CHAPTER 9

From data to effective actions

Providing actionable information for detect and avoid

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Abstract

To integrate remotely operated aircraft into non-segregated airspace, a Detect- and Avoid (DAA) capability is required. To remain Well Clear of other aircraft, a DAA system provides the pilot with actionable information derived from real-time data about cooperative and non-cooperative traffic. In 2017, the first Minimum Operational Performance Standard (MOPS) for DAA systems was published by RTCA. To promote interoperability between systems, NATO Study Group 268 is working on the validation of a performance-based requirements standard. To prevent requirements dictating a particular technology, data requirements are specified as sensor-agnostic. To meet the data requirements, advanced data-processing is required for detection, tracking and fusion/integration. This chapter describes the DAA process from an OODA perspective, discusses the potential of AI/ML techniques, and identifies questions that must be answered before a safe fully autonomous remain Well Clear capability can be realised.

Keywords: Unmanned aircraft, Detect and Avoid, Autonomy, Artificial intelligence, Machine learning

9.1. Introduction

Detect and Avoid (DAA) is an essential capability for Remotely Piloted Aircraft to share the airspace with manned aircraft. In a world without disturbances, in the presence of perfect data and with perfect knowledge of the dynamics, achieving a goal can be performed by actions that do not require any corrections. For the aviation domain such a world would allow all missions to be flown exactly along the pre-planned route and without the need for any deviations. Clearly, this is not the case. The need for a closed-loop approach to achieve desired goals is recognised both implicitly and explicitly in a wide range of disciplines. The Second World War drove the development of control theory for guidance and weapon control. It was recognised that for tasks such as aiming, using the observed data was not enough.

The movement of a target needed to be compensated through a prediction of the future state. Such prediction requires a model of the system. A model encapsulates the knowledge that allows the future state to be derived from (observations of) the current state and the inputs to the system. For certain applications it may be sufficient to use a linear extrapolation of the current state. At the other end of the spectrum are models that are created using Artificial Intelligence / Machine Learning (AI/ML) approaches. In recent years, advancements in the area of AI/ML have caused many speculations regarding its potential to replace human decision making in a wide variety of roles. For the military domain, one advantage is comparable to the use of remotely operated aircraft to replace manned aircraft for dull, dirty and dangerous missions. A potentially even more decisive advantage is the possibility to significantly increase the speed with which the Observe-Orient-Decide-Act (OODA) loop can be closed due to the elimination of the time humans need to assess the situation and make a decision.[1] Koch discusses the ethical implications of replacing conscious decisions with AI for the Defence domain.[2] This chapter discusses the current state-of-the-art in DAA systems, with a focus on how information requirements drive the sensor- and data-processing requirements. The potential benefits of using AI/ML techniques are discussed in the context of the OODA framework.

9.2. Background – navigation, guidance, control and automation

Control loops form the backbone of navigation, guidance and control systems. Aircraft have seen an incremental increase in automation, starting at the inner-most control-loops. In the Seventies, the increase in bandwidth that could be achieved with digital closed-loop control of aircraft attitude enabled artificial stabilisation of unstable aircraft. Closure of the position control loop introduced the capability of automatic navigation. Today's aircraft can be operated in a variety of automated modes, but the authority that determines in which mode still resides with the operator.

A closed-loop system can comprise multiple control-loop closures. The model of a fully automated single control-loop can be divided into the following four components: data acquisition, data processing, action selection, action execution (Figure 9.1). This is similar to the OODA classification often used in the military domain.

Whereas the desire to use dynamically unstable platforms drove the full automation of the inner-loop for manned aircraft, for remotely operated aircraft the control-link latency is a determining factor[3] for automating the inner-loop. Recognising the need and impact of automation for remotely controlled platforms, the first systematic classification of task-allocation between the human operator and the automation was introduced by Sheridan and Verplank.[4] Their one-dimensional Level of Automation (LoA) scale was later extended into a two-dimensional scale by dividing a function into the steps of data acquisition, data processing, decision making and action.[5]

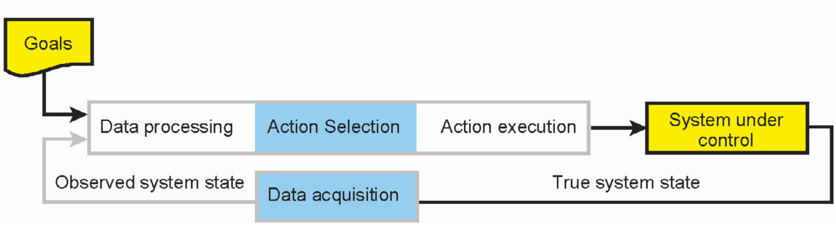

Fig. 9.1. Data acquisition, data processing, action selection and action execution in a feedback control-loop intended to ensure that the state of the system under control meets the defined goals.

