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The critical impact of remote pilot modelling in evaluation of detect-and-avoid systems explained for ACAS Xu

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Abstract

Detect-and-avoid (DAA) systems for remotely piloted aircraft systems (RPAS) can provide remain well clear (RWC) guidance as well as shorter term resolution advisories (RAs) for collision avoidance, which are both provided in the vertical and horizontal planes. Simulation-based studies for large sets of encounter scenarios are used in the development and evaluation of DAA systems, which encompass safety and operational acceptability of the DAA supported operations. Given the key role of the remote pilot (RP) in responding to RWC guidance and RAs, a RP model is an essential element in such simulations. This paper describes the development of a RP model for evaluation of encounter scenarios involving the ACAS Xu DAA system. The model describes RP situation awareness (perception, comprehension, projection) as basis for decision-making, modes for responding to RAs and/or RWC guidance, response delays, response strengths, and the flight control actions. The RP model includes deterministic and stochastic settings. It is integrated in a simulation environment for encounters of manned and/or unmanned aircraft, the involved DAA and airborne collision avoidance systems, the surveillance and communication systems, and the human operators. Simulation results are provided for a set of encounters between pairs of RPAS both having ACAS Xu for various configurations of the RP model, and for cases with and without sensor errors. The results show that there can be large differences between the results of deterministic and Monte Carlo simulations, indicating that limited sensor errors can have a large impact on the nonlinear system dynamics. Furthermore it is shown that livelock conditions can exist where the RPAS show oscillatory behaviour and do not manage to effectively pass each other, dependent on the encounter geometry and RP model settings. It is advised to perform a broad sensitively study for RP performance and to study extending the scope of DAA systems to include guidance for efficiently returning to mission without triggering new conflicts.

1 Introduction

A detect-and-avoid (DAA) system supports a remote pilot (RP) of an unmanned aircraft system (UAS) to observe and avoid nearby air traffic using sensor and guidance technology. In general such a DAA system can have a remain well clear (RWC) and a collision avoidance (CA) function. The RWC function supports detection and analysis of potential conflicting traffic and provides flight path guidance to the RP to prevent the conflict developing into a collision hazard (RTCA, 2021). The CA function provides last-resort resolution advisories (RAs) to the RP to avoid physical contact between the aircraft.

ACAS Xu is a recent DAA system that incorporates both the RWC and CA functions in support of remotely piloted aircraft systems (RPAS) (EUROCAE, 2020a; Owen et al., 2019). Its surveillance and tracking module (STM) incorporates multiple surveillance inputs including automatic dependent surveillance-broadcast (ADS-B), active Mode S/C interrogation and an on-board air-to-air radar (ATAR), and it fuses the tracking data into position and speed estimates of nearby aircraft, using Kalman filtering, interacting multiple model (IMM) trackers and inter-source correlation (EUROCAE, 2020b; Owen et al., 2019). The threat resolution module (TRM) of ACAS Xu is based on two independent partially observable Markov decision process (POMDP) models for advisories in the vertical plane and the horizontal plane. The optimization for the vertical and horizontal dimensions is separated, since the combined problem was considered intractable to solve due to its large (discretized) state space. Such “curse of dimensionality” is a well-known problem in solving Markov decision processes (Sutton & Barto, 2020). The objective function in the optimization specifies costs for ACAS actions and outcomes in simulated encounters. The POMDP is solved through value iteration, a dynamic programming (DP) algorithm, to calculate a Q-function representing the value gained for taking an action in the current state. In ACAS Xu the Q-functions are represented as lookup tables with a total size of 5 GB. For the provision of RAs, ACAS Xu extends these precomputed actions with coordination rules for complementary advisories (assuring that they are in opposite directions), and with online costs for required system performance, e.g. low-altitude inhibits of descend RAs, altitude dependent logic sensitivity, and RA transition penalties. The RWC guidance provided by ACAS Xu is based on a rollout approach (Bertsekas, 2013), which uses the CA POMDP-based cost tables to infer an increase in collision risk in relation to DAA alert timing requirements. The RWC guidance does not use coordination between nearby aircraft.

The vertical RAs that can be announced by ACAS Xu are mostly equal to the corrective or preventive RAs specified by TCAS II (EUROCAE, 2008) or ACAS Xa (EUROCAE, 2023) for manned commercial aviation, e.g. Climb, Descend, Level-off, Increase Climb. Displayed vertical rates to maintain tend to be more limited, in line with the UAS performance characteristics, e.g. 1000 fpm (feet/minute) instead of 1500 fpm for initial RAs (EUROCAE, 2020a). In contrast with TCAS II and ACAS Xa, horizontal RAs are included for ACAS Xu. They include Turn Left and Turn Right, in combination with a target track angle in a heading display. RAs are expected to be responded within 5 s for an initial RA and within 2.5 s for a subsequent RA in the same dimension, with a vertical acceleration of 0.25 or 0.33 g, or with a turn rate of 3 deg/s. The manoeuvre in response to an RA does not need approval of air traffic control (ATC), but a return to course following a clear of conflict would need ATC approval (RTCA, 2021). There may be an automatic response to an RA by an autopilot, which may be overridden by the RP.

The RWC guidance displayed by ACAS Xu informs the RP about the vertical rates and relative track angles that have to be avoided to remain well clear of other traffic, e.g. to avoid turning right by more than 37.5 deg, or to avoid climbing by more than 500 fpm. As a basis ACAS Xu provides an array of 31 vertical bands with widths of 200 fpm from -3100 to 3100 fpm, and an array of 13 horizontal bands with widths of 15 deg from -97.5 to 97.5 deg relative to the ownship track. The following handling of RWC guidance is foreseen (Figure A-22 of (RTCA, 2021)). The RP judges whether a RWC manoeuvre is needed and whether it can be performed. If so, the pilot requests a

DAA manoeuvre clearance to ATC, except when the pilot judges that such request is not needed given the criticality of the conflict or absence of ATC control. If ATC takes too long to respond, RTCA DAA MOPS (RTCA, 2021) indicate that the RP may initiate the deviation without clearance.

It follows from above that the scope of ACAS Xu and the uncertainty that it has to manage are considerably larger than for TCAS II or ACAS Xa. While TCAS II and ACAS Xa basically "only" need to specify within last minute vertical RAs, ACAS Xu specifies RAs both vertically and horizontally, as well as two degrees of freedom RWC guidance at relatively long time horizons (starting at a few minutes before closest point of approach). In relation, the functions to be fulfilled by a RP in handling DAA advisories are considerably more complex than those of a pilot in handling ACAS RAs. While an onboard pilot just needs to follow the provided RAs and inform ATC following the act, the RP needs to interpret the possibly blended RWC guidance in relation to the traffic situation and airspace, decide on an appropriate manoeuvre, possibly interact with ATC, keep tracking the evolving RWC guidance, and respond appropriately to possibly blended RAs.

