Testing Operating Procedures for Large UAS with Detect and Avoid Capabilities in Civil Air Traffic Management Environments

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Abstract— **The Royal Netherlands Aerospace Center (NLR), in partnership with General Atomics Aeronautical Systems, Inc. (GA-ASI) and Information Systems Delft (ISD), has conducted several series of human-in-the-loop simulation experiments to assess and refine the safety and efficiency of fully integrating operations of large uncrewed aircraft systems (UAS) into typical civil air traffic scenarios. These experiments used a high-fidelity Air Traffic Control (ATC) simulation facility to provide professional controllers and pilots with the experience of introducing large UAS operations into otherwise familiar air traffic situations. Currently, there are no UAS operating approvals that would allow such tests to be conducted in the real world, so the experience gained and lessons learned are invaluable in preparing for safe and smooth introduction of large UAS into civil airspace operations in the near future.**

Detect and Avoid (DAA) technologies are key to allowing non-segregated, beyond visual line-of-sight (BVLOS) operation of large UAS, by enabling their remote pilots to keep the universal right of way rules of the air, without the conventional ability to see out of the aircraft's cockpit. The focus of these experiments, therefore, has been to test DAA capabilities and operating procedures needed for remote pilots and air traffic controllers to maintain separation of the uncrewed aircraft (UA) from other aircraft and to avoid collisions. Scenarios were carefully designed to trigger DAA alerting and guidance to the remote pilot, requiring a response with appropriate procedures, including coordination with ATC, to assess the safety and operational efficiency of those procedures. Many of the scenarios required traffic to make procedural mistakes in order to create conflict geometries that would trigger DAA alerts. UAS contingencies were also incorporated, such as loss of C2 link, to evaluate remote pilot and controller response procedures.

GA-ASI's SkyGuardian, a turboprop-powered, large fixed-wing UAS, was used as the performance model for a UAS operating from conventional runways that could perform flights as diverse as infrastructure surveying to cargo transport. Rotterdam airport and its surrounding airspace was selected as the operating context, to typify moderately busy and complex European airspace. The UAS flight scenarios spanned all the typical domestic airspace ATC roles, involving Tower, Approach and Route controllers, and included typical background commercial and general aviation traffic patterns and densities.

The DAA capabilities tested are based on RTCA DO-365B Minimum Operational Performance Standards (MOPS). Earlier series of experiments tested the capabilities of a Class 1 system with air-to-air radar, active surveillance, ADS-B In and DAA alerting and guidance for en-route self-separation, plus Class 5 for DAA alerting and guidance in the terminal area. The latest series of experiments upgraded the DAA system to Class 2 capabilities with the addition of TCAS II collision avoidance logic, also with automatic execution of TCAS Resolution Advisories by the UA. A new operating mode was also added for Cockpit Display of Traffic Information (CDTI)-assisted visual separation (CAVS), to test the efficiency and effectiveness of procedures for controllers to delegate separation responsibility to the remote pilot during the landing approach. Operating procedures were initially based on those described in the Operational Services Environment Description appendix of RTCA DO-365B.

The professional participants provided qualitative assessment of several human factors aspects for each scenario and the procedures employed, including their perceptions of safety, operational acceptability, situational awareness and workload. The experiments proved that appropriately-equipped UAS can be introduced safely into the existing airspace system, and that controllers adapt quickly to the few unique considerations needed when managing UAS traffic. The DAA system gave remote pilots unprecedented traffic awareness compared to conventional in-cockpit situations, enabling them to identify potential conflicts at a similar time to ATC, or even before. This situation emphasized the need for procedures that support efficient coordination between remote pilots and ATC, to avoid contrary resolutions to the same identified conflict. Beneficial changes to DAA procedures were also identified that would improve overall safety and operational efficiency. For example, by providing more options when responding to traffic alerts in the terminal area, and to ensure that remote pilots follow all right of way rules, for predictability when responding to DAA alerting and guidance. Furthermore, when the UA executes an automatic Resolution Advisory while in the Lost C2 Link state, controllers expressed a preference for the UA to return automatically to its approved lost link altitude, after becoming clear of the conflict, to minimize the

incidence of secondary conflicts and to reduce controller workload. These findings and others will be fed back to RTCA committees to further improve DAA MOPS.

Keywords—UAS, Detect and Avoid, DAA, self-separation, collision avoidance, airspace integration, air traffic control

I. INTRODUCTION

Large Uncrewed Aircraft Systems (UAS) exhibit the flight performance characteristics of conventional, crewed aircraft, and can be equipped with all the communications, navigation and surveillance systems normally required to enter civil controlled airspace. Nevertheless, existing flight rules, whether instrument flight rules (IFR) or visual flight rules (VFR), ultimately rely on the pilot's ability to look out of the cockpit to observe other air traffic or features on the ground in certain inevitable circumstances. For large UAS, the remote pilot is typically located in a Control Station (CS) on the ground, unable to use natural vision to observe conditions around the aircraft, and therefore unable to comply with those visual operational requirements. Furthermore, useful operations extend well beyond visual line-of-sight (BVLOS) of any one point on the ground. Relaying video from cameras onboard the aircraft to screens in the CS provides the remote pilot with some situational awareness, and may be sufficient for identifying distinctive features on the ground, such as required to acquire the runway environment before descending to land. However, video relay does not perform well enough to enable the remote pilot to see and avoid potential collisions with other air traffic, as required by Rules of the Air in [1] (see Section 3.2, Note 1) and [2] (see §91.113(b)).

Without a suitable means of compliance with the "see and avoid" rule, UAS operations are constrained to segregated airspace, and/or airspace where all traffic is under positive control from air traffic services. This constraint would exclude large UAS operations from civil airspace in most geographic regions. Detect and Avoid (DAA) systems provide an alternative, technological means of compliance with the pilot's obligation to see and avoid potential collisions with other air traffic. DAA systems are the key to BVLOS operation of large UAS integrated into non-segregated civil airspace. Technical performance standards have been developed for DAA systems that provide remote pilots with adequate alerting and guidance to perform the actions needed to avoid potential collisions with other aircraft, including coordination with air traffic controllers when required. These published standards, [3] and [4], have been accepted by the Federal Aviation Administration (FAA) in [5] and [6] for the certification of DAA equipment, but certified DAA systems are not yet available or in regular use.

The industry consensus standards for DAA, and the Operational Services and Environment Definition (OSED) [7] on which they are based, were developed by experts in the fields of airspace surveillance systems, collision avoidance systems, human factors, UAS design and flight operations, and with experienced pilots and air traffic controllers. The performance specifications were validated by multiple studies including fast-time simulations of thousands of traffic encounters. Studies included vehicle performance, traffic density, sensor performance and pilot reaction models. Early in the DAA development process, NASA conducted human-in-the-loop simulations of traffic conflicts between transponder-equipped aircraft and a UAS equipped with DAA guidance capability, as reported in [8] and [9]. These studies involved air traffic controllers and pilots simulating background traffic in Class E airspace in the Dallas-Ft. Worth, TX area. The focus of the first study was to determine horizontal miss distance criteria for the DAA guidance that were acceptable to the controllers, and the second was to assess the acceptability of communications delays in the UAS C2 link. More-recent human-in-the-loop studies were conducted to compare pilots' ability to maintain adequate separation from non-cooperative aircraft using different alerting and guidance criteria, such as reported in [10]. With a focus on developing performance requirements for the DAA system, the operating procedures for UAS with DAA systems were not tested in a broader air traffic management (ATM) environment while developing the standards. Prototype DAA systems have been developed, tested and fielded, but due to current operating approvals and limitations, there is little real-world experience of UAS DAA operations in busy air traffic environments.

To better understand the safety and efficiency implications of integrating UAS operations into civil airspace, and to discover any unforeseen issues with the proposed UAS operating procedures, General Atomics Aeronautical Systems, Inc. (GA-ASI) commissioned a series of experiments to test UAS operations with DAA in an immersive, human-in-the-loop ATM simulation environment. Furthermore, because the DAA performance standards were developed and validated for the U.S. National Airspace System, a European civil airspace context was chosen for these experiments, to demonstrate universal applicability of a compliant DAA system. The Royal Netherlands Aerospace Center (NLR) provides and develops the simulation facilities, and plans and manages the experiments, and Information Systems Delft (ISD) provides DAA traffic display capabilities and analysis of traffic encounters relative to DAA alerting and guidance criteria. This paper discusses the simulation capabilities, objectives, scenarios and results of the third round of experiments in this series.

II. DAA AND CONFLICT MANAGEMENT

A. *Conflict Management Concept*

In its Global ATM Operating Concept [11], the International Civil Aviation Organization (ICAO) defines three layers of conflict management, as shown from the perspective of an uncrewed aircraft (UA) in Fig. 1. This concept includes separation of aircraft from all hazards, including other aircraft, terrain, weather and wake turbulence. However, in this paper we will focus only on the hazard of other aircraft.

Strategic conflict management generally occurs prior to takeoff, to ensure that the planned route is de-conflicted from other planned flights or volumes of air activity. It includes the airspace structure, airways and published arrival, approach and departure procedures. It also includes route changes requested in flight. Separation provision is the tactical layer of conflict management. It mitigates the inability of strategic conflict management to capture all aircraft movements or unplanned flightpath changes.

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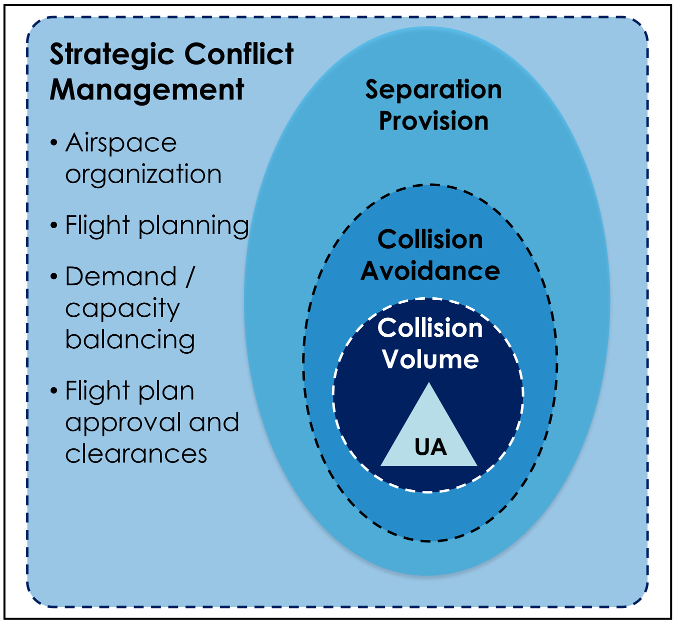


Fig. 1. Layers of conflict management

A separation provision involves all of the following elements:

- *Separation minima.* These are the observable distances between aircraft (horizontal and vertical) considered to be the minimum standards for safe operation. The separation minima allow for uncertainties in the altitude and position measurements available to the separator.
- *Separator.* This is the agent with primary responsibility for ensuring that the separation minima will be maintained within the observable conflict horizon. The separator must have the ability to detect potential conflicts in time to prevent aircraft violating separation minima.
- *Separation mode.* This is the approved set of rules and procedures associated with the separation minima that can be used by the separator to alter flightpaths if necessary to prevent violation of separation minima.

