Fast Time and Real Time Validation of a Remain Well Clear Function for Airspace Classes D to G

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***Abstract*—A relevant step in the full seamless integration of Remotely Piloted Aircraft Systems (RPAS) in unsegregated airspace is the development of a Detect-And-Avoid (DAA) system that supports their insertion in airspace classes D to G, where the interaction of RPAS with aircraft flying Visual Flight Rules, possibly not transponder equipped, poses major challenges. These challenges mainly arise from the need to assure a level of safety, specifically against the risk of Mid-Air Collision events, as high as that currently characterising manned civil and commercial aviation. While a DAA system last resort is represented by the Collision Avoidance component, the Remain-Well-Clear (RWC) component acts as a Decision Support System to assist the Remote Pilot in preventing collision hazards. This paper discusses the results of fast-time and real-time simulations performed to validate a prototype RWC system for RPAS integration in European airspace classes D to G. The RWC functional and operational context was defined. Fast-time simulations were used to tune RWC system parameters such as the quantification of the well-clear volume and the time-to-alert. Real-time simulations evaluated how acceptable RWC functionality was for remote pilots and air traffic controllers. Future research activities are also proposed.**

Keywords-detect and avoid; remain well clear; remotely piloted aircraft systems; fast-time simulations; real-time simulations, human performance.

I. Introduction

There is a general consensus among experts in the field of air transport that we will see a growth in the use of certified remotely piloted aircraft systems (RPAS) for civil and commercial purposes, from monitoring and surveillance to autonomous cargo delivery servicing remote and isolated regions [1],[2]. Safety of these operations will be a critical issue as increasing numbers of unmanned vehicles enter civilian airspace. In this context, a Detect and Avoid (DAA) system represents an enabling technology to guarantee an equivalent level of safety with respect to manned aircraft. DAA systems support Remote Pilots (RP) in becoming aware of, and resolving, potential conflicts by means of a Remain Well Clear (RWC) function that operates in the long-to-midterm and a Collision Avoidance (CA) function that operates in the short term as last resort in case the RWC function fails. The most challenging environments for the design of the DAA system are operations in Class D-G airspaces. Those airspaces refer to low altitude layers below 18,000 feet, in which small and medium-sized aircraft typically fly under Instrument Flight Rules (IFR) and Visual Flight Rules (VFR). Table I gives an overview of services and responsibilities in the airspace classes discussed. Air Traffic Controllers (ATCo) in airspace classes D and E guarantee separation provision only with respect to IFR aircraft giving just air traffic information (TFCI) in the case of aircraft flying under VFR. In airspace class G, no separation provision is given by Air Traffic Control (ATC) which only gives flight information (FIS), as reported in Table I [3]. In such airspace classes, aircraft might not be equipped with transponders of any kind, so that they are only visible to the RPAS through active traffic sensors like radar, which in turn are limited in their range and field of view, and not even visible to the ATCo.

In this context the present paper proposes a RWC function for unmanned air vehicles, of any class and type, flying under IFR into European airspace classes from D to G. Results of Fast-Time (FT) and Real-Time (RT) simulation campaigns are described. The work has been carried out in the framework of the URClearED exploratory research project [4], co-founded by the Single European Sky Air traffic management Research (SESAR) Joint Undertaking under the European Union's Horizon 2020 research and innovation program.

TABLE I. AIRSPACE AND AIR TRAFFIC SERVICES

Airspace Class	**D**		**E**		**G**	
Flight Rules	IFR	VFR	IFR	VFR	IFR	VFR
Permitted	Yes	Yes	Yes	Yes	Yes	Yes
ATC Clearance	Yes	Yes	Yes	No	No	No
ATC Separation Service	Yes, only IFR-IFR	No	Yes, only IFR-IFR	No	No	No
ATC Information	TFCI w.r.t. VFR	TFCI	TFCI w.r.t. VFR when possible	TFCI when possi ble	FIS if requested	

The notion "Well-Clear" is used in International Civil Aviation Organisation (ICAO) Annex 2 [5] but without specifying any minimum separation distance. This leaves room for the manned aviation pilot to judge safe separation distances when no ATCo support is provided. With the RPAS lacking a pilot on board, a proper mathematical definition of RWC is needed in order to operate safely.