The purpose of this paper is to describe the development of a RP model for CA advisories and RWC guidance of ACAS Xu in an agent-based modelling and simulation environment for evaluating DAA systems, and to share initial simulation results that show the impact of RP performance on the interrelated trajectories of UAS pairs. Section 2 presents simulation studies, existing RP models in the literature and our simulation environment. Section 3 presents the development of the RP model. Section 4 provides simulation results for various configurations of the RP model in handling ACAS Xu advisories. Section 5 discusses the findings and their implications.

An initial version of this paper was published at the SESAR Innovation Days 2023 (Stroeve et al., 2023). The current paper contains enhanced explanation of the model, new simulation results with additional metrics, and an extended discussion.

2 Context

2.1 *Simulation studies*

Human-in-the-loop (HITL) simulations for an early version of ACAS Xu provide insight in the way that advisories and guidance are handled by RPs (Rorie et al., 2020). The mean response time to RWC guidance found in these simulations is 17 seconds, including time for coordination with air traffic control. The average response time for RAs is about 2.8 s, where there exists considerable dispersion with response times within 1 s to more than 10 s. The observed compliance rate to RAs differed considerably for horizontal and vertical RAs. The pilots complied consistently with initial and subsequent vertical RAs in 94% of the cases, while compliance with horizontal RAs decreased from 94% for initial RAs to less than 50% for subsequent RAs from the fourth update, which was attributed to the large number of updates. Several losses of DAA well clear (LoWC) were observed in the HITL simulations that were attributed to pilot mistakes, including (1) a pilot attempting to return to the route too soon following an avoidance manoeuvre, (2) a poor manoeuvre choice by the pilot, and (3) a too long coordination time with ATC. These cases illustrate the complexity of dealing with the DAA advisories by the RPs.

Validation studies of ACAS for manned aviation have extensively used fast-time simulation of encounters for evaluation of safety and operational suitability metrics (EUROCONTROL, 2022; FAA, 2018). These simulations typically build on Bayesian network encounter models (Dean et al., 2022; Kochenderfer et al., 2010) for safety and radar data for operational suitability, and assume a pilot response using the ICAO standard pilot response model (ICAO, 2014) (delay of 5 / 2.5 s for initial / subsequent RAs with an acceleration of 0.25 or 0.35 g to the advised vertical rate). It is known that the pilot response, especially the probability of non-response, has a large impact on the ACAS effectiveness (Stroeve, 2023). Similar to studies for TCAS II and ACAS Xa, evaluation of

ACAS Xu system performance has been achieved by simulation of model-based and radar encounters (Owen et al., 2019). In (Owen et al., 2019) the model for the RP behaviour has not been described, but it is obvious that given the complexity of the RP decision making process, such models have a large impact on the evaluation of the effectiveness of ACAS Xu.

2.2 *Remote pilot models*

In support of Monte Carlo (MC) simulation of encounters involving unmanned aircraft, Guendel et al. (Guendel et al., 2017) developed a rule-based stochastic model of responses of RPs based on data collected from a succession of HITL experiments. The model describes the RP response for RWC guidance of DAIDALUS (Munoz et al., 2015), which is a reference system of (RTCA, 2021). The delay in responding to RWC guidance is decomposed in initial delay, ATC coordination delay, execution delay, and update delay, which are each chosen from exponential or gamma distributions. It is assumed that the RP only uses single-axis manoeuvres. The model uses a pairwise elimination process for horizontal preference (left or right), vertical preference (up or down), and finally vertical or horizontal. Return-to-course decisions are not modelled. The model cannot be directly used for ACAS Xu, since it applies DAIDALUS specific aspects, such as altitude bands instead of vertical rates as used in ACAS Xu, and since it does not include responses to RAs.

In (SESAR Joint Undertaking, 2022) deterministic, rule-based models were developed for RP responses to RWC and CA alerting by ACAS Xu. They incorporate decision rules for initial and updated RWC guidance, for vertical or horizontal manoeuvres, and for end of alerts. They include fixed response latencies, which depend on the order in the sequence of RWC alerts and the option of ATC coordination. Results of an initial set of simulations including these RP models are presented in Appendix I of (SESAR Joint Undertaking, 2023) for encounters between an RPAS with ACAS Xu and a manned aircraft with TCAS II or ACAS Xa. Deterministic simulations were done with focus on the impact of initial RWC guidance.

2.3 *CAVEAT agent-based modelling and simulation*

The RP model developed in this paper is part of an agent-based model for evaluation of ACAS in encounter-scenarios (Stroeve et al., 2020; Stroeve & Villanueva Cañizares, 2023) by simulation in the Collision Avoidance Validation and Evaluation Tool (CAVEAT). CAVEAT includes TCAS II and ACAS X systems and provides the option to perform MC simulation. The agent-based model describes the continuous-time dynamics of interacting agents in an encounter-scenario. In particular it describes a number (typically two) of manned and/or unmanned aircraft that come at a closest point of approach (CPA) with particular horizontal and vertical miss distances (HMD/VMD). Aircraft have ownship state estimation of pressure altitude, heading, global navigation satellite system (GNSS) based speed and position estimates, and height above terrain. ACAS II systems (TCAS II or ACAS Xa) use 1030/1090 MHz signals for coordination, ADS-B data sharing and measurement of the range and bearing with respect to intruders that are equipped with a suitable transponder. ACAS III systems, such as ACAS Xu, may also use an ATAR to estimate the relative position and speed of an intruder without transponder. All models of ownship state estimation and intruder measurement include sensor error models, describing biases and/or jitter components by stochastic processes (Stroeve et al., 2020; Stroeve & Villanueva Cañizares, 2023). A manned aircraft may be equipped with TCAS II (EUROCAE, 2008) or ACAS Xa (EUROCAE, 2023), while an unmanned aircraft may be equipped with ACAS Xu (EUROCAE, 2020b). The ACAS algorithms are in agreement with the associated minimum operational performance standards (MOPS) and the lookup tables for the logic of ACAS Xa and ACAS Xu, which are distributed by RTCA, have been incorporated. The model of the pilot flying includes components for situation awareness, response mode, delay, vertical rate and acceleration, and flight control action, which can be applied in deterministic or stochastic settings (Stroeve et al., 2020; Stroeve & Villanueva Cañizares, 2023). The model for the RP will be explained in detail in the next section.

Model components can be evaluated in stochastic or deterministic settings by adjusting their parameters. A single run simulation can be used to evaluate a completely deterministic model. Multiple MC simulation runs can be used to evaluate models including stochastic components. Both deterministic and MC simulations can be performed for single encounters or for sets of encounters. The simulations can support retrospective studies (analysis of ACAS events that occurred) as well as prospective studies for new ACAS generations (ACAS X) and airspace design (potential impact on ACAS events).