Collision avoidance is the final layer of conflict management and must be available when the separation provision has failed to maintain separation minima between aircraft. Aircraft equipped with Airborne Collision Avoidance Systems (ACAS), provide alerting and coordinated maneuvers using a prescribed separation mode (resolution advisories). For aircraft not so equipped, the Rules of the Air permit pilots to take such action as will best avert collision with another aircraft.

B. Availability of Air Traffic Control (ATC) Separation Services in ICAO Airspace Classes

ICAO defines classes of airspace, labeled A-G, with varying access and equipage requirements, and with prescribed ATC services to IFR and to VFR traffic. Class A is the most tightly controlled airspace, and Class G is effectively uncontrolled. Nations are free to structure their airspace using these ICAO airspace classes as they see fit, so there are considerable variations as to where and how airspace classes are used. For example, in the USA, Class A airspace is used exclusively above Flight Level (FL) 180, whereas in Europe, Class A is used for major airways below FL 195, and in major terminal maneuver areas down to 1,500 ft. Nevertheless, the requirements and services are common within a given class of airspace

The OSED assumes that all UAS operations are conducted under IFR due to the aforementioned inability of remote pilots to perform visual flight functions. Therefore, the ATC separation services provided to UAS in a given class of airspace will be the same as those provided to crewed IFR flights, as listed in TABLE I.

In Class A-C airspace, ATC is the separator for UAS flights for all traffic. In Class D and E airspace, ATC is the separator for UAS flights for IFR traffic, but the remote pilot must self-separate from VFR traffic, often with prompts from ATC of the need to do so. In Class G airspace, the remote pilot must self-separate from all other traffic.

The approved separation mode for self-separation in Visual Meteorological Conditions (VMC) is described by the right-of-way rules in [1] (see Section 3.2.2) and in [2] (see §91.113). This visual self-separation mode does not have clearly defined separation minima, since visual judgements of distance are highly subjective. The right-of-way rules require pilots to pass "well clear" if passing in front of, above or below the other aircraft.

C. DAA Functions for Conflict Management

A DAA system provides the remote pilot with the traffic information, alerting and guidance cues needed for self-separation, primarily required for VFR traffic, and for collision avoidance against IFR and VFR traffic. Reference [3] defines several classes of DAA systems, with different capabilities and configurations, as shown in TABLE II. This round of experiments tested a Class 2 DAA system with Class 5 capability.

TABLE I. ATC SERVICES TO IFR AIRCRAFT

Airspace Class	**ATC Service Provided by Traffic Type**	
	IFR	***VFR***
A	Separation	Traffic not present
B	Separation	Separation
C	Separation	Separation
D	Separation	Traffic information
E	Separation	Traffic information, workload permitting
G	Traffic information, if possible, on request	Traffic information, if possible, on request

TABLE II. DAA EQUIPMENT CLASSES AND CAPABILITIES

DAA Equipment Class	Architecture	Capability
1	Airborne DAA	En-route self-separation, suggestive collision avoidance
2	Airborne DAA with TCAS II	En-route self-separation, directive collision avoidance for cooperative traffic, vertical Resolution Advisories (RAs)
3	Airborne DAA with ACAS Xu	En-route self-separation, directive collision avoidance for all traffic, vertical and horizontal RAs
5	Software-based capablity	Adds terminal area alerting and guidance
6	Adds ground-based surveillance system (GBSS) with airborne processing	Adds detection of non-cooperative traffic in terminal area
7	Adds GBSS with ground processing	Adds detection of non-cooperative traffic in terminal area
8	Ground-based DAA with GBSS	Terminal area and en-route self-separation, suggestive collision avoidance, within GBSS coverage volume

This DAA system provides the following functions:

- *Cooperative traffic detection*. Hybrid surveillance, a function of TCAS II equipment, interrogates and locates aircraft with Mode C and/or Mode S transponders, including those also equipped with ADS-B. Separately, the ADS-B In receives the traffic information from all ADS-B-equipped aircraft. ADS-B In detects aircraft up to 100 miles away, while Hybrid surveillance has a range of approximately 40 miles.

- *Non-cooperative traffic detection*. The air-to-air radar (ATAR) detects all traffic within its field of regard, including those aircraft that are not equipped with a functioning transponder (i.e. non-cooperative). The ATAR is required to detect traffic within a range of approximately 6 miles, within ±110° in azimuth and ±15° in elevation from the longitudinal axis of the UA. When the UA is below a specified altitude, ground clutter prevents the ATAR meeting detection and tracking performance requirements, so it cannot provide coverage all the way to the ground – particularly in terminal areas.

- *Aircraft tracking*. The tracker function correlates detections from the different surveillance sensors that are likely to be from the same aircraft, updates the tracked position of each unique aircraft and calculates the velocity of aircraft that are not self-reporting velocity through ADS-B.

- *Cockpit display of traffic information (CDTI).* Tracked aircraft within the pilot-selected horizontal and vertical range are shown on a traffic display, with symbols depicting the alert status of the track, its direction and speed (if known) and climb or descent. Traffic ID and relative altitude are displayed on an accompanying data tag.

- *Self-separation alerting*. Reference [3] took the subjective term "well clear" along with the general method used by ACAS systems to determine when collision avoidance is needed, to define quantitative separation minima for self-separation. These separation minima are labelled "DAA Well Clear" (DWC). Different DWC values are used for cooperative versus non-cooperative traffic in the en-route environment, and for all traffic in the terminal area. When a loss of DWC is predicted on the UA's current trajectory within a certain period of time, a DAA alert is triggered. If a loss of DWC is predicted within 75 seconds, a corrective (yellow) alert is issued. If a loss of DWC is predicted within 55 seconds, a warning (red) alert is issued. A preventive (yellow) alert is issued if the horizontal DWC minimum is predicted to be compromised within 75 seconds, and the conflicting traffic is near but outside the vertical DWC minimum.

- *Standard self-separation guidance*. The standard method of displaying self-separation guidance is using colored guidance bands on the heading ring and altitude tape of the CDTI. Bands on the heading ring indicate directions where a DAA alert would occur at the current altitude. The band color corresponds to the corrective (yellow) or warning (red) level of the alert. Bands on the vertical tape indicate altitudes at which a DAA alert would be issued on the current heading. Directions and altitudes with no guidance band indicate trajectories predicted to be free of conflict with the aircraft associated with any guidance band or alert. The separation mode associated with DAA systems is referred to as "remain well clear" or remain DWC. This involves maneuvering the UA towards a trajectory clear of guidance bands. The remote pilot is also expected to observe right-of-way rules when selecting from available clear trajectories.

- *Enhanced self-separation guidance*. The DAA traffic display developed for GA-ASI, known as the Conflict Prediction and Display System (CPDS), includes additional symbology for self-separation guidance. Known as "probes", the display depicts conflict areas in plan and vertical sections, as shown in Fig. 2. Yellow areas indicate the space relative to ownship position and velocity where loss of DWC would occur. Red areas indicate where there is risk of near mid-air collision (NMAC).

- *Collision avoidance alerting and guidance for cooperative traffic*. The Class 2 DAA system provides Resolution Advisories (RAs) for transponder-equipped traffic on a trajectory that meets TCAS II collision avoidance criteria. RAs specify a climb or descent rate to attain or maintain, calculated to maximize vertical separation from the conflicting aircraft. They are typically displayed as red "avoid" and green "fly to" bands on a vertical speed indicator tape. CPDS instead depicts a vertical cross-section of the airspace ahead of ownship, with the current velocity vector depicted by a dashed line. Red blocks or wedges depict the "avoid" zones, and the velocity vector turns green when in the "fly to" range. With TCAS coupled to the flight control system, RAs can be executed automatically.

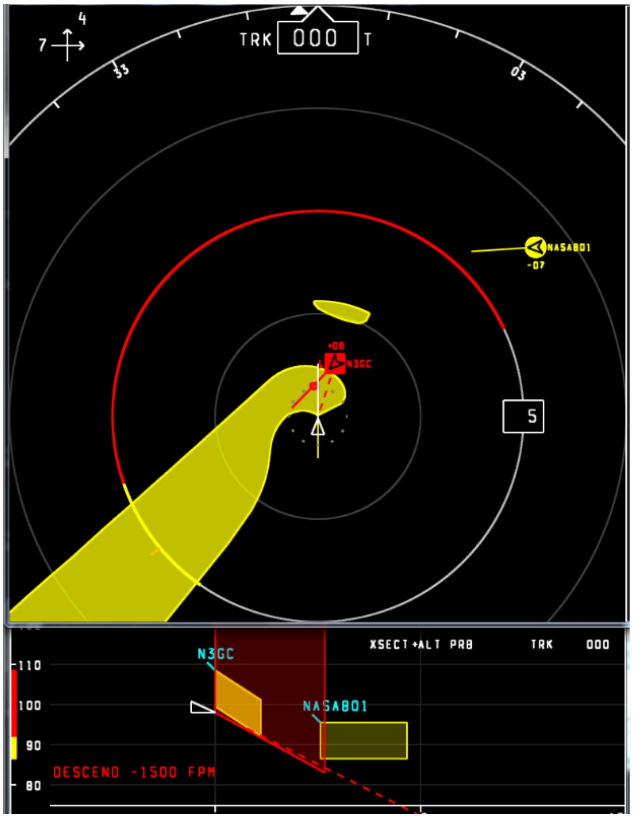


Fig. 2. Example CPDS display with DWC and TCAS RA guidance.

- *Collision avoidance alerting and guidance for non-cooperative traffic*. For non-cooperative aircraft, which are not detected by TCAS, loss of DWC means that the separation provision has failed to maintain separation minima, and the conflicting aircraft are now in a collision avoidance regime, which is referred to as "Regain DWC"[1]. The remote pilot will know when DWC is lost when CPDS indicates the ownship position is within the yellow conflict probe areas. Prior to this occurrence, CPDS will have issued a DAA Warning alert, and the remote pilot's attention should be on the traffic display already. There is no additional alert on loss of DWC. Guidance bands may not help in this situation, because clear trajectories, if any are shown, are likely to be unreachable within the remaining timescale of the conflict. CPDS's conflict probes still help the remote pilot, particularly if there is a smaller red area indicating that NMAC is possible at the current altitude and/or heading. The yellow and red zones help the remote pilot to determine the turn and/or climb/descent maneuver that will most quickly increase separation from the conflicting traffic.