In this field various international research projects have addressed and are still working on the quantitative definition and implementation of a RWC function. In the U.S.A., RTCA has been developing the Minimum Operational Performance Standards (MOPS) for DAA systems used in unmanned aircraft transiting and performing extended operations in Class D, E, and G airspace along with transiting Class B and C airspace [6]. Here a quantitative definition of the Well-Clear Volume (WCV) (i.e. a temporal and/or spatial boundary around the aircraft intended to be an electronic means of avoiding conflicting traffic) and the RWC function is given. In Europe EUROCAE has issued an Operational Services and Environmental Definition (OSED) document [7] providing a basis for assessing and establishing operational, safety, performance, and interoperability requirements for the DAA RWC and CA functions in class D–G airspaces for RPAS. A past European project such as MIDCAS [8] and on-going projects such as SESAR PJ13-Sol. 111 [9] and EUDAAS [10] are working on the RWC definition first for airspace classes from A to C and then in all airspace classes.

Taking advantage of the results available from the European projects previously described and the issued standards, the current paper focuses on the:

- Analysis of quantifying the WCV independently from airspace classes.
- Definition of the alerting times of the RWC function to avoid Loss of Well-Clear (LoWC) without interfering with the ATCo separation provisions and allowing interoperability with ACAS (e.g. TCAS-II [11]) equipped intruders.
- Validation of the proposed solution through FT simulations with a European Encounter Model and RT simulations with hardware (HW) and human in-the-loop.

The following sections describe: II) the operational concept of the proposed RWC function; III) objectives for the validation of the RWC function; IV) FT results for the definition of the WCV and RWC alerting time; V) RT results analysing human performance and VI) Conclusions on the overall concept and needs for future research.

II. OPERATIONAL CONCEPT

The proposed solution aims to support the integration of RPAS in airspace classes D-G by designing and assessing a DAA-RWC concept for unmanned aircraft flying under IFR. Several elements characterise the operational context in which the solution shall operate, as depicted in Figure 1.

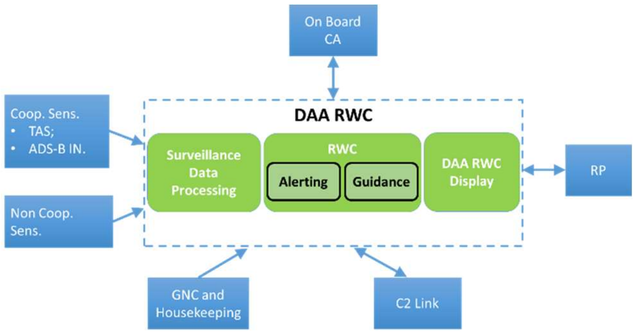

Figure 1- RWC operational context.

The DAA RWC system, including the RWC Alerting and Guidance functions, the Surveillance Data Processing function and the DAA RWC Human-Machine Interface (HMI), exchange data with several other systems. A suite of both cooperative and non-cooperative sensors supplies air traffic measurements, the Guidance Navigation and Control (GNC) system provides Remotely Piloted Aircraft (RPA) navigation measures and vehicle status, while the Command and Control Link (C2L) connects the RPAS airborne segment to the control station on the ground in order to exchange traffic information and DAA data.

In the proposed context we suppose that the RP is aware through other means of the airspace class, weather conditions and forbidden areas in which the RPA is flying. This increases their situational awareness improving the selection of a permissible RWC guidance manoeuvre to execute.

The Surveillance Data Processing function mainly elaborates the on-board air traffic sensor inputs as detailed in [12]. It generates a consolidated set of tracks that are an input to the RWC alerting and guidance functionalities supporting the RP in avoiding the violation of the WCV.