3 Remote pilot model for ACAS Xu evaluation

3.1 Introduction

The RP model (Figure 1) has been developed such that it can be applied in deterministic as well as in MC simulation runs. The basis of RP performance is the situation awareness, which is updated for new information as explained in Section 3.2. Response modes describes whether the RP responds to particular types of DAA output (Section 3.3). Delays and strength in RP responses are modelled in Sections 3.4 and 3.5, respectively. Flight control actions implemented by the RP based on above elements are explained in Section 3.6. An associated model for the UA control station, specifying additional closed loop delay components, is presented in Section 3.7. There is no separate ATC actor in the model. The sole ATC impact is by a delay component in the RP response for coordination with an air traffic controller. Mathematical details of the models are available in (Stroeve & Villanueva Cañizares, 2023).

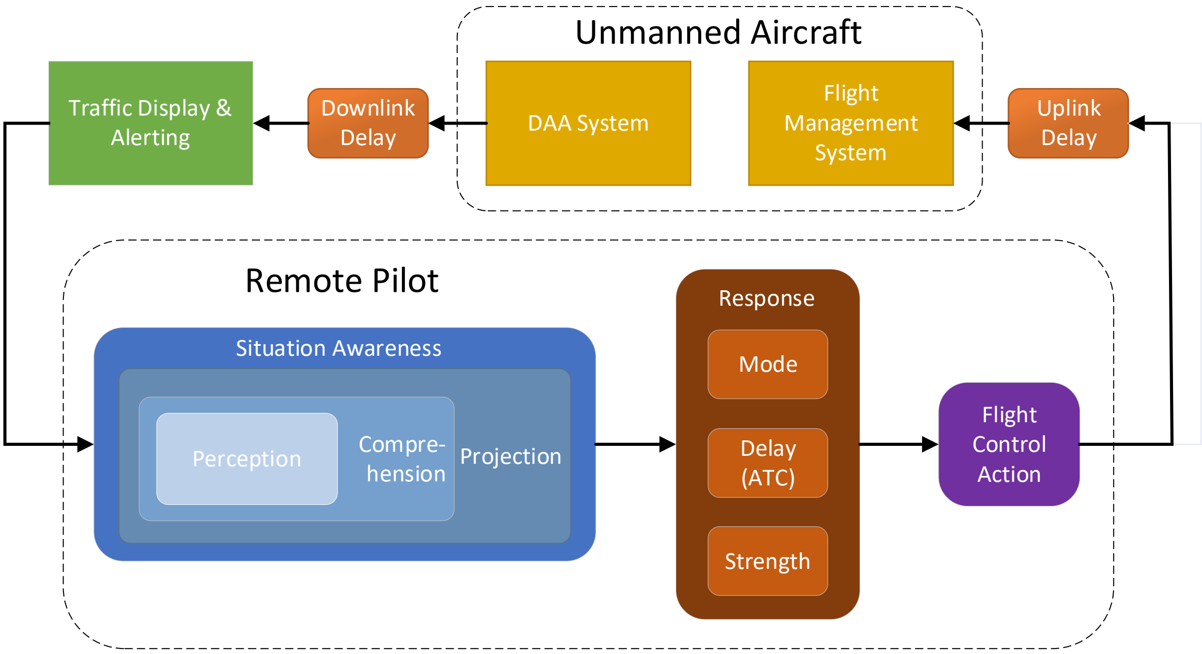

Figure 1. Diagram of remote pilot model and the interconnections with the unmanned aircraft.

3.2 Remote pilot situation awareness

The situation awareness (SA) model describes the awareness processes and components of the RP. This is done at three SA levels: perception, comprehension, and projection. At the SA perception level the following aspects are discerned:

- *Ownship state*: position, airspeed, heading, course, turn rate;

- *Flightplan*: planned positions and ground speeds (this is the trajectory that the aircraft would fly without manoeuvring in response to DAA advisories / guidance);
- *Environmental data*: wind speed and direction;
- *Vertical RAs*: corrective / preventive/ vertical RA clear, advised vertical rate to achieve (corrective RA), advised vertical rate limit (preventive RA), initial / subsequent RA, reversal RA, increase rate RA;
- *Horizontal RAs*: corrective / horizontal RA clear, advised course to achieve, initial / subsequent RA;
- *Vertical RWC guidance*: vertical RWC band elements active or not;
- *Horizontal RWC guidance*: horizontal RWC band elements active or not.

The perceived vertical and horizontal RAs provide direct advisories on the vertical speed and course. At the SA comprehension and projection levels the advised vertical speed and course of the RAs are adopted without further processing.

At the SA comprehension level the RP interprets the RWC guidance as a basis for flight control actions. Based on the vertical RWC bands, first the nearest lower and upper bounds of the vertical speeds that need to be avoided are determined, where the RP can add a fixed margin. The bounds adhered by the RP depend on the condition that the current vertical speed is inside the RWC bands, thus requiring a manoeuvre, or outside the RWC bands, not requiring a manoeuvre. For instance, if there are active RWC bands between (-500, 100) fpm, the current vertical rate is 0 fpm, and the RP uses a margin of 100 fpm, then the nearest bounds adhered by the RP are (-600, 200) fpm. With the same bands and margin, but a current vertical rate of 400 fpm, the RP is aware to not adjust the vertical rate below a minimum bound of 200 fpm.

Similarly for the horizontal RWC bands, upper and lower bands that need to be avoided are determined, where the RP may apply a margin, and where the bands depend on the need for a manoeuvre. For instance, if there are active RWC bands for relative track angles between -22.5 and 37.5 deg and the RP applies a margin of 7.5 deg, then the bounds adhered by the RP are (-30, 45) deg. For active RWC bands of 22.5 to 52.5 deg and a margin of 7.5 deg, the RP is aware to not turn right for more than 15 deg.

At the SA projection level the RP applies the interpretation of the vertical RWC bands to decide on the required vertical speed, in the case that a vertical manoeuvre is needed. If the aircraft is not flying level, the RP uses a decision bias to favour continuing the current vertical rate sign (i.e. climb or descend). For instance, if the aircraft is descending with 200 fpm, the RP uses a decision bias of 200 fpm, and the bounds to avoid are interpreted as (-600, 100) fpm, then the RP sets the vertical speed to attain at -600 fpm, even though this descent speed is farther from the current speed than the upper limit of the bounds. Furthermore in this decision making process the RP uses minimum and maximum vertical speeds. For instance if the speed limits would be (-500, 500) fpm, then in above example the vertical speed would be set as 100 fpm, since -600 fpm would be below the minimum. If both vertical speed limits cannot be adhered, then the RP applies the closest speed limit.

Similarly for the decision on the turn magnitude if a horizontal RWC manoeuvre is needed, the RP uses a decision bias to favour the current turn direction, and the RP uses turn limits.

The SA model is completely deterministic. Its performance can be tuned by a set of 10 parameters (e.g. margins, vertical speed and turn limits) (Stroeve & Villanueva Cañizares, 2023).