- *CDTI-Assisted Visual Separation (CAVS)*. Recent revisions to the DAA standards added requirements to allow remote pilots to accept from ATC delegation to maintain separation from a leading aircraft, such as on approach (see [3] section 2.2.5.13). The CAVS capability for UAS provides an equivalent capability to that developed for crewed aircraft equipped with ADS-B In, but without requiring the remote pilot to see the leading aircraft. The DAA traffic display allows the remote pilot to positively identify the aircraft specified by ATC, by callsign and/or relative position, and then to designate that aircraft on the display to provide additional data and cues that assist with maintaining separation. This study provides the first human-in-the-loop test of the CAVS capability for UAS.

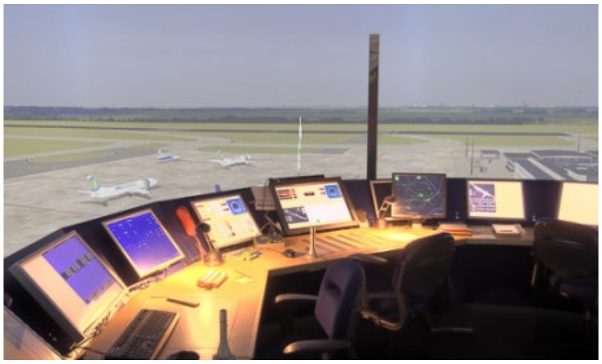
III. SIMULATION FACILITY AND CAPABILITIES

A. NLR ATM Research Simulator (NARSIM)

NARSIM is used to simulated air traffic, and it also offers multiple Air Traffic Controller and pseudo-pilot working positions. Its aim is to evaluate new operational procedures, new controller assistance tools, and new human-machine interfaces. The NARSIM software simulates the most important aspects of a real ATC system, including realistic radar information and aircraft behavior. It has the capability to use actual recorded radar data, computer-generated data, pseudo pilot generated data, or combinations of the three. In this experiment, pseudo-pilot generated data was used to drive the simulation.

NARSIM provides controller positions that can be configured to provide radar displays used for approach or en-route control. It also includes an ATC tower simulation with a 360° visual system and fully equipped controller working positions, shown in Fig. 3.

NARSIM Radar Simulator



NARSIM Tower Simulator with Rotterdam Airport Scenery

Fig. 3. NARSIM controller positions

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[1] CPDS uses an alternative method of providing Regain DWC guidance than specified in [3], which was developed prior to publication of the standard.

B. *Multi-UAS Supervision Testbed (MUST)*

MUST was developed by NLR as a reconfigurable generic RPAS research simulation facility. MUST consists of two main components: the UAS flight dynamics simulator and the UAS Control Station (CS). For the purposes of this study, the UAS flight dynamics simulator was configured to replicate the important performance characteristics of GA-ASI's SkyGuardian Medium Altitude Long Endurance (MALE) UAS. MUST provides remote pilots with two control modes, namely Autopilot (AP) and Flight Management System (FMS) modes. In AP mode, UA heading, altitude, speed and vertical speed values can be can be controlled using 3 different input methods based on the preference of the pilot: the autopilot touchscreen, keyboard & mouse or sidestick & throttle. In addition to these control modes, MUST simulates the basic functionality of an Automatic Take-Off and Landing System (ATLS).

C. *DAA Sensor Modeling*

To enable DAA simulation, ADS-B and ATAR models were developed for NARSIM and MUST. ADS-B data was used to track cooperative targets, and it was the primary source of data for DAA in this study. The ADS-B model consists of two parts: an ADS-B Out model on the NARSIM side for the traffic, and an ADS-B In model on the MUST side for the UAS. The model was configured such that it is possible to turn-off ADS-B OUT for specific aircraft as required by the experiment scenario.

A simple ATAR model was developed to track non-cooperative targets. The model was configured such that the radar only detected aircraft within the field of regard of the radar, which was set to the minimum requirements described in [4]: range 6 NM, azimuth ±110°, elevation ±15°.

A best-source approach was used for track correlation in this study. Here, ADS-B was considered to be the preferred sensor, and data from the air-to-air radar was only used for non-cooperative targets. The tracker developed for MUST used this simple approach to determine the tracks of each detected aircraft. Subsequently, this data was sent from MUST to CPDS to display surrounding traffic and to calculate DAA alerts and guidance. For the purpose of DAA alerting, it can be assumed that the ADS-B tracks are validated (by active surveillance) otherwise no DAA Warning alerts would be issued.

D. *New Capabilities*

Several new capabilities were developed for MUST and NARSIM for this round of experiments, to further enhance the simulation's realism and DAA capabilities. The effects of wind were previously available for other aircraft in the NARSIM environment, but had not been implemented for the UAS simulated by MUST. The effects of wind were added for the UAS because the wind direction can influence the effectiveness and selection of DWC maneuvers, especially for relatively slow UAs. Adding wind also required changes to the MUST FMS, to compensate for wind while maintaining ground track.

The previous (second) round of experiments introduced DAA and CPDS to MUST for the first time, representing a Class 1 DAA system (DWC) with Class 5 (terminal area alerting) capabilities. In order to simulate the Collision Avoidance (CA) functionality of a Class 2 DAA system, a full TCAS II v7.1 module was developed for the NARSIM and MUST simulators in this project. Conflict detection was based on Mode-S transponder data which was already available in both simulators. CPDS was already Class 2 capable, with the symbology needed to display TCAS RAs. Mode S RA downlink was presented on the radar displays of NARSIM's controller working positions. The downlink provides controllers with an indication if an RA occurs for any TCAS-equipped aircraft in the airspace under their control. The RA is shown as a red TCAS label with an arrow indicating the direction of the RA (^, - , v) above the callsign of an aircraft. The TCAS label is removed once the clear-of-conflict state is declared by that aircraft's TCAS. This capability is not currently available to ATC in the Netherlands.

In order to give the UAS a lower priority than airline traffic in any TCAS conflict, the UAS simulated in MUST was configured to have a higher ICAO 24-bit address than the addresses of all aircraft in NARSIM. The ICAO address in Mode S replies is used by TCAS to resolve tie-break situations, such as when both aircraft want to initially perform a climb RA. Therefore, the UAS would always be the one required to perform RA reversals during tie-break conditions. Also, to reflect the reduced climb performance of a MALE UAS compared to airliners, the target climb/descent rate for RAs on CPDS was reduced to 500 ft/min for initial RAs and 1,000 ft/min for "increase" RAs (from 1,500 ft/min and 2,500 ft/min respectively).

With the recent addition of CAVS capabilities to the DAA standards, CPDS was upgraded to meet the new requirements, including a new traffic symbol to identify the designated aircraft. When the pilot selects and designates the leading aircraft, then CPDS adds ground speed to its associated data tag, and also displays the ground speed differential next to the ownship symbol, shown in Fig. 4. These cues help the remote pilot to match speed and maintain separation. For experimental purposes, an Enhanced CAVS mode was also developed, which adds a ring around the ownship position at a range selected by the remote pilot. This range ring remains white while the designated aircraft is beyond that range, ands turns yellow when the designated aircraft gets closer than the selected range, shown in Fig. 5. This extra feature is intended to assist the pilot with a visual reminder when action is required to maintain separation.

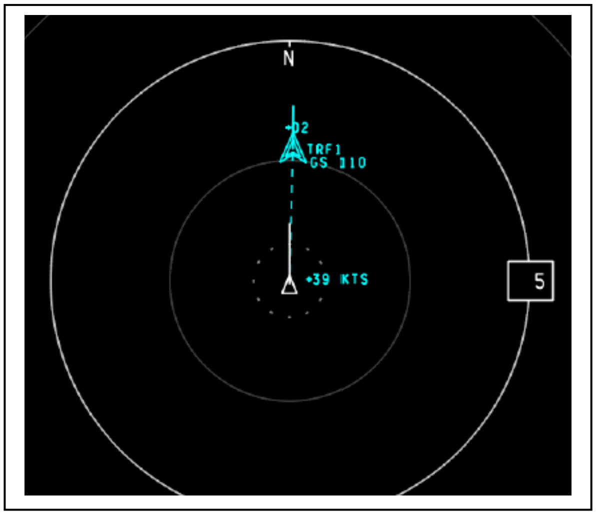

Fig. 4. Basic CAVS mode features on CPDS

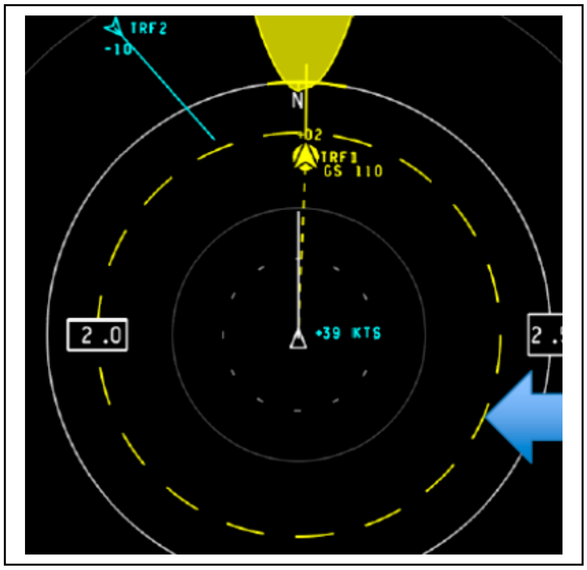

Fig. 5. Enhanced CAVS mode features on CPDS

To make it easier for the RPAS pilot to control the distance between the UA and the lead aircraft during the CAVS procedure, a new functionality has been added to the MUST auto-land system that allows the pilot to manually vary the UA's approach speed. Previously, any manual speed changes during final approach would cancel the auto land functionality, forcing the pilot to perform a manual landing.

The final improvement to MUST added a capability for aural alerts, so that the remote pilot would hear the annunciations that accompany DWC alerts and TCAS RAs. This capability completes the simulation of Class 2 DAA alerting and guidance, and was also added in response to feedback from an experiment in the previous round, when the remote pilot had maneuvered pre-emptively in response to CPDS guidance, unsure whether an alert had been issued.

IV. PRIOR EXPERIMENTS AND KEY FINDINGS

The second round of human-in-the-loop experiments with NARSIM and MUST, conducted in November 2020, was reported in [12]. These were the first experiments in this series to include DAA capabilities. The study focused on scenarios that would trigger DWC alerting and guidance, to test the safety and efficiency of procedures for remote pilots and controllers when using DAA for self-separation.

