS-B and Automatic Dependent Surveillance – Rebroadcast (ADS-R) that retransmits ADS-B on a separate frequency from that received: ADS-R is specifically used in the United States where both 1090 MHz and 978 MHz (UAT) frequencies are used for ADS-B.

2. The one-way communications path and improved receiver sensitivity typically improve ADS-B detection ranges over airborne secondary active radar. However, it is similarly prone to interference from other transmitters. ADS-B also benefits from better accuracy than other sources. Because the ADS-B receiver does not make independent measurements, ADS-B is easier to spoof than other surveillance modalities. Thus, it is often validated with a distinct modality, such as airborne secondary active radar—e.g., ACAS II surveillance. Lastly, like ground-based secondary radar, ADS-B is used for ATC separation services, so a lack of independence should be considered during system development.

6.2.1.4. Multilateration and Multiangulation

1. Multilateration and multiangulation use multiple geographically dispersed receivers to estimate transmitter (intruder) location with time difference of arrival or independent angular measurements, respectively. Multilateration and multiangulation can also be combined in an integrated system, where both time and angles are used. As an example, ADS-B ground stations use multilateration to validate ADS-B reported position where only precise timing measurements are needed.

2. With respect to their use for SAA, multilateration and multiangulation suffer from the same drawbacks as ground-based radar in that the operational volume is limited. Additionally, the architecture is complex, requiring communication between the receivers and the SAA system. The benefit is simplicity in the individual receiver design in that a transmitter is usually not employed and multilateration can be accomplished without a directional antenna.

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