3.3 *Remote pilot response mode*

In manned aviation it is well known that TCAS RAs are not always followed by pilots and that the pilot response mode (to respond or not) is an important factor in evaluating ACAS effectiveness. A RP response mode model needs to account for more aspects, namely the horizontal and vertical dimensions, and the CA and RWC functionalities. To do so the model includes the following response modes for the CA and for the RWC functionalities:

- *NoRe*: the RP does not respond;
- *HorRe*: the RP responds only to advisories or guidance in the horizontal plane;
- *VerRe*: the RP responds only to advisories or guidance in the vertical plane;
- *2DRe*: the RP responds to advisories of guidance in two dimensions at the same time (blended response).

If the model is used in a deterministic setting, each of these modes can be set as desired (2 parameters). This allows the user to evaluate the impact of combinations of response modes for the involved aircraft that are of interest. The model can also be applied in a stochastic setting, where probabilities of independent RP response modes are specified (8 parameters), which determine constant response modes in a MC simulation run.

3.4 *Remote pilot response delay*

In line with the ICAO standard pilot response model for ACAS RAs in manned aviation (ICAO, 2014), DAA standards (EUROCAE, 2020a) and other RP models (Guendel et al., 2017; SESAR Joint Undertaking, 2022), it is assumed that there are different delays for initial RAs and RWC guidance and for any subsequent RAs and updated RWC guidance. As a basis we distinguish between preparation delays and action delays. A delay for an initial CA/RWC advisory is the sum of preparation and action delays, while the delay to subsequent advisories equals the action delay. In a deterministic setting both the preparation and action delays are constants, while in a stochastic setting the preparation delay is assumed constant and the action delay is chosen from a lognormal distribution. It is assumed that the RP uses a same action delay for all vertical and horizontal RAs in the run of an encounter-scenario, thus representing a RP who consistently responds in a particular (slow or fast) manner. Similarly, a same action delay is assumed for all (vertical/horizontal) RWC guidance. For responding to RWC guidance it is assumed that the RP may coordinate with ATC, which imposes an additional coordination delay. In a deterministic setting this simply is a constant additional delay, while in a stochastic setting there is a probability for the coordination mode and a coordination delay chosen from a lognormal distribution. Also these delay components are chosen once per run. As a result all responses of the RP strictly follow the order of the RAs and RWC guidance updates, thus supporting explainability to a user of the model. The performance of the response delay model can be tuned by 6 parameters in a deterministic setting or by 9 parameters in a stochastic setting (Stroeve & Villanueva Cañizares, 2023).

3.5 *Remote pilot response strength*

The model for the RP response strength describes the vertical accelerations and the rates of turn applied for RAs and RWC guidance. The vertical acceleration for RAs depends on the perceived need for moderate of a high acceleration; the latter is the case for reversal or increase rate RAs. In a deterministic setting constant values are set for all vertical accelerations and rates of turn, separately for the CA and RWC functionalities (5 parameters). In a stochastic setting, the variables are chosen once between a minimum and maximum using uniform distributions (10 parameters).

3.6 *Remote pilot flight control actions*

The model for the RP flight control actions describes the integrated impact of the situation awareness, the response mode, the closed loop delay, and the response strength on the UAS manoeuvres. It is a deterministic model (3 parameters), but the flight control actions reflect the possibly stochastic behaviour of the underlying components. It is assumed that the manoeuvres in the horizontal and vertical planes are independent. The following types of processes can be distinguished.

- *Prior to RAs / RWC guidance.* Here the flight is controlled in accordance with the position data in the flight plan, implying that the specified trajectory points are closely followed in the horizontal and/or vertical plane.
- *Limit processes.* Here the flight is controlled in accordance with the vertical rate or the course (flight track angle) in the flight plan, while maximum or minimum limits in the vertical rate or course as decided by the RP based on the DAA output (see Section 3.2) are adhered to. These processes are also applied if there are no longer effective DAA advisories, thus controlling the UAS to the vertical rate and course of the flight plan.
- *Goal processes.* Here the flight is controlled towards a specific vertical rate or course as decided by the RP based on the DAA output. This implies that the original trajectory as specified in the flight plan is no longer adhered to.

3.7 Unmanned aircraft control station

The UA control station is a remote facility that houses RP control for the UAS. The DAA MOPS (RTCA, 2021) specify allowable latency contributions for DAA subsystems, including maximum latencies of 1 s for C2 link downlink, 1 s for C2 uplink, and 0.5 s for DAA traffic display. The control station model represents a latency for downlink of DAA data and processing for display to the RP, and a latency for processing and uplink of RP control data for the UAS. Both latencies can be set as a constant (2 parameters), or they can be chosen from uniform distributions (4 parameters); they do not change during a run of an encounter-scenario. These latencies add to the RP response delays explained in Section 3.4, thus enlarging the overall closed loop delay for the flight control.

4 Simulations

The developed RP model was integrated in the CAVEAT simulation software, as explained in Section 2.3. The current section provides a number of simulation results which illustrate the impact of the RP model and sensor errors in encounters between UAS pairs that are both ACAS Xu equipped. The purpose of the simulations is not to provide a complete validation of ACAS Xu; for such purpose much broader sets of encounters scenarios would be needed. The set of encounters, scenario configurations and metrics evaluated in the simulations are described in Sections 4.1, 4.2 and 4.3, respectively. Results of particular simulated encounter-scenarios and statistics of sets of encounter-scenarios are provided in Section 4.4.

4.1 Encounters

A set of encounters with the following characteristics was used:

- All encounters consider two UASs with a VMD and HMD of 0 ft at flight level (FL) 80 (altitude is 8,000 ft). This altitude is well within the range of 400 to 18,000 ft where ACAS Xu equipped RPASs are intended to operate, proving ample room to climb or descend during the time of an encounter.
- The duration of the encounter is from 300 s before to 300 s after CPA at time t=0 (or 12:00:00), i.e. the time of closest approach (TCA) is at t=0. This duration is sufficiently long to prevent RWC guidance or RAs to exist before the start of the encounter and it provides ample room to analyse the performance after TCA of the encounter.
- The speed of aircraft AC1 is 120 or 140 kt, and the speed of aircraft AC2 is always 120 kt in zero wind conditions (2 combinations). These are typical RPAS speeds and represent cases with equal as well as different speeds.
- The relative course of AC2 with respect to AC1 is 45, 90, 135, or 180 deg (4 combinations). These represent a basic set of encounter angles (180 deg is opposing traffic).

- The vertical rates of AC1 are -900, 0, or 800 fpm, while those of AC2 are -800, 0, or 700 fpm (9 combinations). These are typical RPAS vertical speeds and the combinations describe all options of the vertical speed modes.

In combination these characteristics lead to 2×4×9=72 encounters.