To facilitate conflicts, the UAS did not use standard Air Traffic Services (ATS) routes. Instead, a different route was designed for the UAS for each scenario. In some scenarios, pseudo-pilots of other aircraft in the scenario were directed to make procedural errors. UAS contingencies were also included in some scenarios, such as loss of C2 link or loss of radio communication.

A. Remain DWC Procedures in En-route Airspace

The use of DAA on UAS in civil controlled airspace was new to all controllers and pilots participating in the experiment. Training for the remote pilot provided an understanding of the features of CPDS, the meaning of symbols, indications and alerts and the expected actions. The en-route conflict scenarios validated the DAA system's capability to enable the remote pilot to maintain safe separation from traffic, but highlighted a need for procedural and training refinements to improve the efficiency of coordination with ATC. Although the DAA system provides alerting and guidance for all potential conflicts that meet the DWC alerting criteria, ATC is also providing a separation service to the UAS as IFR traffic. The division of responsibilities between the remote pilot and controller for maintaining separation between the UAS and other traffic needed to be clarified for efficiency. The specific findings and recommendation were as follows:

- CPDS increased the traffic situation awareness of the remote pilot during nominal operations and during conflicts, to a greater level than is usually available in crewed aircraft cockpits.
- In many cases, controllers detected and began to resolve conflicts at the same time as an alert was issued by the DAA system. This suggests that the self-separation alert timings used for DAA match the separation provision standards used by controllers.
- When presented with DWC alerting and guidance, the remote pilot had a tendency to report traffic to ATC that the controller was already preparing to manage, with a negative effect on controller workload.
- Remote pilots should not report traffic to ATC causing DWC Preventive alerts.
- When in controlled airspace, it was better for the remote pilot to wait for a short time after receiving a DWC Corrective alert before reporting the traffic to ATC, to listen for related controller instructions or to observe whether it was a nuisance alert caused by a maneuvering aircraft that would self-resolve.
- When in controlled airspace, the remote pilot should only maneuver to resolve a DWC Corrective alert after receiving ATC clearance, as specified in [3].
- Remote pilots should be aware that non-cooperative traffic can disappear from the DAA display if the aircraft flies outside the ATAR's field of regard (FOR). It is recommended to depict the radar's FOR as a toggleable feature on the DAA traffic display.

B. DWC Procedures in Terminal Areas

The DWC separation minima are reduced in terminal area airspace to avoid nuisance alerts where aircraft are expected to operate with closer trajectories. Therefore, when a DWC alert is issued, there is less time to react and select a suitable maneuver that maintains safe separation. Consequently, only DWC Warning alerts are issued in terminal airspace, and the only separation mode defined in [3] when on approach is to perform a missed approach procedure. The tested scenarios indicated that immediately performing a missed approach was not always the safest or most efficient response to the alert. Observing the traffic behavior on CPDS before and after the alert is issued may provide the remote pilot with less-disruptive corrective options. The examples supporting this finding were as follows:

- In scenarios where the conflicting aircraft was above the UA or was overtaking the UA, a simultaneous missed approach by the other aircraft, which is likely, could potentially aggravate the conflict severity in such cases.
- Some DWC Warning alerts on final can be resolved using minor horizontal flightpath adjustments, after which the UAS can safely continue its landing. This was demonstrated in some experiment scenarios.
- The controllers considered Warning alerts caused by VFR aircraft loitering near the runway to be nuisance alerts because such encounters would not cause a crewed IFR aircraft on final to declare a missed approach.

C. *UAS Contingencies*

Loss of C2 link is a contingency unique to UAS, which in effect separates the cockpit from the aircraft. This prevents the remote pilot from performing active control of the UA and from using the UA's radios to communicate with ATC. It requires pre-programed, predictable and safe automatic behavior by the UA. Lost C2 link behavior typically involves setting the transponder code to 7400 and navigating to a defined hold waypoint to provide opportunity for the C2 link to be restored and/or to provide notice to ATC of the UA automatically entering an approach procedure after a predetermined delay. When the remote pilot loses radio communications with ATC through the UA, the telephone can be used to contact the controlling ATC facility. The key findings were as follows:

- In addition to pre-defining the horizontal route towards lost C2 link hold waypoints in the UAS flight plan, it is also necessary to pre-define the vertical profile towards such waypoints in order to increase the predictability for controllers who must deconflict other traffic.
- Lost C2 link hold waypoints should be predefined for all phases of flight, and should be geographically separated from prevailing traffic flows to avoid conflicts on the way to and during the hold.
- Because the remote pilot is more likely to notice the failure of radio telephony (R/T), it should be the remote pilot's responsibility to establish communications with ATC using the backup telephone.
- When radio communications are lost, the remote pilot should telephone the last ATC facility the UAS was in contact with, except during take-off and during hand-over from one sector to the next. In these cases, the pilot should contact Approach or the next ATC route center in the flight plan, respectively.

V. EXPERIMENT OBJECTIVES AND DESIGN

A. *Experiment Objectives*

The previous round of experiments tested operations with Class 1 and Class 5 DAA capabilities, including DWC alerting and guidance for safe separation in terminal and en-route regimes. With the upgrade to Class 2 DAA and the addition of CAVS capabilities for these experiments, the aim was to test operations involving the new capabilities, including TCAS RA alerting and guidance, and to test the effectiveness of the DAA system during aerial work flight patterns, such as for an area survey.

There are several significant operational differences between DWC alerts and TCAS RAs. Whereas ATC has primary responsibility to provide separation for the UAS from most traffic in controlled airspace, ATC does not have the tools to assist with collision avoidance, and so it is always the pilots' responsibility. Guidance to remain DWC is suggestive, indicating to the pilot which trajectories to avoid, but requiring the pilot to decide which clear trajectory to maneuver towards. In contrast, TCAS RAs provide directive guidance for collision avoidance, indicating to the pilot exactly what to do, and effectively alleviating the pilot's decision-making responsibility in these critical situations.

In both UAS and crewed aircraft, TCAS can be directly coupled to the flight control system, to automate RA maneuvers and eliminate the delay of the pilot's reaction time to the alert and guidance. This is particularly beneficial for UAS, because C2 link latencies compound with pilot reaction time. Automatic RA maneuvering provides a further benefit for UAS, in that it can still be accomplished while the UA is in a lost C2 link state.

The objectives of this round of experiments were to test UAS operations with DAA in the following situations:

- Collision avoidance in en-route and terminal airspace
- Collision avoidance while in lost C2 link state
- Self-separation with challenging cross winds
- Separation from cooperative and non-cooperative traffic during aerial work operations
- Delegated separation on approach, with Basic and Enhanced CAVS

B. *Unmanned Aircraft Model*

As for previous experiments, the performance of the UA in the MUST simulation was modeled on GA-ASI's SkyGuardian UAS. SkyGuardian is a turboprop-powered aircraft with 24 m wingspan, maximum gross takeoff weight of 5,670 kg and maximum speed of 210 kts, as shown in Fig. 6.

Fig. 6. GA-ASI SkyGuardian MALE UAS

Although SkyGuardian was designed for Medium Altitude Long Endurance (MALE) surveillance missions, it can perform other public safety or commercial surveying flights that could be conducted from civil airports in domestic airspace. Emerging commercial roles for large, fixed wing UAS include transporting cargo as part of an express logistics network. The SkyGuardian performance model can also act as a surrogate for uncrewed conversions of existing turboprop aircraft commonly used in this role, such as the Cessna 208.

C. *Operations Area and Airspace*

The experiments were performed within the context of Rotterdam airport (ICAO: EHRD) and surrounding airspace. Scenarios considered conflicts in controlled and uncontrolled airspace classes, in en-route, Control Traffic Region (CTR) and Terminal Maneuver Area (TMA) settings. Rotterdam airport was selected for this experiment because a mix of both VFR and IFR traffic operate from this airport, and because it is surrounded by different classes of airspace. At Rotterdam, Runway 24, with a length of 2,220 m, was used for all simulation runs as it is the preferred runway direction for the prevailing winds.

The airspace zones and classes used in the simulation are listed in TABLE III. and shown in Fig. 7. As before, background traffic followed standard ATS routes and procedures. The UAS used either the standard approach to Runway 24 for IFR traffic arriving from the south (RR), or one of two custom approach procedures that intersect the RR approach with a shorter final leg (2.5 NM versus 10 NM). These custom approaches were designed to create conflicts between the UA and other traffic, to test the procedures that follow DAA alerting and guidance.

Fig. 7. Sectional chart of Rotterdam area (Source: SkyVector.com)

TABLE III. AIRSPACE ZONES AND CLASSES IN ROTTERDAM AREA

Airspace Zone Name	Class	Altitudes
Rotterdam CTR	C	Surface – 3,000 ft
Rotterdam TMA 1	E	1,500 ft – 5,500 ft
Schipol TMA 1	A	1,500 ft – 9,500 ft
Schipol Sector South 1-2 (en-route)	A	9,500 ft – 19,500 ft
Uncontrolled, outside Rotterdam CTR	G	Surface – 1,500 ft

D. *Scenario Development and Encounter Modeling*

To ensure that the scenarios are as realistic as possible, they were designed with the help of a DAA expert from ISD, and two controllers who familiar with the airspace around Rotterdam. Achieving all of the experiment objectives is very challenging, particularly as DAA alerts occur in controlled airspace only if ATC fails to notice a conflict in time. This is even more difficult in en-route airspace where controllers are supported with the Short-Term Conflict Alert (STCA) system which identifies potential conflicts with a look-ahead time of 120 seconds. After consultation with the controllers involved in the design process, the following types of scenarios were used:

- Blunders made by both the UA and the other traffic. This was considered the best way to trigger the conflicts, and most encounter scenarios are designed use this approach.
- Scenarios that overload the controller. This was considered to be more suitable in the TMA than in en-route airspace because en-route controllers receive STCA support.
- Multiple intruder aircraft options for triggering a conflict to take into account the timing uncertainties of a real-time simulation (RTS).
- Use special instructions for controllers, remote pilot and airline pilots when necessary to increase the likelihood of a conflict.

Using this approach, a total of 21 unique encounter geometries were designed. For several of these geometries, variations were also proposed (e.g. different wind directions, failures, CPDS operating modes), resulting in a total of 31 scenarios for the initial RTS evaluation, as listed in TABLE IV.