For more than 40 years, the automatic execution of a flight plan has been performed by a Flight Management System (FMS) that provides inputs to the Automatic Flight Control System (AFCS). Similarly, remotely piloted aircraft can fly a mission without the need for a pilot controlling stick, rudder and throttle. However, in case an event requires a deviation from the plan, pilot intervention is required. The OODA depiction of this supervisory control with the possibility to intervene is illustrated in Figure 9.2.

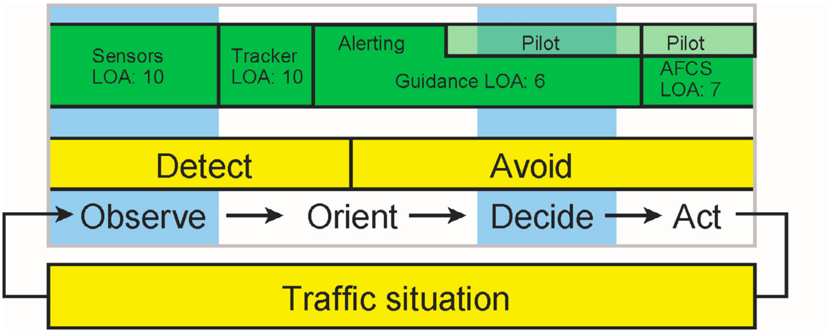

Fig. 9.2. OODA depiction of the supervisory control with the possibility to intervene. Detect and Avoid is intended to maintain a traffic situation with sufficient separation. Sensors provide the data observations that are transformed into actionable information in the Orient phase. In case of an alert, guidance is computed to remain well clear and provided to the flight control system for automatic execution. The pilot is 'on the loop' and can both alter the guidance and intervene in the execution.

During supervisory control, the role of the pilot is to compensate for the limited flexibility of automated systems in the event of an unforeseen circumstance for which the system was not designed. To benefit from the flexibility of the human operator, the system must be designed so that the pilot is able to safely and rapidly respond to unexpected events. One possible reason for the pilot to intervene is if the planned trajectory is likely to cause a loss of Well Clear with another aircraft. The pilot will have to override the automation that controls the aircraft along the planned route and command a speed, direction and/or altitude that will keep ownship Well Clear. To continue the automated closure of the navigation loop, the decision on *when and how* to manoeuvre to remain Well Clear would need to be automated. A particular challenge is associated with deciding upon the course of action in situations where the available data leaves considerable uncertainty about the potential future situation and/or the situation lacks unambiguous normative decision criteria.

This chapter will discuss the current state-of-the-art in DAA systems and identify challenges and questions that must be successfully addressed before autonomous operation through automatic closure of the DAA OODA-loop is safely possible.

9.3. Detect and avoid systems

DAA is an electronic means of staying Well Clear[6] of other traffic to meet the intent of the See-and-Avoid requirement. If remaining Well Clear fails, a situation may develop that necessitates a Collision Avoidance (CA) manoeuvre. In 2017, the first Minimum Operational Performance Standard (MOPS) for DAA systems was published by RTCA.[7] To promote interoperability between systems, NATO Study Group 268 is working on the validation of a performance-based requirements standard.

When using the OODA classification, the role of the components in the DAA system can be illustrated as follows:

1. Observe: Sensors
2. Orient: data filtering, fusion/integration, extrapolation, display
3. Decide: the pilot
4. Act: the control inputs made by the pilot that affect speed, course and altitude of the aircraft

Because the requirements for making an informed decision drive the requirements for the Observe and Orient phase, the Decide and Act will be discussed first.

9.3.1. Decide and act

Regarding *Decide*, in the Operational Services and Environment Description (OSED) of the DAA MOPS,[8] the use of a DAA system by the pilot is described as follows:

1. The remote pilot uses training, judgment, and the traffic display to assess the threat and the need to manoeuvre.
2. If the remote pilot cannot manoeuvre in response to an ATC Traffic Advisory, the remote pilot will inform ATC. During approach or departure, the manoeuvre to remain DWC must consider the procedures for making an instrument approach/departure, including flying the missed approach. When flying below the minimum safe altitude, manoeuvres are constrained to avoid obstacles and terrain.

