Remote pilot modelling for evaluation of ACAS Xu

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***Abstract*—A remote pilot (RP) model is developed for evaluation of unmanned aircraft (UA) manoeuvring in response to remain well clear guidance and resolution advisories by the ACAS Xu detect-and-avoid system. The model describes RP situation awareness, decisions, response modes, delays, strengths and flight control in deterministic and stochastic settings. It is integrated in a simulation environment that describes sets of aircraft and their sensing systems. Simulation results illustrate the impact and complexity of UA manoeuvring by RPs for ACAS Xu advices.**

Keywords - Remote pilot; detect-and-avoid; ACAS Xu; validation

I. 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 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 [1]. 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 [2, 3]. 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 trackers and inter-source correlation [2, 4]. 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 was separated, since the combined problem was considered intractable to solve due to its large (discretized) state space. 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 [5], 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 [6] or ACAS Xa [7] 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 [3]. 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 [1]. 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. The following handling of RWC guidance is foreseen (Figure A-22 of [1]). 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. If ATC takes too long to respond, the RP may initiate the deviation without clearance.

It follows from above that the complexity 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 (blended), and it specifies blended 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.

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 [8]. 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 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. These simulations typically build on Bayesian network encounter models [9, 10] for safety and radar data for operational suitability, and assume a pilot response using the ICAO standard pilot response model [11] (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. Similar to such studies for TCAS II and ACAS Xa, evaluation of ACAS Xu system performance has been achieved by simulation of model-based and radar encounters [2]. In [2] 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 model has a large impact on the evaluation of the effectiveness of ACAS Xu. Validations should show robust performance with a range of RWC models and parameters.

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 illustrate the impact of RP performance on the interrelated trajectories of UAS pairs. Section II concisely presents RP models in the literature and our simulation environment. Section III presents the development of the RP model. Section IV provides some illustrative simulation results for ACAS Xu. Section V discusses the findings and their implications.

II. CONTEXT

A. *Remote pilot models in the literature*

In support of Monte Carlo (MC) simulation of encounters involving unmanned aircraft, Guendel et al. [12] 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 [13], which is a reference system of the DAA MOPS [1]. 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 [14] deterministic, rule-based models have been 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.

B. *CAVEAT agent-based modeling and simulation*

The developed RP model is part of an agent-based model for evaluation of ACAS in encounter-scenarios [15, 16] by simulation in the Collision Avoidance Validation and Evaluation Tool (CAVEAT). CAVEAT is a successor of the InCAS tool of EUROCONTROL, including TCAS II and ACAS X systems and providing 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. Aircraft use transponders (mode S, mode C) for coordination, ADS-B data sharing and measurement of the range and bearing with respect to otherships that are equipped with a suitable transponder. Unmanned aircraft may also have an ATAR to estimate the relative position and speed of an othership without transponder. All models of ownship state estimation and othership measurement include sensor error models, describing biases and/or jitter components by stochastic processes [15, 16]. A manned aircraft may be equipped with TCAS II [6] or ACAS Xa [7], while an unmanned aircraft may be equipped with ACAS Xu [4]. The ACAS algorithms are in agreement with the associated 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 [15, 16]. 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).

III. REMOTE PILOT MODEL FOR ACAS XU EVALUATION

A. Introduction

The RP model has been developed such that it can be applied in deterministic as well as in MC simulation runs of CAVEAT. The basis of RP performance is the situation awareness, which is updated for new information as explained in Section B. Response modes describes whether the RP responds to particular types of DAA output (Section C). Delays and strength in RP responses are modelled in Sections D and E, respectively. Flight control actions implemented by the RP based on above elements are explained in Section F. An associated model for the UA control station, specifying additional closed loop delay components, is presented in Section G.

B. 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.

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.

C. 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. 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, which determine constant response modes in a MC simulation run.

D. Remote pilot response delay

In line with the ICAO standard pilot response model for ACAS RAs in manned aviation [11], DAA standards [3] and other RP models [12, 14], 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 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.

E. 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. In a stochastic setting, the variables are chosen once between a minimum and maximum using uniform distributions.

F. 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 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 B) 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.

G. Unmanned aircraft control station

The UA control station is a remote facility that houses RP control for the UAS. The DAA MOPS [1] 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, or they can be chosen from uniform distributions; they do not change during a run of an encounter-scenario. These latencies add to the RP response delays explained in Section D, thus enlarging the overall closed loop delay impacting the flight control (Section F).