TABLE IV. INITIAL ENCOUNTER SCENARIOS LIST

#	Encounter Name	Airspace	Type	Variations
1	Head-on conflict	En-route	DWC	2 different wind conditions
2	Crossing conflict at the intersection of two airways	En-route	CA	
3	Aerial work parallel to an airway	En-route	DWC	2 different RPAS directions
4	Aerial work under arriving traffic	En-route	DWC	2 different RPAS directions
5	Overtaking conflict	En-route	DWC / CA	CA variation with DWC system failure
6	Lost C2 link	En-route	CA	
7	Ground speed reduction of VFR	TMA	CAVS	Basic and Enhanced CAVS mode
8	Speed reduction of IFR traffic on final	TMA	CAVS	2 CAVS modes
9	Speed increase of RPAS on final for spacing	TMA	CAVS	2 CAVS modes

#	Encounter Name	Airspace	Type	Variations
10	Blunder by non-CAVS traffic	TMA	CAVS	Enhanced CAVS only
11	Incorrect CAVS target selected	TMA	CAVS	2 CAVS modes
12	Conflict with non-cooperative intruder in Class E airspace	TMA	DWC	
13	Overtaking conflict during RPAS final	TMA	DWC	
14	Lost C2 link	TMA	CA	
15	Non-cooperative arrival during RPAS departure	TMA	DWC	2 different wind conditions
16	Sandwich conflict on final by 2 VFRs	TMA	DWC	
17	RPAS approach vs. VFR departure	TMA	DWC	
18	Blunder by overtaking IFR during RPAS approach	TMA	DWC / CA	CA variation with DWC system failure
19	Conflict during holding pattern	TMA	DWC	
20	Head-on conflict in Rotterdam CTR	TMA	DWC	
21	Ad-hoc aerial-work with VFR intruders	TMA	DWC	

To validate each conflict scenario, the flightpath trajectories and timing of the ownship UA and conflicting aircraft (“intruders”) were run by ISD in a simulator equipped with CPDS. This was done to ensure that DAA alerts would be triggered as intended for each scenario. Consequently, some adjustments were made to Scenario 7, to eliminate a DWC Warning alert that was triggered prior to the intended conflict.

E. Scenario Down-selection

The main RTS experiment was to be conducted with professional pilots and controllers operating the NARSIM and MUST positions. The availability of these professional participants would allow for 10 scenarios to be performed and assessed in a two-day block. To select 10 scenarios for the main experiment from the 31 developed scenarios, a preliminary RTS experiment (RTS 1) was conducted with NLR staff in the operator positions, but without ATC intervention. The aim of RTS 1 was to down-select 3 en-route, 3 TMA and 4 CAVS scenarios that would be the most challenging and/or interesting from operations and human factors perspectives. The following subjective criteria were used to assess each scenario from the remote pilot’s perspective:

- Workload,
- Situational awareness
- CPDS human factors

After each simulation run, the NLR operating staff assessed the scenario against the criteria above, giving it a score of 1-5 in each category. For workload, a low score is good, whereas for the other criteria, a high score indicates a scenario that was easy for the participants to manage. For the main experiment (RTS 2), the objective was to test the most challenging scenarios in each operating category, so the scenarios with high workload score and low human factors scores were selected. An example of a scenarios that was not selected for RTS 2 is shown in Fig. 8, where callsign “CRONUS” identifies the UA’s flightpath.

Fig. 8. Trajectory and scoring for RTS 1 Encounter 4 (Aerial Work)

The 10 most challenging scenarios from RTS 1 are listed in TABLE V., including encounters that test all of the experiment’s objectives. CPDS traffic information files, which are updated every second, were recorded for every scenario. For the 10 selected scenarios, these CPDS data logs were analyzed with data tools that visualize time histories of guidance bands (see Fig. 9), time to closest point of approach (CPA) and distance to CPA for each intruder. This detailed analysis provides understanding of which aircraft was causing alerting and guidance, when and why, to further refine the encounters if needed. Note that the MUST operator did not necessarily resolve the conflicts in RTS 1, because the aim was only to assess the workload and traffic situation awareness up to the point at which a maneuver decision and action were needed.

TABLE V. ENCOUNTERS SELECTED FOR RTS 2

RTS 2 #	RTS 1 #	Encounter Name	Airspace	Type	Variation(s)
1	1	Head-on conflict	En-route	DWC	Cross wind from right
2	2	Crossing conflict at the intersection of two airways	En-route	CA	-
3	3	Aerial work parallel to an airway	En-route	DWC	RPAS direction NE-SW
4	16	Sandwich conflict on final by 2 VFRs	TMA	DWC	-
5	14	Lost C2 link	TMA	CA	-

RTS 2 #	RTS 1 #	Encounter Name	Airspace	Type	Variation(s)
6	21	Ad-hoc aerial-work with VFR intruders	TMA	DWC	-
7	7	Ground speed reduction of VFR	TMA	CAVS	Both CAVS modes
8	8	Speed reduction of IFR traffic on final	TMA	CAVS	Both CAVS modes
9	10	Blunder by non-CAVS traffic	TMA	CAVS	Enhanced CAVS only
10	11	Incorrect CAVS target selected	TMA	CAVS	Both CAVS modes

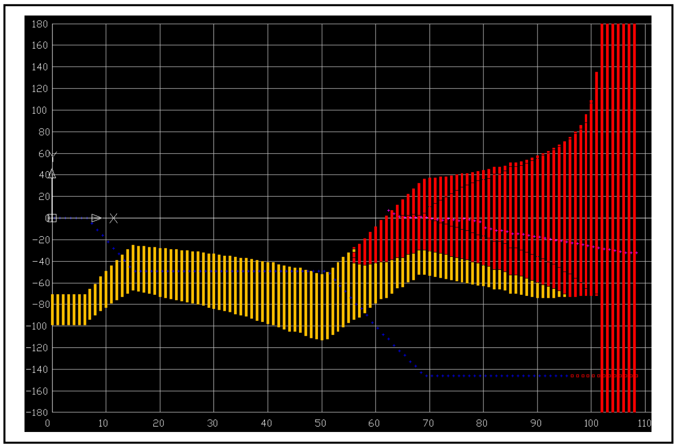

Fig. 9. Azimuth guidance bands time history for RTS 1 Encounter 21

VI. EXPERIMENT PROCEDURE

A. Participants and Training

The experiment participants are experienced professionals, either retired from or actively performing the same roles as in the simulation. As such, none of the participants needed training in the normal duties of their roles. Several of the participants performed the same role in previous studies in this series. Their roles and backgrounds are listed in TABLE VI.

TABLE VI. EXPERIMENT PARTICIPANTS AND EXPERIENCE

Role	Professional Experience
Remote Pilot[a]	Active RNLAF MQ9A pilot with 8+ years' flight experience
Tower Controller[a]	Retired with 30+ years' experience
Approach Controller[a]	Retired with 35+ years' experience
En-route Controller[a]	Retired with 35+ years' experience
Pseudo Pilot[a]	Active B737 instructor, Ex F50 pilot
Pseudo Pilot[a]	Active A320 pilot
Pseudo Pilot	Active B737 pilot
Pseudo Pilot	Active BD700 pilot
Pseudo Pilot	Active general aviation pilot

[a] Prior study participant

Training was conducted for all participants during the week prior to the experiment. Because several pseudo pilots involved in RTS 2 had never participated in such an experiment before, two dedicated half-days were used to train these new pilots for their role in NARSIM experiments. Subsequently, all pseudo pilots involved in this experiment were provided with a combined training session. The training for the remote pilot consisted of MUST familiarization and CPDS usage. MUST familiarization was performed by NLR staff. A DAA expert from ISD remote pilot with a tutorial on CPDS features and usage. For this a number of synthetic scenarios representing all the different DAA alert types were used. Specific attention was paid to the new DAA aural annunciations and to the usage of the CAVS functionality.

The controllers that took part in the experiment were already familiar with NARSIM. Nevertheless, they were given a primer on the most important NARSIM functionalities, including the new RA downlink functionality that was introduced for the first time in this experiment. The en-route controller was specifically briefed that STCA would be unavailable for this experiment, to make it more likely that an encounter with the UAS develops into a conflict that requires a DAA maneuver.

Finally, all participants performed combined training scenarios over half a day. This consisted of one en-route and one TMA training scenario, with a duration of 45 mins each. Then two 15-min CAVS training scenarios were performed. The format of the combined training scenarios was comparable to that of the experiment scenarios, and also included conflicts so that the participants became familiar with the correct DAA R/T phraseology before the assessed experiment runs.

At the start of the experiment, all participants were provided with a pre-experiment briefing. This briefing provided information on the following details common to all scenarios:

- How to react to DAA alerts as described in [3].
- Procedures to deal with the C2 lost link contingency. These procedures were developed during prior experiments.
- Procedures for the CAVS approach.
- Characteristics of the airspace, including any changes made from the standard configurations.
- NARSIM updates and settings used for this experiment.

B. Scenario Brief

Each scenario briefing consisted of two parts. In the first part, all participants were provided with the UAS route, and its take-off time. Because conflicts are time sensitive events, all participants were strongly encouraged to follow the UAS take-off time with an accuracy of ±5 seconds so that the planned conflicts had a greater chance of occurring during the run. Additionally, controllers were provided with specific instructions that were only applicable for that run. After this, the controllers left the briefing room. They were not provided with information about the nature of the conflict, including the call-signs of the intruder aircraft, prior to each run.

In the second part of the scenario brief, the pilots were provided with a more detailed description of the scenario, including the exact details of the planned conflict between the UAS and an intruder aircraft (call-signs, conflict times, intruder trajectories etc.). This part of the briefing also provided specific instructions to the pilots to increase the likelihood of conflicts, including the blunders they were expected to perform as part of each scenario. In some cases, this included disregarding certain ATC instructions to facilitate conflicts with the UAS.

The remote pilot participated in the second part of the briefing for the en-route and TMA scenarios, but *not* for the CAVS scenarios. Thus, the remote pilot was aware of the nature of the planned conflicts for the en-route and TMA scenarios, but not for the CAVS scenarios.

C. *Baseline Scenarios*

Before each set of scenarios (en-route and TMA), the participants performed a baseline scenario, against which to compare human factors aspects of the conflict scenarios. These baseline scenarios included typical background traffic levels and procedures and a flight plan to be followed by the UAS, but no planned conflicts.

D. *Assessments and Post-scenario Discussion.*

Immediately after each scenario, the remote pilot and controllers completed a human factors questionnaire. Each contained questions in 4 categories requiring evaluation on a Likert 1-10 scale (very low to very high, or disagree to agree). The answers in each category are aggregated to produce an overall score out of 10 for each of the following 4 aspects of the participant's experience[2]:

- Workload
- Situational Awareness (SA)
- Perceived Safety
- Operational Acceptability

The remote pilot's questionnaire included additional questions about what type of maneuver was selected to resolve the conflict (horizontal, vertical or combined), why that maneuver was selected, and whether wind was a factor in the decision. The assessment scores for the baseline en-route scenario are shown in Fig. 10, indicating low workload and very high levels of SA, safety and acceptability.

After each run, all experiment participants took part in a post-run debriefing. During these discussions the participants described the sequence of events, rationale behind their decision-making process, and the interactions that occurred between the participants. The discussions placed particular emphasis on any conflicts or off-nominal events that occurred involving the UAS, and considered if the procedures developed by RTCA to resolve conflicts needed to be revaluated in a European airspace context.