Whereas the text in the OSED states 'traffic display', during the development of DO-365, it was concluded by Working Group 1 (WG-1) of Special Committee 228 (SC-228) that the mere depiction of traffic neither provides the pilot with sufficient information to assess the threat under all circumstances nor enables the pilot to always identify an effective manoeuvre to avoid the hazard. Currently (2022) ongoing projects that are developing requirements for DAA in European airspace have reached the same conclusion. To support the pilot with timely detection and assessment of threats, alerting functions are required. To support the pilot with manoeuvre selection, directions and altitudes that will result in an alert are colour coded yellow or red[9]. The alerting and guidance functions require a sufficiently accurate observation of the current situation and models to estimate the future situation.

9.3.2. Observe

Clearly, an informed decision to avoid a threat can only be made if the aircraft posing the hazard is detected in time and the pilot is provided with adequate information. The specification of the information requirements drives the sensor (observe) requirements. For DAA, information about the position, speed and direction of other traffic is needed. To prevent information requirements dictating a particular system and/or (sensor) technology, data requirements are specified as sensor-agnostic. Using a performance-based approach, various (combinations of) sensors have been identified that have the potential to provide this data with the required accuracy, availability, continuity and integrity. To transform the sensor measurements into state estimates, (advanced) data-processing is required for detection, tracking and fusion/integration[10].

For DAA, obvious data sources comprise Automatic Dependent Surveillance Broadcast data (ADSB-in), radar and Electro-Optical / Infrared (EO/IR). Minimum performance requirements are specified in documents such as RTCA DO-366. ADSB-in directly provides information on the position, direction and velocity of cooperative aircraft. Radar provides range and bearing to a target. Additional processing on a sequence of observations (part of the Orient phase) is required to provide directional information. EO/IR systems provide a sequence of images that require further processing to support detection of traffic and extraction of the required information about its position and velocity.

9.3.3. Orient

The required output of the Orient phase is actionable information for the Decide phase. For a DAA system, the Orient phase can be divided into three types of processes: those related to transforming the measurements into estimates of relative traffic position, direction and velocity, those related to assessing which traffic poses a threat, and those related to developing manoeuvre options to mitigate the threat.

1. From measured data to traffic state

Whereas ADSB directly provides information about the location, direction and velocity of traffic, this is only the case for cooperative traffic. Radar and EO/IR systems can detect non-cooperative targets but will also detect cooperative ones. Because of limited measurement accuracies, the same detected target will yield different estimates of position, direction and velocity. Data fusion or best-source selection is required to prevent a single target causing multiple (different) traffic entities to be displayed to the pilot.

Radar data contains range and bearing to a target but requires further processing to provide target velocity and direction. EO/IR systems require image-processing techniques for the detection of targets and the estimation of relative position, velocity and direction. AI/ML techniques have proven to provide capabilities that go well beyond today's state of the art for observed data in areas such as radar data and camera images.[11] On the other hand, to put the associated interpretation into perspective, for data on the surrounding environment that is observed by a camera, AI has matured to a level where it may detect and identify certain particular features faster, but it still falls short in terms of correct interpretation compared to humans. Research into adversarial examples illustrates the types of vulnerabilities this introduced.[12]

The technical possibility to use EO/IR for DAA was already being explored over 15 years ago.[13] Flight testing of an EO-based system revealed the need to improve declaration range and reduce false track rate. The main conclusion from the technology demonstration in 2007 was '*there is much work and technology maturation required before such a system can be deemed ready for operational use*'.[14] Meanwhile, the sensor-resolution and available computing power have increased significantly, and AI/ML algorithms have further matured. Successful demonstrations of a DAA system using EO/IR with DO-365 compliant alerting and guidance is reported by Lee et al.[15]