IV. ILLUSTRATIVE SIMULATION RESULTS

A. Encounters

A set of 36 encounters with following characteristics is used:

- All encounters consider two UASs with a VMD and HMD of 0 ft at FL80.
- 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 $t=0$.
- The speed of both aircraft is 80 kt (no wind).
- The relative course of AC2 with respect to AC1 is 45, 90, 135, or 180 deg.
- The vertical rates of AC1 are -800, 0, or 600 fpm, while those of AC2 are -700, 0, or 500 fpm (9 combinations).

B. Scenario configurations

Simulations were performed for the following scenario configurations:

- Both UASs are equipped with ACAS Xu [4], 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 othership measurement processes following sensor error models documented in [16] (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 36 encounters were simulated once per scenario configuration, while in the scenarios with sensor errors they were simulated using 10 MC simulation runs each.

C. Metrics

Statistics of the following metrics were evaluated over sets of 36 runs per scenario configuration for the deterministic simulations and for sets of 360 runs per scenario configuration for the MC simulations.

- *NMAC multiplier.* In ACAS validation studies traditionally near mid-air collision (NMAC) events are considered 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 average and the minimum of the NMAC multiplier over the sets of runs are provided.
- *Time of closest approach (TCA).* The average and standard deviation of TCA are provided. These indicate the drift and variability from the TCA at *t=0* in the original encounters due to the DAA advisories/guidance.
- *RA percentage.* The percentage of runs where there was at least one RA is provided.

D. Results

Figures 1, 2 and 3 show runs for different scenarios of the same encounter. AC1 is climbing with 600 fpm, AC2 is descending with 700 fpm with a relative course of 45 deg w.r.t. AC1, and both aircraft travel at 80 kt. In the figures horizontal views (left) and vertical views (right) of the trajectories are shown. Here the original trajectories are shown by saturated (blue and red) colours, while the trajectories modified due to the DAA output is shown by lighter colours. In all scenarios both RPs follow ACAS Xu RWC guidance in two dimensions.

Figure 1 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 start at time -125 s, end at 49 s, and they change 44 times (on average once per 4.0 s); AC2 horizontal RWC bands are from -125 s to 49 s, changing 32 times (once per 5.4 s). The vertical RWC bands for AC1 last from -112 s to 147 s and they change 33 times (once per 7.8 s); AC2 vertical RWC bands are from -118 s to 151 s, changing 32 times (once per 8.4 s). However, not all these changes in RWC bands require a change in altitude or course. 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 50 s, when the horizontal distance is about 8000 ft. The CPA is attained later at time 163 s, when VMD is 2394 ft and HMD is 558 ft.