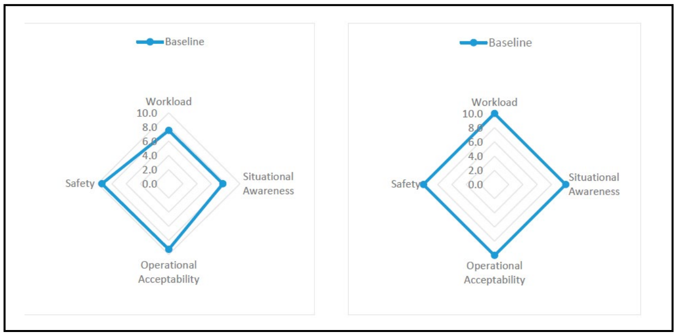

Fig. 10. Baseline en-route questionnaire scores for controller (left) and remote pilot (right)

VII. RESULTS

Selected scenarios from RTS 2 are discussed in this section, to illustrate the process and how the key findings were derived.

A. *Scenario 1: Head-on Conflict in En-route Airspace*

1) Conflict description: In this scenario, 3 airliners in trail, are flying East, inbound to Rotterdam, while the UAS is departing Rotterdam on a route that crosses below their flightpath. The conflict is created by the third airliner, which blunders by responding to the descent clearance of the aircraft ahead, thus descending early towards the UAS. The events related to the conflict (see Fig. 11) are listed in sequence below:

- After take-off from Rotterdam, the RPAS was cleared for a stepped climb to flight level (FL) 140.
- The en-route controller cleared KLM211, the second inbound aircraft, to descend to FL 60 after passing the RPAS. The UA was level at FL140.
- KLM121, the third inbound aircraft at FL160, blundered and started a descent. Initially CPDS projected that the intruder would pass behind the UA.
- KLM121 suddenly increased its descent rate. Because of the increased descent rate, the intruder was now expected to pass in front of the UA. This triggered a DWC corrective alert on CPDS with a time to CPA of just 18 seconds; see Fig. 12.

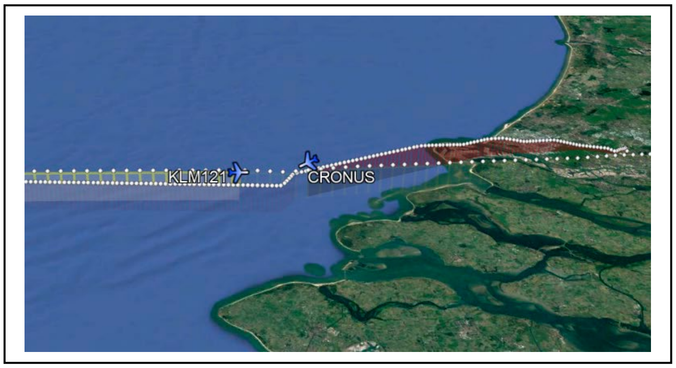

Fig. 11. Route flown by UA and conflicting intruder, Scenario 1

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[2] Questions were based on the well-known NASA TLX workload metric, and the Eurocontrol SASHA methodology for measuring SA.

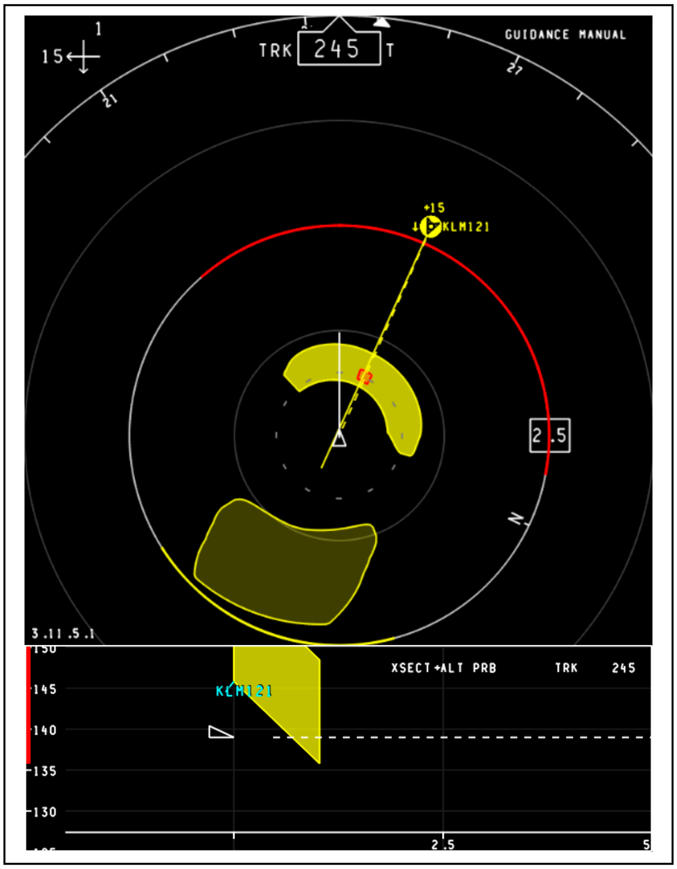

Fig. 12. CPDS display at time of DWC corrective alert, Scenario 1

- The remote pilot responded by initiating an immediate left turn in the downwind direction to resolve the corrective alert. This resolution was performed without ATC clearance because of the severity of the conflict.
- A few seconds later, when the UA had turned just 4 degrees to the left, the conflict escalated to a "monitor vertical speed" TCAS RA for the UA. The remote pilot did not notice the RA and continued steering left to resolve.
- Almost simultaneously, the TCAS on the intruder declared a climb RA. This instruction was followed by the intruder. Additionally, TCAS RA downlink messages informed the en-route controller of the ongoing TCAS situation.
- Approximately 5 seconds after the RA, a "clear of conflict" message was declared on CPDS. At this point KLM121 was 900 ft above the RPAS. The RPAS had steered 40 degrees to the left. The intruder passed behind the RPAS.
- The RPAS pilot stopped the left turn, contacted ATC and reported that he had steered left to resolve a conflict. The pilot requested a 'direct' to the next waypoint. The direct was approved by ATC.
- The scenario continued without any further incidents.

2) *Post-scenario assessment:*

a) En-route controller: The controller rated workload and situational awareness worse than for the baseline scenario, but safety and operational acceptability to be equivalent (see Fig. 13). This was because the conflict developed quickly, and seemingly without warning before the RA status was indicated on his display. Furthermore, he was surprised that the UA made a horizontal maneuver, expecting instead a vertical maneuver following the RA. The horizontal avoidance maneuver by the UA took it 3 miles off course, which had the potential to cause conflicts with other aircraft, which would require additional controller intervention.

b) Remote pilot: The remote pilot rated workload and situational awareness as equivalent to the baseline scenario, but safety and operational acceptability to be worse. This may be because the remote pilot considered the guidance on the traffic display to be clear and helpful for selecting a suitable maneuver, but with only 18 seconds prior to CPA before the first alert, felt that the aircraft got too close for comfort. In the post-scenario discussion, he stated that he was unaware of the RA, which was a "monitor vertical speed" preventive RA (see Fig. 14), and so continued the horizontal maneuver, thinking that the red traffic symbol was for a warning-level DWC alert. He asked whether a remain DWC maneuver should be stopped when an RA is issued?

3) *Conflict analysis:*

a) Alerting and guidance: Ultimately, this conflict was resolved by the Climb RA issued to the pilot of KLM121. The original blunder by KLM121, which was exaggerated with an increased rate of descent, created a conflict for which TCAS is very well adapted and DWC separation minima less so. Standard DWC alerting does not consider time to co-altitude, only a fixed vertical separation boundary. DWC alerting is not required until the intruder is within 800 ft vertical separation.

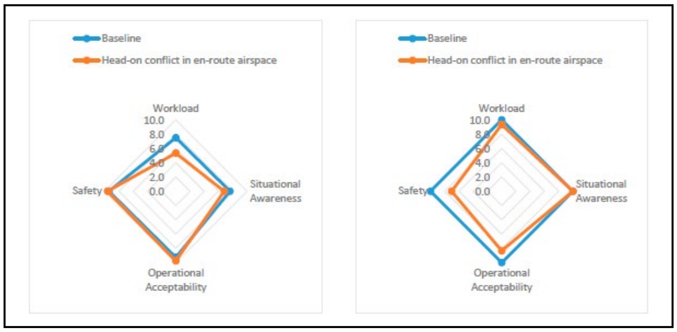

Fig. 13. Questionnaire Scores for Controller (left) and Remote Pilot (right), Scenario 1

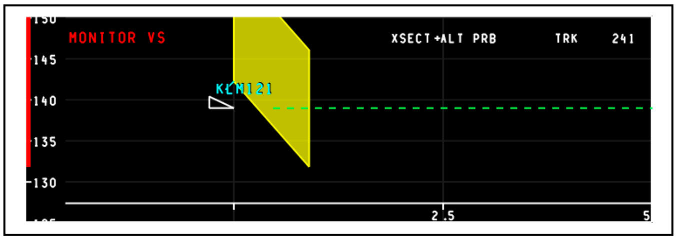

Fig. 14. CPDS Display of RA Guidance, Scenario 1

TCAS includes time to co-altitude in its alerting and guidance calculations, and so issued the complementary RAs when the aircraft were separated 1,300 ft vertically. CPDS exceeds the DAA minimum performance specification in this regard by also including a time-to-co-altitude factor, and issued the DWC corrective alert at 1,500 ft vertical separation. Standard DWC guidance would only ever have showed a red vertical guidance band above the ownship altitude, because the intruder leveled off 900ft above ownship. Because CPDS includes the vertical trajectory of the intruder aircraft in its guidance calculations, it depicted a horizontal conflict zone ahead and to the right of ownship, and provided a red horizontal guidance band based on the time to loss of DWC on the current trajectory. Its Vertical Profile Display (VPD) depicted the conflict probe above and in front of ownship, with a red guidance band extending from above to just below ownship altitude.

b) Remote pilot response. Given the horizontal and vertical CPDS picture (in Fig. 12), the remote pilot chose a horizontal maneuver to the left to maximize separation from the intruder aircraft. This happened to be in the downwind direction, but wind was not likely a factor in the decision. The VPD indicated that a vertical maneuver would be unlikely to avoid loss of DWC separation, because the rate of descent of the intruder was much greater than the UA could achieve. The dynamic depiction of the conflict space, moving downwards towards ownship (see Fig. 14), further reinforced the impression of having no suitable vertical escape option. It is understandable that the remote pilot missed the preventive RA. This type of RA usually requires no action. The aural alert “monitor vertical speed”, is similar to a DWC preventive alert “traffic, monitor”, and the traffic display changes little, with red text appearing on the VPD and the vertical trajectory turning green. Therefore there was no clear indication that would cause the remote pilot to cease the horizontal maneuver he had initiated. If TCAS had issued the UAS a corrective RA (climb or descend), it is likely that the remote pilot would have stopped the turn and followed the directive guidance.