2. From traffic state to threat assessment

Threat assessment requires the definition of what constitutes a threat. In the existing See-and-Avoid rules, the definition of Well Clear is intentionally ambiguous, thus leaving room for pilot interpretation of the specific situation. When automating traffic threat assessment, a quantitative definition of Well Clear is required. In support of RTCA SC-228, the Sense and Avoid Science and Research Panel (SARP) evaluated three UAS Well Clear candidates in four modelling and simulation environments.[16] The resulting Well Clear Volume (WCV) is described by a spatial and a temporal horizontal boundary and a spatial vertical boundary. The boundaries were quantified using the requirement that an unmitigated penetration of the volume would not exceed a 2.2% probability[17] of a Near Mid-Air Collision (NMAC). One million uncorrelated encounters were used to verify the selected values for *en-route* operations[18]. This approach, in which large, representative datasets are used to develop quantified definitions of previously subjective separation criteria, is fundamental for performance-based alerting and guidance requirements. In Europe, in the context of the SESAR URClearED project, similar analyses have been performed in 2022, using encounter models developed by EUROCONTROL. However, there are differences in the alerting concept. In the U.S., the rules of the air allow the pilot of a remotely controlled aircraft to initiate a manoeuvre to remain Well Clear in case ATC does not provide timely guidance to resolve the conflict. To support the pilot, two alerts are defined. The first alert (Caution) is issued if the system detects that a future loss of DWC will occur, but there is still time to contact ATC to resolve it. The second alert (Warning) occurs briefly before the last moment a manoeuvre is possible to prevent a loss of DWC. Appropriate manoeuvring after a Warning should prevent a loss of DWC and thus also prevent the triggering of a CA system. The current vision in the European approach does not allow the pilot to manoeuvre without ATC clearance, except in a CA situation. Therefore, in the current European concept, the Warning alert does not exist. Recognising that there will be different approaches to DAA and that different standards will exist, to ensure interoperability NATO is developing a performance-based requirements document for DAA systems.

Given that penetration of the WCV constitutes a hazard, threat assessment is performed by predicting whether any of the tracked aircraft will penetrate the ownship WCV within a specific time[19]. In the DAA MOPS, a first-order model for the prediction is deemed acceptable.[20] Besides prediction inaccuracies due to limited fidelity of the model, inaccuracies in the measurement of the ownship and traffic position, direction and velocity impact the result. In the research by Tadema et al., the impact of observation (i.e. sensor) errors on the presentation of guidance provides an example of how, in particular, limitations in accuracy of observed direction and velocity negatively impact the look-ahead time that can be used as a basis for the guidance.[21] However, even in the presence of very accurate data about the current state, the lack of information on traffic manoeuvre intent limits the look-ahead time for the prediction function. To constrain the number of unjustified / nuisance alerts, the DAA MOPS require sensor uncertainty mitigation and impose a no-earlier limit[22] on the alert time.

3. From threat assessment to decision support

If a threat is detected, decision support to select a manoeuvre must be generated. Whereas for the threat assessment a prediction was only performed using the current ownship and traffic states, for decision support the future state will be evaluated for variations to ownship current state. Those variations that are predicted to prevent the loss of Well Clear are candidate solutions. The design philosophy of the decision support determines which candidate solutions are conveyed to the pilot. Levels 2 to 4 of the LoA scale[23] classify this decision support from '*The computer offers a complete set of decision/action alternatives*' to '*suggests one alternative*'. With a level 4 (command-based) concept, the manoeuvre direction is determined by the design of the particular algorithm. Pilot judgement will only impact the manoeuvre when the pilot is convinced that the commanded manoeuvre is unsafe, but it is to be expected that in almost all other situations the pilot will manoeuvre into the commanded direction. A system that uses a set of criteria to reduce the available options to a single one takes an important part of the decision-making process away from the pilot. In such a case, one cannot claim an informed pilot decision[24]. To mitigate the loss of the pilot's ability to deal with uncertainty and exercise judgement, the design process must assure that the likelihood of a hazardous situation resulting from obeying the command is extremely low. In contrast, by presenting information about the predicted locations of hazards and have the pilot make a manoeuvre decision based on this and other available information (LoA 2), the burden on the design and certification process of the decision support is reduced.

A useful construct to classify depiction of data is based on the required mental processing needed to make an informed decision. Using the 3-level Situation Awareness (SA) classification[25], data that must be combined with other data (integrated) by the user only provides level 1 SA. If, instead of requiring the user to (mentally) combine/integrate the data, this is already achieved with the depiction, that presentation provides level 2 SA. A display can support level 3 SA by showing predicted data that answers the 'what if' question that otherwise would require the pilot to mentally extrapolate the current situation into the future.

Fig. 9.3. Simulation environment used for the evaluation of the intercept guidance concept in March 2022. The picture was taken at the moment the intercepting aircraft had reached the desired position behind the TU-160 Blackjack.