4.2 Scenario configurations

Simulations were performed for the following scenario configurations:

- Both UASs are equipped with ACAS Xu (EUROCAE, 2020b), transponders (mode S, ADS-B), GNSS, pressure altimetry, and an air-to-air radar (ATAR);
- Sensor errors may be absent (deterministic simulation), or there may be sensor error in all ownship state estimation and intruder measurement processes following sensor error models documented in (Stroeve & Villanueva Cañizares, 2023) (MC simulation);
- The performance of the RPs of both UASs is deterministic and the following conditions are distinguished:
    - RWC guidance may be followed, or not;
    - RAs may be followed, or not;
    - Guidance/advisories may be followed only vertically, only horizontally, or in two dimensions;
    - The response delay may include an additional delay for coordination with ATC (10 s), or not. The former implies a closed loop delay of 14.5 s for most (i.e. subsequent) guidance/advisories, while the latter implies a closed loop delay of 4.5 s for subsequent guidance/advisories;
- The RP does not use margins or decision biases in the comprehension or projection of RWC guidance.

For deterministic settings the 72 encounters were simulated once per scenario configuration, while in the scenarios with sensor errors they were simulated using 10 MC simulation runs each.

4.3 Metrics

Statistics of the following metrics were evaluated over sets of 72 runs per scenario configuration for the deterministic simulations and for sets of 720 runs per scenario configuration for the MC simulations.

- *Loss of DAA Well Clear (LoWC) percentage*. A loss of DAA Well Clear has been defined to occur for en-route cooperative aircraft (RTCA, 2021) if the following three conditions all apply: (1) the projected horizontal miss distance (assuming constant speed) is less or equal than 4000 ft, (2) the so-called modified tau (for large range approximately the time to pass the range) is less or equal than 35 s, and (3) the vertical separation is less or equal than 450 ft. The LoWC percentage is the part of the runs in a scenario configuration where a LoWC occurred.
- *NMAC multiplier*. In ACAS validation studies traditionally near mid-air collision (NMAC) events are used as a key metric. It is defined as VMD being less than 100 ft and HMD being less than 500 ft. Now we define an NMAC multiplier as $\lambda_{NMAC} = \min_t(\max(\frac{1}{100}\Delta h_t, \frac{1}{500}\Delta r_t))$, where Δh_t is the difference in altitude in feet at time t, Δr_t is the horizontal distance in feet at time t, and where the minimum is attained over all times in the encounter. So an NMAC has occurred if $\lambda_{NMAC} < 1$, and otherwise λ_{NMAC} values closer to one indicate that an NMAC was more imminent. The minimum of the NMAC multiplier over the sets of runs is provided. A value above one implies that no NMAC occurred in the set.

- *Mean additional distance*. As a result of the DAA advisories the trajectory is adapted and additional distance is traversed. The distance for each aircraft is determined horizontally and vertically by the integrals of the traversed distance for the original trajectory and the modified trajectory. The additional distance of an aircraft is the difference of the traversed distances plus the distance between the points at the end of the original and modified trajectories. The additional distance in a run is the sum of the additional distances. The mean additional distance is the average over the runs of the encounter scenarios.
- *RA percentage*. The percentage of runs where there was at least one RA is provided.
- *Long DAA percentage*. There may be runs with enduring DAA advisories. A long DAA advisory for an aircraft is defined as the presence of a DAA advisory (RWC or RA) at more than two minutes after the time of closest approach of the original trajectories. The percentage of flights with long DAA is provided.

4.4 Results

Figures 2, 3 and 4 show runs for different scenarios of the same encounter. AC1 is climbing with 800 fpm, AC2 is descending with 800 fpm with a relative course of 45 deg w.r.t. AC1, and both aircraft travel at 120 kt. In the figures horizontal views and vertical (altitude – time) views of the trajectories are shown in the left and right plots. Here the original trajectories are shown by saturated (blue and red) colours, while the trajectories modified due to the RP responses to the DAA output is shown by lighter colours. In all scenarios both RPs follow ACAS Xu RWC guidance in two dimensions.

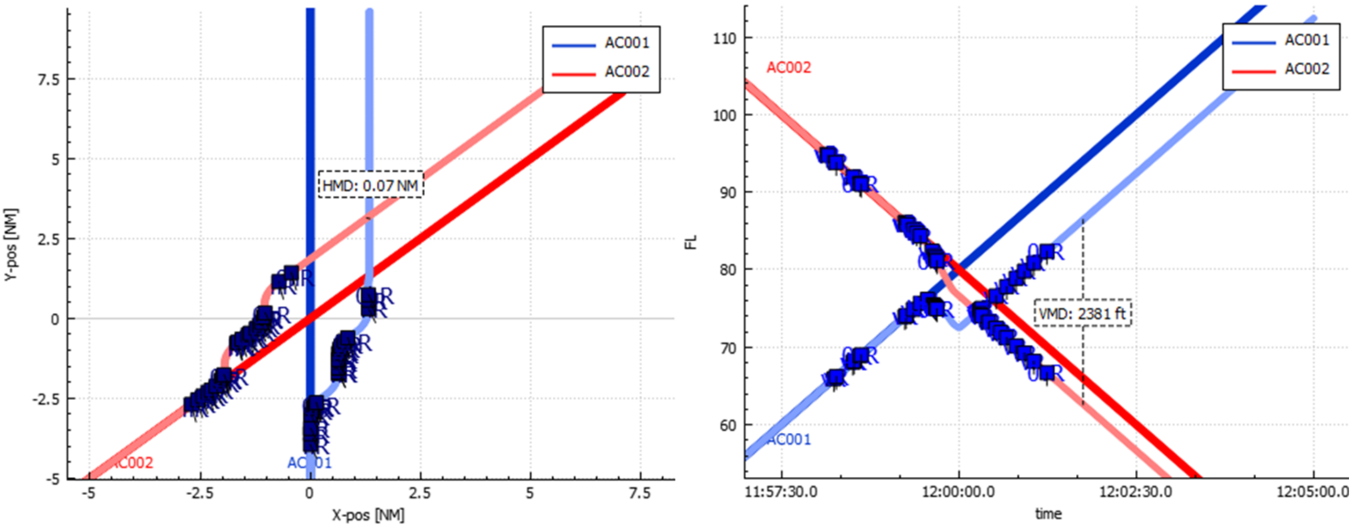

Figure 2. Deterministic simulation of two UASs with RPs following blended ACAS Xu RWC guidance with long delays (including ATC). The symbols on the trajectories represent changes in the RWC guidance.

Figure 2 shows the results for a deterministic simulation for a scenario where the RPs use long response delays (including ATC coordination). The symbols plotted on the trajectories reflect changes in the RWC bands. In this run for AC1 horizontal RWC bands last from -118 s to 33 s, changing 22 times (on average once per 6.9 s); AC2 horizontal RWC bands are from -114 s to 33 s, changing 23 times (once per 6.4 s). The vertical RWC bands for AC1 last from -105 s to 65 s, changing 24 times (once per 7.1 s); AC2 vertical RWC bands are from -111 s to 65 s, changing 27 times (once per 6.5 s). It can be observed that the basic manoeuvring strategy that follows from the RWC guidance in combination with the RP model is to move away from the other aircraft and to return to the original vertical rate or course if allowed by the RWC bands. In this case this leads to some horizontal and vertical fluctuations before the aircraft cross vertically at time 16 s, when the horizontal distance is about 14,000 ft. The CPA is attained later at time 105 s, when VMD is 2381 ft and HMD is 435 ft. There is no LoWC, the additional distance flown is 16,800 ft horizontally and 1,400 ft vertically. The lack of RWC coordination leads to counteracting vertical manoeuvres in the same vertical direction.