In this scenario, because the intruder’s pilot folowed the climb RA which corrected his blunder, the UA’s horizontal maneuver was not necessary to resolve the conflict. But, if the intruder pilot had ignored the RA, or if the intruder had not been equipped with TCAS, the UA’s horizontal maneuver would still have ensured safe separation, increasing the CPA from 0.3 NM to 0.7 NM, with KLM121 passing behind the UA. The red guidance bands conveyed the urgency of the situation, so the remote pilot did not attempt to contact ATC first, or to apply right-of-way (ROW) rules which would not have helped in this conflict. Therefore, it can be concluded that the additional display features of CPDS helped to increase safety in this conflict.

c) CPDS human-machine interface (HMI). A display fully compliant with DAA minimum operational performance standards (MOPS) [3] would remove all DWC guidance bands from the display for the intruder against which an RA has been issued, and shows only the vertical rate guidance associated with the RA. CPDS continues to show the DWC guidance bands and DWC conflict probes while simultaneously depicting the RA. This has the potential for confusion, such as in Fig. 14, where the green RA trajectory passes through the vertical conflict probe at an altitude within the red guidance band. Furthermore, the shape of the vertical conflict probe does not convey the flight direction of the intruder, making it more difficult to determine a suitable vertical escape trajectory. Adding an icon for the relative position and trajectory of the intruder to the VPD might help in challenging scenarios like this, where the intruder’s maneuver causes the conflict probe to appear suddenly and close to ownship.

B. Scenario 3: Aerial Work Parallel to an Airway

1) Conflict description: In this scenario, the UAS performed planned aerial work, representing an area survey, close to an airway (see Fig. 15). ATC provided it with a volume of airspace between FL 210 and FL 230 encompassing the work area. Even though there was more than 5 NM between the aerial work area and the airway, the DAA system is expected to trigger DWC alerts. This is because the DAA system does not know the routes of any aircraft, including the route of the UAS itself. It detects conflicts only on the basis of current aircraft states. The goal of this scenario was to observe how a remote pilot deals with such nuisance alerts. The conflict occurred with the following sequence of events:

- During the second east bound leg of the survey, a conflict probe appeared on CPDS for one of several airliners in trail in the airway ahead (NOZ1495).
- The DAA system issued a DWC corrective alert, with aural alert (“traffic, avoid”) and yellow traffic symbol for NOZ1495; see Fig. 16.
- The en-route controller called the UAS callsign to warn about the potential conflict with NOZ1495, just in case the UA would inadvertently leave its designated volume.
- The remote pilot had already determined that the next pre-programmed turn would occur before loss of DWC, depicted by the conflict probe. Therefore, no action was taken.
- The corrective alert resolved itself when the UAS made its next planned turn about 20 seconds later.

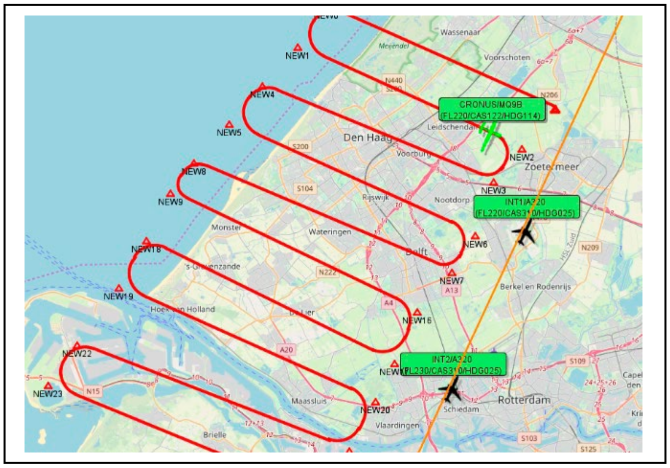

Fig. 15. Planned route of UAS (red) and intruder traffic (orange), Scenario 3

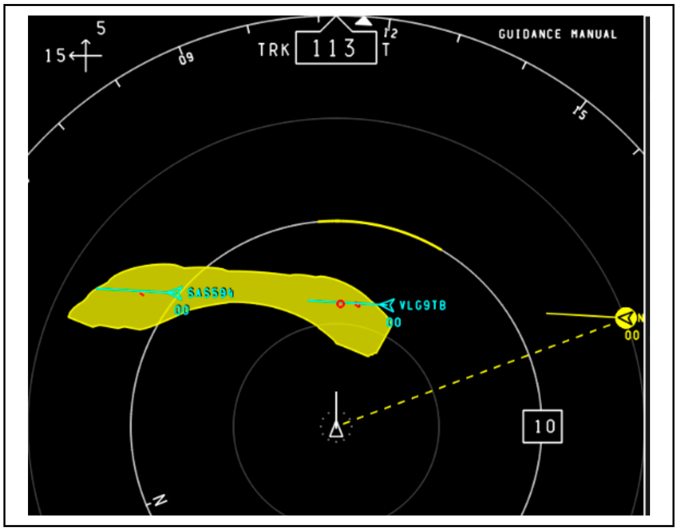

Fig. 16. CPDS Display at Time of DWC Corrective Alert, Scenario 3

2) Post-scenario assessment: The remote pilot did not perceived the corrective alert as a nuisance, because the indications did increase his awareness about the proximity of other aircraft, and the importance to not cross the border of the planned aerial work zone. However, he was uncertain whether he was required to report such alerts to ATC. In this case the controller had already identified the potential conflict and initiated the radio call.

3) Conflict analysis: This scenario showed that the conflict probe functionality of CPDS is very useful during aerial-work missions to identify when potential conflicts are are false alerts, due to the planned flightpath. This is because conflict probes on the CDTI show the distance to loss of DWC. If the pilot has an easy way to assess distance to the next turn, this information can be used to determine if the planned route will automatically resolve a potential conflict without further intervention. Showing the planned route on the CDTI itself would make this determination even simpler.

C. Scenario 5: Lost C2 Link in TMA Airspace

1) Conflict description: In this scenario, the UAS experiences a loss of C2 link after take-off. During loss of C2 link, no traffic data can be sent to the control station for display and the remote pilot no longer has active control. Consequently, the UA can only respond to traffic conflicts with automated TCAS RAs. Furthermore, during lost C2 link the remote pilot can no longer use the UA's radios to communicate with ATC must use the backup telephone instead. The planned routes are shown in Fig. 17. The sequence of events was as follows:

- During its departure climb, the UAS experienced a loss of C2 link.
- The UA initiated its lost C2 link procedure: it automatically changed its transponder code to 7400, turned SE and flew a predefined horizontal route to the ROT waypoint at the last cleared altitude of 3,000 ft.

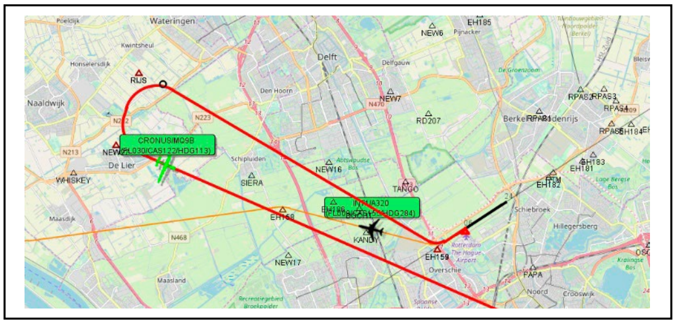

Fig. 17. Planned route of UAS (red) and intruder traffic (orange), Scenario 5

- About 20 seconds after the loss of C2 link, the remote pilot contacted Approach via the backup telephone. The lost link procedure was verified with the approach controller.
- En-route to the ROT loiter waypoint, the UA experienced a conflict with a B737, callsign TRA5243, on departure from Rotterdam.
- The conflict triggered a TCAS TA. A few moments later, it escalated to a TCAS RA.
- The pilot of TRA5243 did not respond to the RA, as instructed for this scenario.
- The UA automatically followed the "descend" RA issued by its onboard TCAS.
- When TCAS declared "clear of conflict", the UA returned automatically to its pre-conflict altitude of 3,000 ft and continued to fly its pre-planned route to ROT.
- At ROT, the UA initiated its loiter.
- After 2 loiter orbits, the C2 link was restored.
- The RPAS pilot established radio communications with Approach and hung up the backup telephone.

2) Post-scenario assessment:

a) Approach controller: To increase the remote pilot's situational awareness during lost C2 link, the controller used the speaker phone function such that the remote pilot could hear other R/T transmissions via the backup phone. However, the communications between the remote pilot and controller were not broadcast on the radio to be heard by other pilots on the frequency. Communications with the backup telephone went well, but it was not clear to the controller when exactly R/T communications were restored. The conflict between TRA5243 and the UA could be clearly seen on the controller's working position. The TCAS RA downlink added to NARSIM for this experiment helped to see that the UA was following its RA, and the controller found this to be very useful.

b) Remote pilot: The remote pilot rated situational awareness and safety only slightly lower than for the baseline TMA scenario. This is partly because he was unaware of the conflict and RA, and would have preferred to have been informed of it by ATC on the backup telephone, in case the C2 link had been restored during or immediately after the RA maneuver. He was unsure when to hang up the backup telephone after the C2 link was restored, and would have prefered some coordination procedures.

3) Conflict analysis: The automatic execution of an RA by the UA in its lost C2 link state ensured a safe outcome for the conflict, even when the conflicting traffic took no action. In this scenario, the UA automatically returned to its cleared lost C2 link altitude after TCAS indicated "clear of conflict". The merits of this behavior were considered by the participants in comparison with the alternative approach, which would be for the UA to continue at its post-RA altitude. The main considerations for automatic return to lost C2 link altitude were as follows:

- Could cause the original conflict to return, but TCAS and ATC (instructing the intruder) would resolve the conflict again until it is safe for the UA to return to its lost C2 link altitude.
- More predictable for ATC.

For the UA continuing at post-RA altitude:

- UA could descend outside ATC controlled airspace.
- UA is likely to level off at a non-standard FL, and block multiple FLs that then must be cleared of other traffic by ATC.

On balance, it was agreed that the automatic return behavior is safer and more efficient for air traffic management and should become the standard for UAS lost C2 link logic.