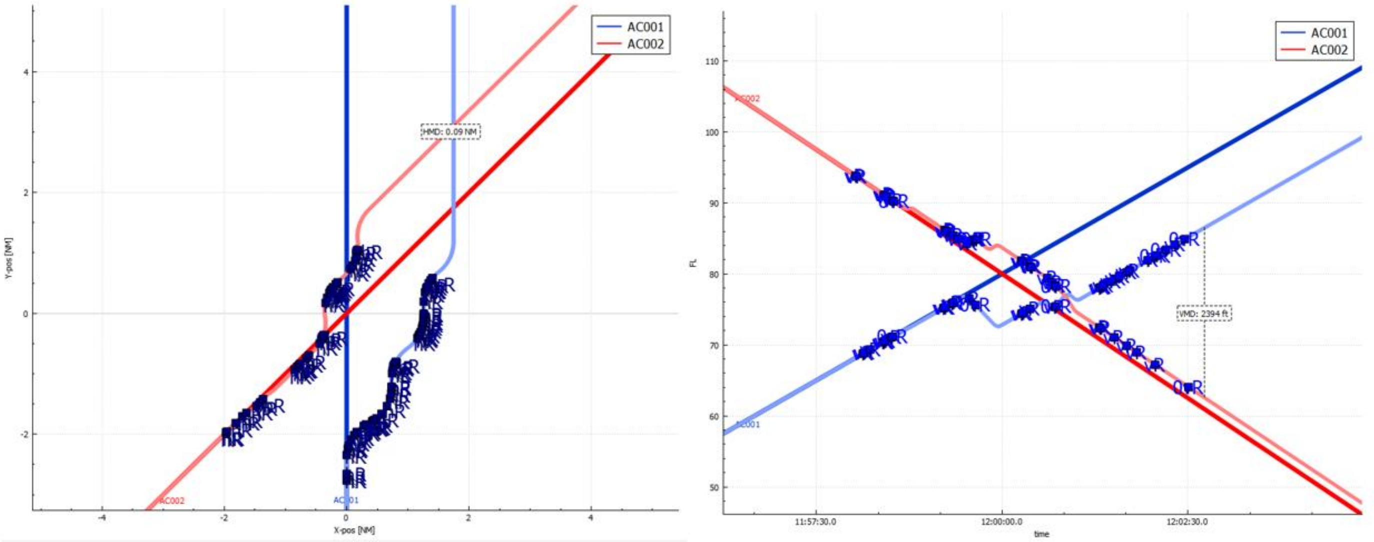

Figure 1. Deterministic simulation of two UASs with RPs following blended ACAS Xu RWC guidance with long delays (including ATC). The symbols on the trajectories represent changes in the RWC guidance. VMD is 2393 ft and HMD is 558 ft at time 12:02:43.

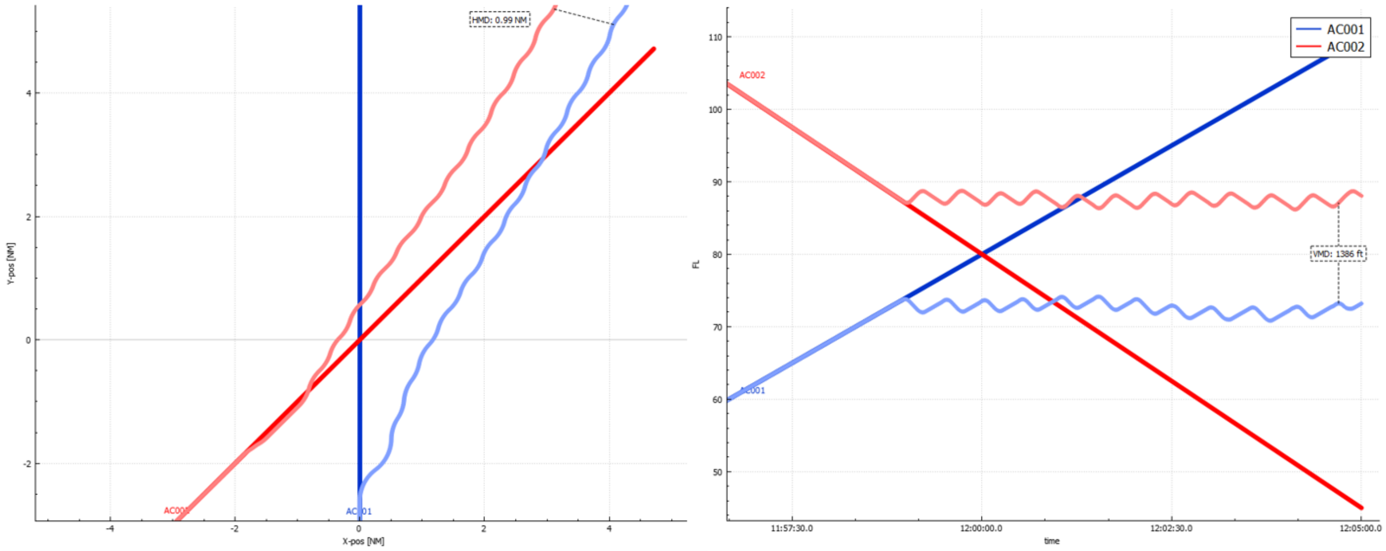

Figure 2. Deterministic simulation of two UASs with RPs following blended ACAS Xu RWC guidance with short delays (excluding ATC), leading to a deadlock condition. For clarity the RWC guidance is not shown. VMD is 1386 ft and HMD is 6011 at time 12:04:42.