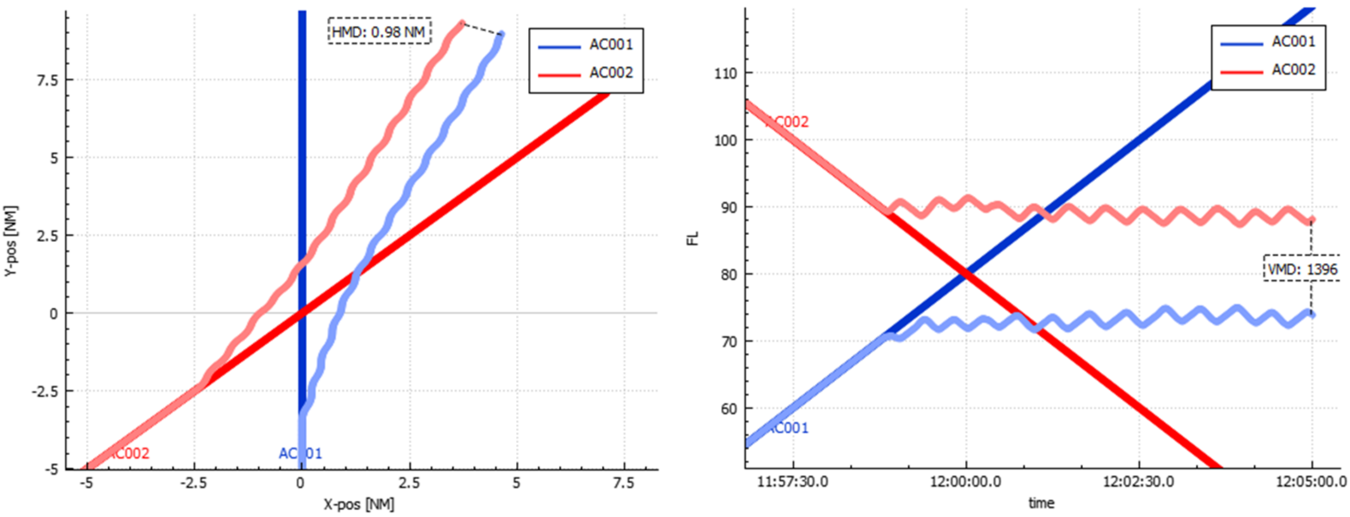

Figure 3. *Deterministic simulation of two UASs with RPs following blended ACAS Xu RWC guidance with short delays (excluding ATC), leading to a livelock condition. For clarity the RWC guidance is not shown.*

Figure 3 shows the trajectories that are obtained by a deterministic simulation of the same encounter and conditions as those of Figure 2, except the response delays of both RPs, which are now without ATC coordination, leading to closed loop delays of mostly 4.5 s instead of 14.5 s. As a result of these smaller delays it can be observed in Figure 3 that the frequencies of the vertical and horizontal fluctuations are increased. The fluctuations lead to a livelock situation during the simulation time, where the vertical distance is about 1,500 ft and where the horizontal distance slowly decreases to about 6,000 ft. The CPA is attained near the end of the simulation. The horizontal RWC bands become active at -118 s and keep changing with an average frequency per aircraft of once per 3.6 s until the end of the simulation. The vertical RWC bands become active at -105 s and keep changing with an average frequency per aircraft of once per 4.1 s. Obviously such continuing horizontal and vertical fluctuations would be operationally unacceptable and they are unlikely to be implemented by human actors, as will be further discussed in Section 5. There is no LoWC, the additional distance is 53,400 ft horizontally and 8,300 ft vertically.

Figure 4 shows the results of a MC simulation run for a scenario including sensor errors and where the RPs use the same short response delays as in Figure 3 (excluding ATC coordination). As a result of the sensor errors there are some differences in the fluctuations in the trajectories of Figure 4 in comparison with those of Figure 3. In this run these sensor errors contributed to breaking through the livelock situation of Figure 3. In particular, the aircraft cross horizontally at the CPA with a VMD of 1596 ft at 157 s after the original TCA. Shortly after, the RWC bands cease to exist and the desired vertical rates and courses are attained. There is no LoWC, the additional distance is 26,500 ft horizontally and 4,900 ft vertically. In the series of ten MC simulation runs for this encounter-scenario the livelock condition was resolved in seven cases, while in the other three cases it remained until the end of the simulation time.

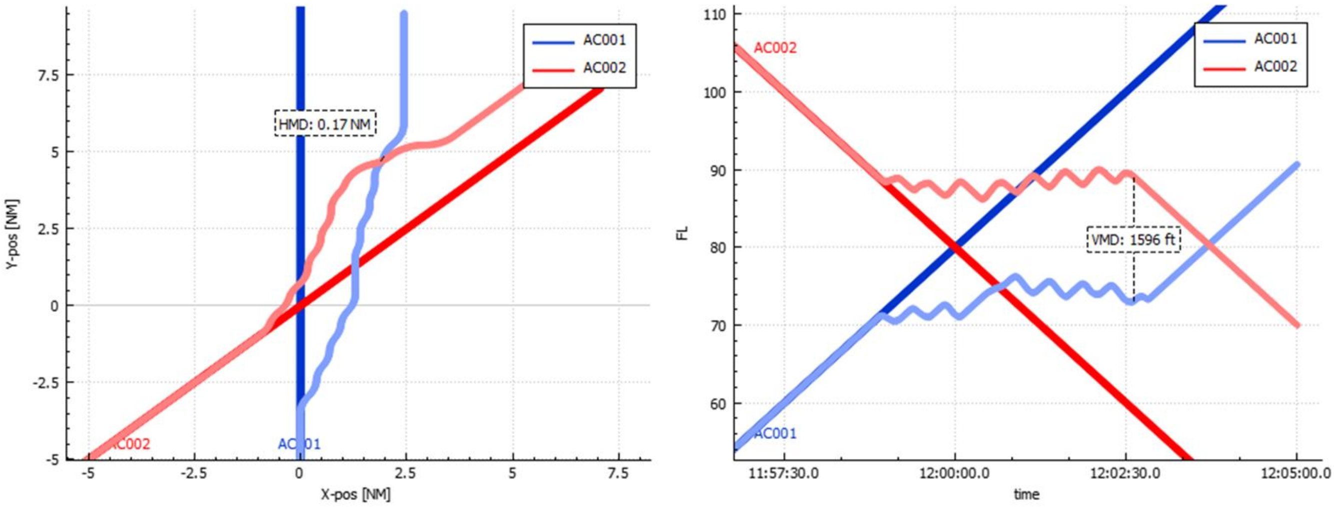

Figure 4. MC simulation run of two UASs including sensor errors with RPs following blended ACAS Xu RWC guidance with short delays (excluding ATC). For clarity the RWC guidance is not shown.