Supporting pilot decision making by providing level 3 SA support has been the focus area of several studies into the design of DAA displays. In 2008, researchers from the Netherlands Defence Academy (NLDA) presented a DAA display concept relying on the depiction of the predicted conflict space.[26] The basis for the computation of the conflict space is a process referred to as 'probing'. With such a concept, the manoeuvre decision of the pilot is based on his/her perception of the current encounter geometry, the projection of this geometry into the future for the considered manoeuvre options and information about other relevant constraints. In other words, the presentation of the predicted future conflict space supports the pilot in obtaining level 3 SA.

The underlying idea was based on concepts pursued in the nautical domain from the early Seventies, such as the Integrated Collision Avoidance System (INCAS) [Chase and Tiblin, 1971]. One of the reasons for pursuing the concept of conflict space depiction was the possibility to create an integrated hazard avoidance system that combines the hazard space formed by traffic with that of terrain and other potential hazards.[27] Together with experts from General Atomics Aeronautical Systems Inc. (GA-ASI), the idea to integrate a conflict space display into their Unmanned Aircraft System (UAS) Control Station Architecture was pursued. In 2013 and 2014 follow-on studies, various ideas for hybrid spatial temporal thresholds were pursued.[28] The GA-ASI Conflict Prediction and Display System (CPDS) became the first operational DAA system to use conflict space depiction[29]. In 2018, CPDS was used to support NASA MQ-9 Ikhana, making it the first unmanned aircraft to achieve a No Chase Certificate of Waiver or Authorisation (COA) flight without the need of a chase plane or visual observers as it operated in various classes of airspace.[30,31]

To be able to evaluate the impact of the differences in alerting philosophy between the existing DO-365 and emerging European requirements, NLDA has implemented both concepts in the DAA system used in its UAS laboratory. As a spin-off to the DAA research, underlying algorithms have been used to develop a concept to support pilots with so-called ‘intercept guidance’. The guidance algorithms use the same data, but instead of using it to show predicted conflict space for all relevant nearby traffic, guidance is provided towards a selectable target, independent of range. This is a useful pilot support tool for air-policing missions. A first evaluation of these algorithms was performed in April 2022.

A first step towards automatic Remain Well Clear is to reduce the number of manoeuvre options generated in the Orient phase to a single one. The Decide phase could be implemented with a LoA between 5 to 7. Rather than selecting a manoeuvre from an understanding of the directions to be avoided, the pilot now has to decide whether to accept or reject the scheduled manoeuvre. Given the dynamics of the situation, the proposed manoeuvre may change during the time that is available for the pilot to make a decision. In the research study by Theunissen and Zijlstra an experiment is described in which pilot decisions were compared to those generated by an algorithm.[32] Pilots were also asked to comment on the manoeuvre suggested by the automation. Comments comprised:

- “The guidance is provided too soon during a manoeuvring encounter. Initially it seems beneficial to directly get a heading to fly, but it is counterproductive if a reversal follows.”
- “The moment the intruders manoeuvre the pilot sees that the initial heading of the guidance command is incorrect. The pilot has to be able to overrule the guidance.”
- “Due to the guidance reversals the pilot develops a sense of doubt about the system. Because of this, use of the system will be limited.”

In this context it is important to note that the automation in most cases achieved sufficient separation, but the fundamental difference with the pilot manoeuvre decision was in situations with significant uncertainty regarding the intruder manoeuvre. Typically, pilots decided to wait a few seconds to reduce this uncertainty. This strategy caused pilots to need fewer reversals of manoeuvre direction, which was the main cause they outperformed the algorithm (that always decided at the required time before CPA).

The difference in perception of the best manoeuvre direction is a fundamental problem for advisory systems, which was identified 40 years ago during research into the so-called Pilot's Associate[33]: '*Especially in critical situations, pilots mistrust the advice from automation in case it differs from what they expect*' [Statler, 1993]. If this problem is not solved, LoA 5 to 7 may be technically feasible, but the mismatch between the pilot's perception and the intent of the system may result in undesirable operational issues.

9.4. Autonomy?

Autonomous[34] DAA requires a closure of the OODA loop described in the previous section without the need for pilot selection of the manoeuvre and without the need for pilot consent on the decision to execute the selected manoeuvre. Automation of such action selection and execution is a capability that already exists for CA.