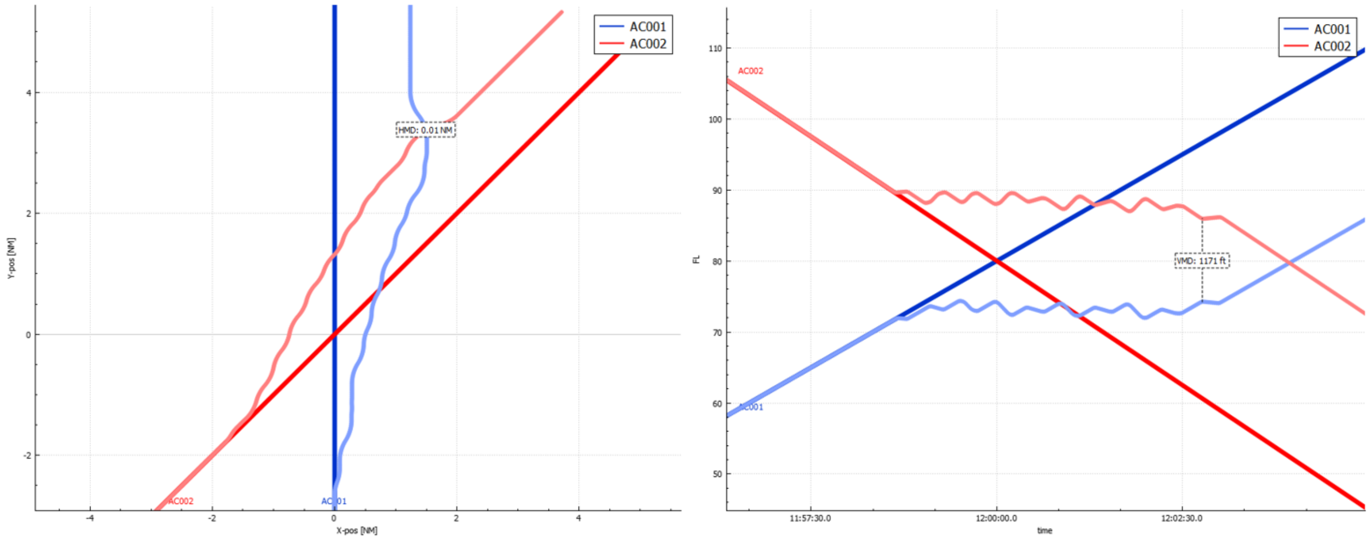

Figure 3. MC simulation run of two UASs including sensor errors with RPs following blended ACAS Xu RWC guidance with short delays (excluding ATC). For clarity the RWC guidance is not shown. VMD is 1171 ft and HMD is 79 ft at time 12:02:46.

Figure 2 shows the trajectories that are obtained by a deterministic simulation of the same encounter and conditions as those of Figure 1, 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 result of these smaller delays it can be observed in Figure 2 that the frequencies of the vertical and horizontal fluctuations are increased. This leads to a deadlock situation during the simulation time, where the vertical distance is about 1500 ft and where the horizontal distance slowly decreases from about 9000 to 6000 ft. The CPA is attained near the end of the simulation. The horizontal RWC bands become active at about -125 s and keep changing with an average frequency of one per 3.8 s until the end of the simulation. The vertical RWC bands become active at -118 s and keep changing with an average frequency of one per 6.1 s.

Figure 3 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 2 (excluding ATC coordination). As a result of the sensor errors there are some differences in the fluctuations in the trajectories of Figure 3 in comparison with those of Figure 2. In this run these sensor errors contributed to breaking through the deadlock situation of Figure 2. In particular, the aircraft cross horizontally at the CPA with a VMD of 1171 ft at 166 s after the original TCA. Shortly after this the RWC bands cease to exist and the desired vertical rates and courses are attained. In the series of ten MC simulation runs for this encounter-scenario the deadlock condition was resolved in three cases, while in the other seven cases it remained until the end of the simulation time.

TABLE I. STATISTICS OF DETERMINISTIC AND MONTE CARLO SIMULATIONS FOR VARIOUS SCENARIO CONFIGURATIONS

Scenario settings					**Deterministic simulation**					**MC simulation (sensor errors)**				
RWC	***CA***	***Ver.***	***Hor.***	***ATC***	***NMAC multiplier***		***TCA (s)***		***RA (%)***	***NMAC multiplier***		***TCA (s)***		***RA (%)***
					Av.	***Min.***	***Av.***	***Std.***		***Av.***	***Min.***	***Av.***	***Std.***	
●		●	●		10.2	7.5	59	95	0.0	9.8	4.6	33	61	1.4
●		●			8.5	6.0	0	2	11.1	8.8	4.7	0	1	1.9
●			●		11.1	5.9	90	100	0.0	12.1	2.8	93	95	15.6
●		●	●	●	12.7	2.6	66	92	8.3	11.7	5.7	53	80	5.0
●		●		●	8.7	1.0	0	1	19.4	9.9	0.6	0	1	7.2
●			●	●	12.8	1.2	74	77	27.8	13.5	2.3	79	86	26.4
	●	●	●		8.0	3.8	20	37	100.0	8.2	2.8	14	30	100.0
	●	●			7.3	3.8	-2	2	100.0	7.4	2.8	-2	2	100.0
	●		●		8.6	2.5	32	66	100.0	8.4	0.8	30	73	100.0
●	●	●	●		10.2	7.5	59	95	0.0	9.8	4.6	33	62	1.4
●	●	●			8.5	6.0	0	2	11.1	8.8	4.7	0	1	1.9
●	●		●		11.1	5.9	90	100	0.0	12.1	2.8	93	95	15.6
●	●	●	●	●	13.1	6.5	64	93	8.3	11.7	5.7	52	78	5.0
●	●	●		●	9.3	5.0	0	1	19.4	10.0	6.0	0	1	7.2
●	●		●	●	13.6	7.0	72	79	27.8	13.8	3.6	79	88	26.4