Tables 1 and 2 shows the statistics of the metrics described in Section 4.3 for 15 scenario configurations of deterministic and MC simulations described in Section 4.2. For the deterministic simulations they are based on 72 runs and for the MC simulations they concern 720 runs.

The LoWC percentages illustrate the performance of the RWC functionality for the scenario configurations. The results show that DAA Well Clear (DWC) is mostly achieved if the RPs follow both the vertical and horizontal RWC guidance. If the RWC guidance is only followed in one dimension, it is more effective to do so vertically. Longer response delays due to interaction with ATC lead to considerable increases in the LoWC percentages. If the RPs only respond to RAs (and neglect RWC guidance), then LoWC is attained in the majority of encounters. If the RPs respond to both RWC and CA advisories then a LoWC may be avoided in some cases that led to a LoWC with RWC responses only. Interestingly, comparison of Tables 1 and 2 show that the inclusion of sensor errors in the simulations mostly lead to considerable decreases in the LoWC percentages. So the sensor errors support maintaining DWC in these results.

The minimum value of the NMAC multiplier provides insight in the capability of providing sufficient separation by the various configurations for the encounter set. The deterministic simulations indicate that the smallest values are found for scenarios with only RWC and long (ATC) delays; in all these encounter scenario sets NMACs occurred. In all other scenarios no NMACs occurred, but smaller NMAC multipliers exist if the RP responds to RAs only (and neglects RWC guidance). Larger multipliers are attained if the RPs apply both the RWC and CA functionalities (even with long ATC delays), or in the case of RWC only with short delays. While comparing the minimum NMAC multipliers between Tables 1 and 2 it should be realized that they are the minima over all runs, thus supporting the chance of a low value for the MC simulation results. Nevertheless, the inclusion of sensor errors prevented NMACs for RWC only cases with long delays. The sensor errors contributed to NMACs for scenarios with short delays and horizontal manoeuvring in response to RAs, possibly together with RWC guidance.

The percentages of runs that include one or more RAs are smallest if the RPs respond both to the vertical and horizontal RWC guidance, and they are largest if the RPs respond only to the horizontal RWC guidance. In the case of long response delays (due to ATC interaction) the percentages of cases with RAs are mostly higher. If sensor errors are included (Table 2 versus Table 1), the percentages of RAs are increased if the RPs only respond to horizontal RWC guidance, while they are smaller otherwise.

Table 1. Statistics of deterministic simulation (without sensor errors) for scenario settings

Scenario settings					Statistics					
RWC	*CA*	*Ver.*	*Hor.*	*ATC*	*LoWC (%)*	*Minimum NMAC multiplier*	*Horizontal distance (kft)*	*Vertical distance (kft)*	*RA (%)*	*Long DAA (%)*
•		•	•		2.8	5.34	9.9	2.2	4.2	14.6
•		•			12.5	6.27	0	1.6	16.7	0
•			•		16.7	5.01	20.0	0	25.0	12.5
•		•	•	•	9.7	0.55	13.7	2.4	11.1	10.4
•		•		•	23.6	0.04	0	2.2	20.8	0
•			•	•	27.8	0.45	16.4	0	25.0	8.3
	•	•	•		75.0	4.15	8.2	1.8	100	2.8
	•	•			75.0	5.79	0	2.5	100	0
	•		•		87.5	2.53	18.5	0	100	16.7
•	•	•	•		1.4	5.34	9.9	2.1	4.2	14.6
•	•	•			12.5	6.27	0	1.7	16.7	0
•	•		•		13.9	7.55	19.7	0	25.0	11.8
•	•	•	•	•	8.3	7.10	14.2	2.5	11.1	10.4
•	•	•		•	23.6	7.44	0	2.4	20.8	0
•	•		•	•	27.8	4.55	23.8	0	25.0	16.7

Table 2. Statistics of Monte Carlo simulation (with sensor errors) for scenario settings

Scenario settings					Statistics					
RWC	*CA*	*Ver.*	*Hor.*	*ATC*	*LoWC (%)*	*Minimum NMAC multiplier*	*Horizontal distance (kft)*	*Vertical distance (kft)*	*RA (%)*	*Long DAA (%)*
•		•	•		0.8	5.21	5.4	1.5	2.1	6.5
•		•			4.6	4.71	0	1.3	8.8	0
•			•		13.8	1.21	19.9	0	35.1	11.7
•		•	•	•	4.2	2.49	10.6	2.2	8.3	11.3
•		•		•	13.5	0.08	0	2.0	15.4	0
•			•	•	21.4	1.11	22.2	0	41.7	12.7
	•	•	•		69.4	2.87	7.3	2.0	100	5.9
	•	•			73.9	3.17	0	2.5	100	0
	•		•		89.2	0.43	17.4	0	100	12.3
•	•	•	•		0.8	5.21	5.5	1.5	2.1	6.5
•	•	•			4.6	4.71	0	1.3	8.8	0
•	•		•		11.8	0.27	20.0	0	35.1	11.5
•	•	•	•	•	3.9	5.53	10.6	2.2	8.3	11.6
•	•	•		•	13.6	2.22	0	2.0	15.4	0
•	•		•	•	19.9	2.57	22.6	0	41.7	12.6

The DAA advisories lead to additional distances traversed. The results in Tables 1 and 2 show that horizontally the mean additional distance is about 5,400 to 23,800 ft for the pair of aircraft, while vertically it is about 1,300 to 2,500 ft. So the variation in additional distance is considerably more horizontally than vertically. The additional horizontal distances are largest if the RPs are only manoeuvring horizontally and more modest if they are manoeuvring in both dimensions. The inclusion of sensor errors leads to reduction in the additional horizontal distance if manoeuvring with two degrees of freedom. In contrast the additional vertical distances tend to be smaller if the RPs are only manoeuvring vertically, except if responding to RAs only. Also, the inclusion of sensor errors tends to lead to a reduction in additional vertical distance, except if responding to RAs only.

In a number of cases there can b(Stroeve & Villanueva Cañizares, 2023)e enduring DAA advisories as illustrated in Figures 3 and 4. The statistics in Tables 1 and 2 show that runs with long DAA (more than 2 minutes after original TCA) occur in up to 17% of the cases. Long DAA conditions do not occur if the RPs are only manoeuvring vertically. The type of impact of response delays and sensor errors differs for the various scenario configurations.

5 Discussion

Just as for development and evaluation of ACAS for manned flights, simulation-based studies are essential for the development and evaluation of DAA systems for UASs. Since the tasks of a RP in handling possibly blended RWC guidance and RAs of a DAA are considerably more complex than the tasks of a pilot flying in handling vertical RAs of an ACAS, it is manifest that modelling of RP performance is considerably more involved, and that these modelling choices can have considerable impact on the overall DAA performance.