During CA any manoeuvre is allowed to prevent imminent collision. The pilot does not have to consider Right of Way rules, ATC instructions or any other constraints that apply during a normal operation. The associated reduction in constraints that must be considered simplifies the decision making, and CA logic is based on maximising the miss-distance. Automation is beneficial as it reduces the time of the Orient-Decide-Act phase, but the most important justification is that it ensures availability of the CA function in case of a control link failure. Automated CA systems for remotely piloted aircraft have been designed and flight-tested. In 2016, as part of NASA DAA Flight Test 4,[35] automatic Traffic-alert and Collision Avoidance System (TCAS) manoeuvring was demonstrated in scenarios where the pilot intentionally did not manoeuvre based on DAA guidance and continued to trigger the TCAS Resolution Advisory (RA). Unless the pilot intervened, the RA was executed by the AFCS. In 2017, automatic CA manoeuvring using ACAS-Xu[36] was demonstrated.

Unlike CA, for the time-horizon that is associated with remaining Well Clear, a pilot must consider several other factors that impact the decision whether, and if so when and how to manoeuvre. This makes automation of the decision process more complex and raises fundamental legal and ethical questions.

9.4.1. Legal questions

If use of the automation is identified as a factor in an accident, it must be determined whether the manufacturer is (partly) liable. In the lawsuit following the 1995 accident of American Airlines flight 965, the aircraft operator went to court in an effort to force the companies that designed the flight management system and the navigation database to help pay monetary damages. In response, the companies claimed that these were not at fault, and that the pilots committed a series of errors.

An increased transfer of decision authority from the operator to the system will certainly impact how liability is allocated between operator and manufacturer. For example, after the automated system that was intended to counter the tendency of the aircraft to increase pitch angle during certain manoeuvres was regarded as the primary cause of two fatal accidents, the aircraft manufacturer accepted sole responsibility for the crashes.[37]

In the automotive industry, in anticipation of 'self-driving' cars, Volvo has stated it will accept "full liability" for whatever happens when one of its self-driving vehicles is operating in autonomous driving mode. It remains to be seen whether the anticipated liability in case of an accident involving an autonomous DAA system will impact the decision to develop such systems for the commercial market.

9.4.2. Ethical questions

In situations for which multiple manoeuvre options exist and rules/regulations do not provide sufficient guidance for a particular choice, remaining Well Clear relies on pilot judgment to decide. In other words, to remain Well Clear, pilot judgment is required for those situations that lack unambiguous normative decision criteria.

In exceptional situations, the result of such judgement can even be the decision to violate a certain rule. Belzer describes this as "*Exceptional violations occur more as a one-time occurrence where the person assumed the risk basically under the premise that things would work out that one time, or with the idea that their judgement was best in that single situation even though it violated the laws of the flight*".[38] Clearly this is not necessarily always a positive attribute, but it is one of the aspects that needs to be considered/weighed in the context of 'automating' judgment.

This results in the question of whether it is ethically acceptable to replace pilot judgment by automation in the absence of unambiguous normative decision criteria. Very likely the answer is 'no'.

However, similar to the transition from a subjective use of Well Clear to an objective, quantified definition, unambiguous normative decision criteria might be developed through the definition of risk-based cost-criteria and weighing factors. This raises questions such as:

- For a multi-intruder encounter with both manned and unmanned aircraft, how will the weighing factors and cost criteria be determined?
- Does a predicted loss of Well Clear with a manned aircraft allow the right-of-way of another unmanned aircraft to be violated[39]?

Before an attempt is made to answer such questions, the following more fundamental ethical question must be answered with a 'yes':

Given the current reliance on pilot judgement, is it ethically acceptable to define and implement agreed-upon criteria in the automation for the types of questions illustrated in the example situation?

9.4.3. Other challenges

If it is concluded that the legal and ethical questions can be adequately answered, there are challenges in the area of integration and certification. As indicated earlier, the pilot must consider several other factors that impact the decision whether, and if so when and how to manoeuvre. At present, a DAA system, a Terrain Awareness & Warning System (TAWS), a weather radar and a Flight Management System (FMS) are independently designed and certified. Replacing the pilot as the integrator of information will require a considerable change to existing architectures. Although the technical feasibility is not questioned, the associated development cost needs to be justified by operational gains achieved with the increase in autonomy.