Table I shows the statistics of the metrics described in Section C for 15 scenario configurations of deterministic and MC simulations described in Section B. For the deterministic simulations they are based on 36 runs (like those in Figures 1 and 2) and for the MC simulations they concern 360 runs (like Figure 3). Many comparisons of different configurations can be made and next we will highlight some most interesting ones.

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. Also small values are present if the RPs only use the CA functionality. Larger distances 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 (without ATC). Similar results can be observed in the MC simulations, although the minimum NMAC multipliers tend to be smaller, which is supported by the larger number of runs.

In the scenarios where the RPs apply horizontal manoeuvring in response to the DAA output, large values of the average and standard deviation of the TCA are found. They imply that there are large time shifts from the time of CPA (t=0) of the original trajectories and that there are large variations between runs. These TCA shifts are representative of the kinds of behaviour shown in Figures 2 and 3, where there are deadlock conditions, which may be resolved after a prolonged time or not at all. The TCA shifts tend to be smaller if the RPs only use the CA functionality, as a result of the smaller time before CPA when RAs are provided.

There are striking differences between the percentages of runs with RAs for various scenarios. In deterministic simulations with small delays (no ATC) there are no RAs if horizontal manoeuvring is used, while there are RAs in 11.1% of the encounters if only vertical manoeuvring is used. Inspection of these latter cases makes clear that they concern situations where the aircraft remain at the same altitude, and where the vertical RAs are coordinated means to resolve such remaining co-altitude. It can be observed in the MC simulation results for the same scenario the number of RAs is reduced to 1.9%. In this case the sensor errors are a means to resolve remaining co-altitude, since they lead to differences in vertical RWC guidance of the two aircraft. Inspection of the deterministic simulations with only horizontal manoeuvring and small delays reveals that the aircraft either manage to pass each other or they enter in a deadlock condition where the distance remains sufficient to not trigger an RA. Inclusion of sensor errors in these cases can lead to large differences in the horizontal trajectories between runs, which trigger RAs in 15.6% of the cases. In scenarios with long delays (with ATC) the RWC guidance is less effective, leading to larger percentages of runs with RAs.

V. 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 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 involves much more aspects, 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.

The simulation results shown 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 there can be deadlock conditions where the aircraft do not manage to effectively pass each other. Such 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 deadlock conditions and the related back and forth manoeuvres are not operationally acceptable. In real operations these deadlocks may be avoided by the traffic overview and tactical decisions of air traffic controllers, and/or more intelligent decision making by the RPs. However this may not always be straightforward to achieve, such as illustrated by the “pilot mistakes” observed in the HITL simulations of [8], like poor manoeuvre choice and returning to the route too soon following an avoidance manoeuvre.

There can be large differences between results of deterministic and MC simulations. It was shown that (limited) sensor errors can have a large impact on the manoeuvres following RWC guidance. Different RP response delays lead to different results. This implies that 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.

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, 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.

It follows from the simulation results that the manoeuvring following the end of RWC guidance can lead to new RWC guidance and even deadlock conditions. This indicates that it is a limitation of current DAA systems [1, 3] that 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. To do so effectively the DAA system would need to know the planned route of the ownship and preferably also of the othership, 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. Automatic responses strictly following the ACAS Xu RWC guidance could lead to the types of deadlock conditions shown in this paper.

In conclusion, we showed that the manoeuvring of interacting UASs by RPs in response to ACAS Xu RWC guidance and RAs is critically dependent on assumed RP performance. Follow-up research and development is needed to understand in more detail such critical conditions and how to avoid them.

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