D. Scenario 6: Ad hoc Aerial Work with Non-cooperative Intruders

1) Conflict description: In this scenario, the UAS performs aerial work in Class G uncontrolled airspace. During the aerial work, it experiences conflicts with two different non-cooperative VFR aircraft, which can only be tracked by the DAA system's ATAR. The VFR aircraft flew haphazardly through the aerial work volume at the UA's altitude, which may not be realistic but served to stress-test the non-cooperative capabilities of the DAA system in a dynamic, aerial work flight pattern. The planned route was a regular pattern of parallel passes, similar to Scenario 3, but at 2,000ft over the Rotterdam port area. As can be seen in Fig. 18, the UAS had to make frequent deviations from its course to avoid the VFR intruders.

Fig. 18. Route flown by UA, Scenario 6

The characteristics of the conflicts were as follows:

- The non-cooperative intruders were displayed to the remote pilot on CPDS as radar tracks with an ATAR-assigned ID. DWC corrective and warning alerts were issued.
- In some cases, the UAS lost DWC because the intruders were continuously maneuvering during the encounter.
- Not all conflicts resulted in DAA alerts. In some cases, the remote pilot maneuvered before an alert as the UA was in Class G airspace and free to maneuver without ATC coordination.
- The remote pilot primarily used ROW rules when resolving the conflicts.

2) Post-scenario assessment:

a) Approach controller: The controller had a high workload managing other traffic, including an unexpected missed approach at EHRD. Nevertheless, he notified the remote pilot about potential conflicts in Class G airspace whenever he had time to do so, as dictated by normal priorities.

b) Remote pilot: This was a very high workload scenario for the remote pilot, and he rated all critera worse than the baseline TMA scenario. He found the CPDS display to be helpful for visualizing the conflicts and to select a suitable resolution. Because the ATAR has a limited field of regard, some conflicts were noticed late, particularly when the intruder was approaching from behind. Most conflicts could be resolved using ROW rules, but in some cases the intruder was not observing ROW so a different maneuver was needed. In one instance, a warning alert was issued for an intruder descending behind the UA. The correct, ROW-compliant resolution was for the UA to maintain heading and speed, but the corresponding aural alert was "traffic, maneuver now", in contradiction to the expected resolution.

3) Conflict analysis:

a) Non-cooperative intruders: As implied by TABLE I, DAA alerting and guidance is most needed when in Class G airspace with VFR traffic, including non-cooperative aircraft. The ATAR has similar field of regard constraints to a pilot looking out from the cockpit of a crewed aircraft. ROW rules allow for this constraint, requiring aircraft approaching from behind (specified as the 140° arc to the rear in [1]) to always give way to the aircraft ahead. However, aircraft above and below are also out of view, and so it is normal practice for VFR aircraft to perform "clearing turns" before commencing a climb or descent, to bring any aircraft in those blind spots into view. For UAS relying on the ATAR to detect non-cooperative intruders, it would be wise to adopt this same practice.

b) ROW rules: When the intruder is negligently or deliberately violating ROW rules, as in this scenario, the rules are not sufficient to resolve conflicts. Therefore, it is important to train remote pilots to fully understand the cues provided by the DAA display to select the conflict resolution, and to evaluate whether following ROW rules is the best option. Remote pilots should be trained to include an intruder's behavior in addition to its relative position when making the maneuver decision.

c) Aural alerts: The aurals that accompany DWC corrective and warning alerts ("traffic, avoid" and "traffic, maneuver now" respectively) assume that the remote pilot is expected to maneuver in response to the alert. In several conflict geometries, however, the intruder is expected to give way to the UA, while it maintians heading and speed. In these situations, the corrective aural alert may be confusing if the remote pilot does not clearly understand when ownship ROW takes precedence. When a conflict escalates to a DWC warning alert, the remote pilot should be preparing to make a compatible maneuver (such as a turn to the right, climb or descent), even if the UA has the ROW. This scenario uncovered another alerting issue which could affect DAA requirements. In the case where a non-cooperative intruder approaching from behind was first detected by the ATAR within the DWC separation minima, a DWC alert was issued even though the intruder was already past the CPA and diverging from the UA. The "traffic, maneuver now" alert implied that the remote pilot needed to take immediate action, but the conflict was already resolving. This is a corner case, but supressing the nuisance aural alert for this case would help to minimize pilot workload.

E. Scenarios 8-10: CAVS

The 3 CAVS scenarios were down-selected from RTS 1 because they represented challenging situations for the remote pilot and controllers. Each one involved a violation of separation minima during the CAVS procedure, either because the leading aircraft slowed down significantly during the approach, causing the separation to close, or because another aircraft blundered into conflict with the UAS. These scenarios all resulted in cancellation of the remote pilot's delegated separation or a missed approach requiring controller action. The baseline TMA scenario did not use CAVS, but because none of the CAVS scenarios led to a landing completed with delegated separation, there was no human factors comparison to show the controller workload reduction expected with CAVS. Furthermore, the scenario repetition used to test Enhanced CAVS led to scenario learning. During the repeated scenario, all participants took preemptive actions to mitigate the scenario challenges, so that assessment improvements could not be attributed to Enhanced CAVS alone. Scenario 10, with Enhanced CAVS, came closest to a successful demonstration of CAVS, and so will be used for illustration, but analysis will be drawn from all 3 scenarios.

1) Conflict description, Scenario 10: In this scenario, the leader and UAS are established on the instrument approach, while a helicopter on the downwind leg of the visual circuit turns onto base leg too early and conflicts with the UA, as shown in Fig. 19. The sequence of events was as follows:

- The UAS was established on final approach behind Cessna 172, callsign OOTYB.
- The approach controller cleared the UAS to perform CAVS with the leader. The remote pilot accepted the clearance.
- The remote pilot saw a helicopter on CPDS that was approaching the UA on the right hand downwind.
- The helicopter, ZXP26, was instructed by the tower controller to turn to base behind the UA, but it turned to base before the UA had passed.
- ZXP26 turned onto final close behind and above the UA, resulting in an overtaking scenario. This triggered a warning alert on CPDS.
- The remote pilot executed a missed approach. This reduced the horizontal and vertical separation with the intruder, and increased conflict severity.
- Once the UA climbed to 500 ft above the helicopter the conflict resolved.

Fig. 19. Route flown by leader, UA and conflicting intruder, Scenario 10

2) Post-scenario assessment:

a) Remote pilot: The lead aircraft was flying at approximately the same speed as the UA, so the remote pilot found it easy to maintain separation using the CAVS display mode. When the DAA warning alert occurred in the terminal area, he followed the prescribed response, which is a missed approach. However, in this case of being overtaken from above and behind, this action made the conflict worse, whereas a lateral resolution to the left would have been easier and safer. Therefore, it would be better not to prescribe one resolution action for all types of conflict in the terminal area.

3) Conflict analysis:

a) Terminal area DAA alerting: The case of the warning alert caused by an overtaking aircraft is another example of contradiction between DAA alerting and ROW rules. Ordinarily, a pilot would not be able to see the overtaking aircraft, and the pilot of the overtaking aircraft would be required to give way. Furthermore, the tower controller would expect the aircraft being overtaken to continue to land and, given time to respond, would have instructed the overtaking helicopter to go around. In other corcumstance, such as the same conflict at a non-towered airport and no indication that the overtaking aircraft is giving way, the remote pilot should use jusdgement to select a suitable resolution, such as the suggested turn to the left.

b) CAVS procedures: The other failed CAVS attempts highlighted some useful operating procedures. Firstly, ATC should not delegate separation to the remote pilot unless the performance of the lead aircraft and UA are well matched. Otherwise it will be difficult for the remote pilot to maintain separation throughout the approach. Secondly, it would be helpful to establish criteria, such as a minimum separation distance, when the remote pilot should cancel the CAVS delegation, such that approach or tower controllers have adequate time to resolve the situation

VIII. RECOMMENDATIONS AND FURTHER WORK

A. Findings and Recommendations

This section summarizes findings and recommendations discussed in the analysis of each scenario, grouped into common themes.

1) Response to DWC alerting and guidance:

- Non-cooperative intruders can cause sudden alerts when approaching from outside the ATAR's field of regard. These aircraft are usually required to give way, and if already on a diverging trajectory, the warning aural would be classed as a nuisance.
- When operating in Class G airspace or where non-cooperative traffic may be present, procedures designed to compensate for a VFR pilot's limited field of view should be followed, such as clearing turns before climb/descent.
- Remote pilots should be trained to use the traffic display to determine when right-of-way (ROW) rules should be applied after DWC alerts are issued, dependent on an intruder's position and behavior and the alert level.
- When a warning alert is issued in the terminal area, the remote pilot should not immediately initiate a missed approach if the aircraft causing the alert is normally required to give way. The UAS may not need to take action for the conflict to resolve, or an alternative maneuver such as a horizontal turn may be safer. (This is similar to a finding in Step 2).

2) CPDS HMI:

- CPDS's conflict probes, which account for intruder vertical speed, can enhance the safety of DAA operations in some challenging situations such as for an intruder with high vertical speed.
- Adding the traffic position icon and velocity vector to the VPD may help the remote pilot determine suitable vertical maneuvers to maintain separation in sudden conflict situations.
- During aerial work operations, conflict probes help the remote pilot identify which DAA alerts will self-resolve with the next planned turn(s).
- Adding the route plan to the CDTI, especially for aerial work operations, will allow the remote pilot to quickly determine whether conflict probes lie on the planned route.

3) Collision Avoidance RAs:

- If a remain DWC maneuver is underway when an RA is issued, the remote pilot should cease it and follow the RA immediately, or effectiveness of the RA may be reduced.
- Automatic execution of RAs while in a lost C2 link state significantly improves the safety of that contingency operating mode.

4) Loss of C2 Link:

- After automatically executing an RA maneuver in a lost C2 link state, the UA should be programmed to automatically return to its cleared lost C2 link altitude, whether the UA was previously at that altitude or was climbing or descending towards it.
- When a controller observes that a UA in lost C2 link state (transponder code 7400) has executed an RA automatic maneuver, as indicated on the controller's display, ATC should notify the remote pilot via the backup telephone, when workload permits.
- Procedures should be established for ending the backup telephone call to the ATC facility after the C2 link has been restored and normal radio communications are available again.

5) CAVS:

- Baseline CAVS is very effective for enabling the remote pilot to maintain separation from a leading aircraft.
- ATC should not delegate separation to the remote pilot of a CAVS-capable UAS unless the performance of the lead aircraft and UA are well matched.
- Criteria should be established for remote pilots to cancel the CAVS delegation.
- Scenario learning in these experiments invalidated the comparison of Baseline and Enhanced CAVS.

B. Further Work

The next experiments in this series will continue to explore operational issues associated with DAA-equipped UAS in European civil airspace. Planned areas of study include the following:

- Comparison of U.S. and European performance standards for DWC alerting.
- Operations with multiple UAS in same airspace, including UAS vs. UAS conflicts.
- Effects of C2 link latency on DWC alerting and guidance and voice communications with ATC.

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