If it is concluded that conventional approaches to the design of the decision-making logic are prohibitive and an AI/ML approach for the decision-making shows promise, lack of determinism will certainly introduce issues with current certification methods. Here too, research is looking into new techniques such as Behaviour Bounded Assurance to support certification of these types of systems.[40] Also, a different approach to certification is being proposed.[41]

9.4.4.Discussion

Because of aforementioned legal, ethical, integration and certification challenges, a question that deserves particular attention concerns the expected benefits of an autonomous remain Well Clear capability. Since automatic CA is already required to mitigate for the inability of commanding a manoeuvre in case of a control-link failure, the addition of automatic remain Well Clear is not required to mitigate for this type of failure. For airspace classes in which communication with ATC is required after a Caution alert, the operational benefits are difficult to imagine. Since automatic CA is already accepted, the only gain in response-time that could be achieved with an autonomous remain Well Clear manoeuvre at the Warning alert is in the order of

20 seconds before an automatic CA manoeuvre would be executed. Given that such an aircraft operates in an airspace in which most pilots of other aircraft will resort to voice-communication after a Caution alert in order to resolve an impending loss of Well Clear, additional problems could result from the lack of pilot involvement on the side of the remotely controlled aircraft during this phase[42]. Perhaps such a mix of human decision making, and automation is just not a good idea.

9.5. Summary and conclusions

The benefits of using unmanned aircraft for military operations such as ISR, target designation and attacking targets is undisputed. The inability to meet the See-and-Avoid requirement and the resulting need to use a segregated airspace approach for operation of these aircraft is a significant constraining factor[43].

The introduction of DAA as an alternative means of compliance to the See-and-Avoid requirement necessitated a change from the subjective Well Clear requirement to a quantified definition, the so-called DWC boundary. A DAA alerting function supports the pilot with timely detection of a future loss of DWC. Directions and altitudes that will cause a DAA alert are colour coded on the DAA display. These alerting and guidance functions require a sufficiently accurate observation of the current situation and models to estimate the future situation. To prevent dictating a particular technology, data requirements are specified as sensor-agnostic.

The information requirements can only be met by combining data from various sources. In the Orient phase, the use of AI/ML increases the potential of data from radar and EO/IR. However, in the Decide phase, AI/ML at present cannot be used to replace pilot judgement for selecting the manoeuvre to remain Well Clear. If the situation develops into a Collision Hazard, automatic manoeuvre selection and execution is acceptable.

Due to different (emerging) standards, interoperability may be a constraining factor. NATO is addressing this issue with the development of a performance-based standard for DAA systems.

Autonomous DAA is only possible if it is agreed that it is ethically acceptable to define and implement criteria in the automation that replace current pilot judgement. Given the other factors that need to be taken into account, this is fundamentally different from automatic CA in which other constraints can be disregarded.

For autonomous DAA, the transfer of decision authority from the operator to the system will certainly impact how liability is allocated between operator and manufacturer. Also, if techniques such as AI/ML are used in the automation of the 'Decide' phase, new approaches to certification are needed that are able to prove compliance with the performance requirements for a system that is non-deterministic.

Notes

1 John Boyd. *Patterns of Conflict*. Briefing, 1986 (http://www.ausairpower.net/JRB/poc.pdf)

2 Wolfgang Koch. "On Digital Ethics for Artificial Intelligence and Information Fusion in the Defense Domain". *IEEE Aerospace and Electronics Systems Magazine* 36, no. 7, (2021): 94-111..

3 Remotely operated vehicles typically require platform-side closure of high-bandwidth control-loops.

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5 Raja Parasuraman, Tom B. Sheridan and Christopher D. Wickens. "A model for types and levels of human interaction with automation". *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans* 30, no. 3, (2000): 286–97.

6 The quantified definition of the Well Clear boundary is referred to as DAA Well Clear (DWC).

7 RTCA. *DO-365 – Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems*. 2017.

8 RTCA. *DO-365 – Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems*. 2017.

9 Yellow is used for directions and altitudes that will result in a Caution-level alert, red for a Warning-level alert.

10 In ACAS-Xu, a system that combines Remain Well Clear with a CA capability, the Surveillance and Tracking Module (STM) performs both detection and tracking of aircraft [FAA, 2019].

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12 Tencent Keen Security Lab. *Experimental Security Research of Tesla Autopilot*. 2019..

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16 Stephen P. Cook, Dallas Brooks, Rodney Cole, R., Davis Hackenberg and Vincent Rasks. Defining Well Clear for Unmanned Aircraft Systems. *Proceedings of the AIAA Infotech@Aerospace conference*, Jan. 5-9, Kissimmee, FL, 2015. https://doi.org/10.2514/6.2015-0481.

17 The reference mentions a 1.5% probability, but this was later changed to 2.2% because of an increase in the vertical threshold from 450 ft to 700 ft.