The developed RP model describes the perception, comprehension and projection/decision for the DAA output, the modes of response, delays, strengths, and flight control actions. In a completely deterministic setting the performance of the RP model is determined by 26 parameters, and with all stochastic elements active it is determined by 40 parameters. By tuning of these parameters large flexibility is attained to study the impact of various modes, delays and decision strategies by RPs. For evaluation of DAA systems suitable values for these parameters need to be set and clearly communicated in validation reports to assure fair comparison between DAA systems.

In the Operational Services and Environment Description (OSED) of (RTCA, 2021) it is stated that the RP shall use the information of the DAA equipment to properly manoeuvre the UA in accordance with ATC clearances and instructions, as well as Right-of-Way (ROW) rules, to remain well clear and avoid creating a collision hazard with other aircraft. ROW rules in §3.2.2 of ICAO Annex 2 (ICAO, 2005) for instance specify that if two aircraft are approaching head-on then they shall turn right, and if two aircraft are converging at approximately the same level then the aircraft having the other on the right shall give way. A quantification of these ROW rules has been developed in Appendix H of (RTCA, 2021). In the modelled encounter scenarios the RP follows the guidance and advisories of the DAA system (given the chosen response modes, delays, strengths, etc.), without consideration of ROW rules or the possible stabilising effect of instructions by a controller who has oversight over the traffic situation. This limitation needs to be considered when interpreting the simulation results of the encounter scenarios. For instance, in a converging encounter between two drones flying at the same level, the implicit coordination by the ROW rules implies that only one of the drones would need to manoeuvre, thus avoiding possible counterproductive mutual manoeuvres. Nevertheless, in many encounters (e.g. one drone climbing versus another descending) the ROW rules do not apply.

The simulation results presented in this paper indicate that the overall DAA performance critically depends on the response delays and the response modes applied by the RPs. It was shown that in encounters between pairs of drones there can be livelock conditions where the aircraft do not manage to effectively pass each other. The term livelock stems from computer science and describes a situation where interacting processes are repeatedly changing their state without finishing their tasks. It was extended to hybrid control systems in (Abate et al., 2009), including the description of a livelock example for collision avoidance manoeuvring of decentralized agents. In our simulations the observed livelock behaviour depends on the overall dynamics of the interacting systems and RPs, including the encounter geometry, the DAA output, the sensor errors, the delays, the RP response, and the return-to-course manoeuvring. Obviously, such livelock conditions and the related back and forth manoeuvres are not operationally acceptable. In real operations these livelocks may be avoided by the traffic overview and tactical decisions of air traffic controllers, and/or more intelligent decision making by the RPs. However, efficient manoeuvring may not always be straightforward, such as illustrated by the "pilot mistakes" observed in the HITL simulations of (Rorie et al., 2020), like poor manoeuvre choice and returning to the route too soon following an avoidance manoeuvre. So when judging the performance of remote pilots in HITL simulations or real operations, the complexity of the encounter scenario should be well understood. Model-based evaluation of encounters scenarios with various settings of the RP performance can support gaining such understanding, such that a nuanced judgement of the options and difficulties of RPs in solving conflicts can be achieved.

There can be large differences between results of deterministic and MC simulations. It was shown that sensor errors can have a large impact on the manoeuvres following RWC guidance, which also depend on the mode and delay of RP responses. The statistics of sets of encounters show considerable differences in various metrics between various scenario configurations. Interestingly and perhaps counterintuitively the results show that the inclusion of sensor errors often led to improvement of the performance, such as lower LoWC percentages and lower additional distance traversed. To well account for the impact of sensor errors and RP performance variability on the nonlinear dynamics of interacting aircraft in an encounter it is essential to apply MC simulation of stochastic models. This was shown to apply for simulation of TCAS II and ACAS Xa in manned aviation encounters (Stroeve, 2023) and it is even more important for the more complex encounters of RPAS with ACAS Xu. If one would just add position deviations following a deterministic simulation of an encounter-scenario, the error-induced variations on the nonlinear dynamics are not captured.

The simulated encounters were relatively simple. They included only two UASs and no other (manned or unmanned) traffic that would need to be avoided. Also they considered only straight original trajectories with limited sets of speeds, excluding more complicated ones with horizontal turns or vertical rate changes. Extensive sets of encounters need to be considered in DAA validation studies. In comparison with encounter sets that have been used for ACAS validation of manned operations, the duration of the encounters needs to be extended considerably to account for the earlier stage RWC guidance and for the possible extension of the conflict after the TCA of the original trajectories due to the DAA advisories/guidance.

In spite of the relatively simple encounter geometries and the deterministic performance of the remote pilots, considerable percentages of loss of DAA well clear conditions were found. It was shown that the LoWC percentages depend on the applied manoeuvring dimensions, response delays and sensor errors, ranging from 1% to 28%. Previously the developers of ACAS Xu showed LoWC for about 10% of the encounters in a large set (Owen et al., 2019). The large LoWC percentages indicate that the current ACAS Xu system (EUROCAE, 2020a, 2020b) does not well respect the DWC requirements of (RTCA, 2021). As explained in Section 1 the optimization of the look-up tables of ACAS Xu was focussed on the CA functionality and next a rollout approach was used for its RWC guidance. The choices made in these processes have led to RWC performance that quite often violates the DWC limits. The variability in the LoWC percentages means that the performance is sensitive for the settings in RP performance and sensor errors. For validation studies it implies that these settings must be well documented for proper comparison between DAA systems. It also means that assumptions on RP performance and/or sensor errors applied in the ACAS Xu development are likely to have profoundly influenced the overall optimization of the alerting logic.

It follows from the simulation results that the manoeuvring following the end of RWC guidance can lead to new RWC guidance and even livelock conditions. In many configurations we found more than 10% of the runs where the DAA advisories lasted for more than two minutes after the TCA of the original trajectories. This type of performance indicates a limitation in the scope of current DAA systems (EUROCAE, 2020a; RTCA, 2021). They only provide guidance on how to avoid other traffic, but that they do not provide guidance on how to regain the route to the desired destination without inducing new conflicts. This limitation of current DAA systems has also been recognized in (Wang et al., 2021). For returning to mission the DAA system would need to know the planned route (intent) of the ownship. Preferably also the intent of the intruder would be available, such that a coordinated advice can be provided to remain well clear enduringly.

The found problematic cases also indicate that intelligent contributions of RPs and air traffic controllers are essential for effectively dealing with RWC guidance of current DAA systems. Automatic responses strictly following the ACAS Xu RWC guidance could lead to the types of livelock conditions shown in this paper.

In conclusion, we showed that models of RP behaviour for responses to ACAS Xu RWC guidance critically affect the manoeuvres and safety performance in encounters of interacting UASs. Follow-up research and development is needed to understand in more detail such critical conditions and how to avoid them.

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Conflict Of Interest

There are no conflicts of interest.

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