18 In a follow-on activity, the quantification of DAA Well Clear for the airspace in the terminal area was performed.

19 The alert-time.

20 RTCA. *DO-365 – Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems*. 2017.

21 Jochum Tadema, Erik Theunissen, Richard M. Rademaker and Maarten Uijt de Haag. Evaluating the impact of sensor data uncertainty and maneuver uncertainty in a conflict probe. *Proceedings of the 29th Digital Avionics Systems Conference*, Salt Lake City, Utah, 2010.

22 75 seconds before predicted loss of Well Clear.

23 Parasuraman, *A Model for Types* ..., 2000.

24 From a conceptual perspective, there is a fundamental difference between a pilot action that is the result of following a command versus a pilot decision that is based on actionable, real-time information.

25 Level 3 Situation Awareness (SA) is indicative of the ability to correctly anticipate how the situation is likely to develop.

26 Jochum Tadema and Erik Theunissen. A concept for UAV Operator Involvement in Airborne Conflict Detection and Resolution. *Proceedings of the 27th Digital Avionics Systems Conference*, St. Paul, Minnesota, 2008.

27 Jochum Tadema and Erik Theunissen. Design of an Integrated Traffic, Terrain and Energy Awareness Display Concept for UAVs. *Proceedings of the AIAA Guidance, Navigation and Control Conference*, pp.1-12, August 10-13, Chicago, Illinois, 2009.

28 Erik Theunissen, Brandon Suarez and Maarten Uijt de Haag. The Impact of a Quantitative Specification of a Well Clear Boundary on Pilot Displays for Self Separation. Proceedings of the ICNS, April 8-10, Washington, DC, 2014.

29 The concept of operation described in the DAA MOPS is to support pilot decision making by providing the pilot with information about the directions and altitudes that are predicted to cause a loss of Well Clear. The pilot uses this information together with information from other sources about other relevant constraints to determine the best maneuver in a direction and altitude that is not indicated as hazardous. The Conflict Prediction and Display System (CPDS) complies with DO-365, but the addition of conflict space depiction goes beyond the minimum requirements specified in the DAA MOPS.

30 In 2019 this achievement was recognized during the 62nd Annual Laureate Awards, in the category of Commercial Aviation, Unmanned Systems.

31 NASA, https://www.nasa.gov/centers/armstrong/features/ikhana-receives-laureate-award.html

32 Erik Theunissen and Wytze Zijlstra. Comparing Regain Well Clear Guidance. *Proceedings of the 20th ICNS Conference*, September 9-11 (Virtual Conference), 2020.

33 An AI-based second crewmember intended for the Advanced Tactical Fighter that became the F-22.

34 In this context autonomy is achieved with loop closure at LoA 9 or 10.

35 Michael Marston. *Integrated Test and Evaluation Flight Test Series 4 Flight Test Plan*. Armstrong Flight Research Center, Edwards, California, 2016.

36 ACAS-Xu combines the threat assessment and decision support in the TRM: the Threat Resolution Module (TRM), which identifies threats and provides resolution guidance.

37 U.S. Department of Justice, https://www.justice.gov/opa/pr/boeing-charged-737-max-fraud-conspiracy-and-agrees-pay-over-25-billion

38 Jessica A. Belzer. *Unmanned Aircraft Systems in the National Airspace System: Establishing Equivalency in Safety and Training Through a Fault Tree Analysis Approach*. M.Sc. thesis, Department of Electrical Engineering and Computer Science and the Russ College of Engineering and Technology. Ohio University, 2017.

39 Note that in case the situation continues into a collision hazard geometry, such constraints are no longer deemed relevant.

40 Sarathy Prakash, Sanjoy Baruah, Stephen Cook and Marilyn Wolf. Realizing the Promise of Artificial Intelligence for Unmanned Aircraft Systems through Behavior Bounded Assurance. *Proceedings of the 38th Digital Avionics Systems Conference*, Sept. 8-12, San Diego, California, 2019.

41 Stephen Cook, Anna Dietrich, Loyd R. Hook and Andy Lacher. Promoting Autonomy Design and Operations in Aviation. *Proceedings of the 38th Digital Avionics Systems Conference*, Sept. 8-12, San Diego, California, 2019.

42 This problem would not exist if the remain Well Clear function of all aircraft involved was automated.
43 This is not just a limitation during a specific mission, but also during transit flights, joint exercises etc.

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