The alerting functionality determines whether an intruder poses enough risk to warrant an alert and which alert priority is appropriate. Specifically, the alerting function determines the RPA and intruders' measured states in order to issue the following alerts ([7],[12]):

- The *Advisory alert*, indicating when a change in current heading/track or altitude by the RPA may immediately trigger a caution alert (cyan intruder in Figure 2). The RP response to an advisory level alert is to monitor the designated traffic, by assessing the overall situation of the encounter, and being aware of the risk of inducing a loss of well clear situation, due to possible future manoeuvres or mission constraints. Contacting ATC in response to an advisory alert shall be avoided.
- The *Caution alert*, indicating a predicted or current loss of well clear situation (yellow intruder in Figure 2). This alert aims to attract the attention of the RP for determining whether a remain or regain well-clear manoeuvre is needed. The alert necessitates immediate awareness of the RP and subsequent actions.

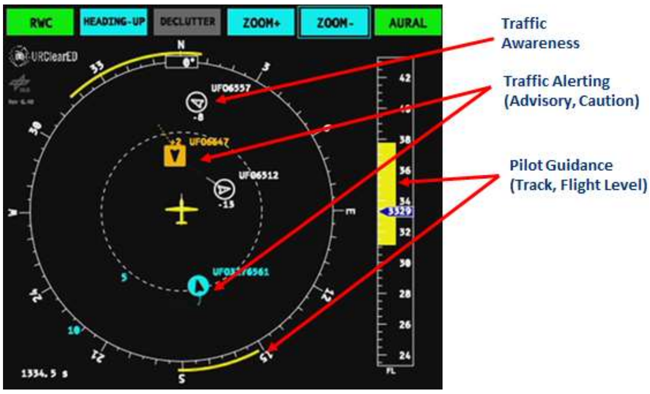

Figure 2. CDTI showing the RWC alerting and guidance indications for the remote pilot.

The guidance functionality computes indications to support RP decisions in the resolution of a potential conflict. For each consolidated traffic track, recognised as a threat by the RWC alerting functionality, the guidance function computes the range of RPA manoeuvres for track/heading angle and altitude that would result in an estimated loss of well clear (LoWC) within a given look ahead time, the so-called conflict bands (see Figure 2). The guidance indications are generated considering the RPA nominal performance.

Alerting indications, conflict bands, detected surrounding air traffic and overall state of the RWC functionality are displayed on the HMI called a Cockpit Display of Traffic Information (CDTI). Its implementation, shown in Figure 2, is based on a standard navigation display as detailed in [13] and [12].

III. VALIDATION OBJECTIVES

The proposed DAA RWC system has been validated by means of FT and RT HW and human in the loop simulations.

The first set of FT simulations defined the well-clear volume taking advantage of European and US standards ([6],[7]) and using results of past international projects ([8]-[10]). The RT simulations focused on the analysis of Human Performance (HP) and interaction between the RP, ATCo and intruder pilot in the resolution of potential conflicts.

The following objectives were defined for the assessment of the RWC function in both FT and RT simulations:

- *RWC nominal performance* to verify that the RWC system provides the RP with alert and guidance indications well in advance with respect to the violation of the WCV, while also minimising the rate of nuisance alerts for different builds of RPAS configurations, including fixed and rotary-wing tactical and MALE RPAS. This had to be verified in encounters with both cooperative and non-cooperative intruders, up to two simultaneously.
- *Collision Avoidance interoperability* to verify that the output of the RWC systems, both in terms of alerts and guidance indications, are well in advance with respect to those provided by the CA function and in general, are not contradictory to them.
- *ACAS Interoperability* to verify that the RWC system provides the RP with Alert and Guidance indications well in advance with respect to the violation of the WCV by also assuring that the guidance indications are not in conflict with the collision avoidance coordination message provided by the intruder (e.g. resolution advisory of TCAS-II [11]).
- *Separation Interoperability* to assess the interoperability of the proposed RWC function with the separation provision function implemented by ATC in airspace classes D-E. The RWC alerts and indications should not overlap with instructions provided by the ATCo.
- *See and Avoid Interoperability* to assess the interoperability of the proposed RWC function with the see and avoid function implemented by manned intruders, especially with those non-equipped with ACAS systems and flying under VFR rules.

IV. FAST-TIME SIMULATION RESULTS

In the FT simulations the first set of analyses was focused on evaluating the WCVs and related caution alerting time thresholds in uniformly distributed encounters with both RPA and intruder performing straight trajectories. This analysis was used for selecting the key parameters of the RWC function to be used in the RT simulation (RTS) campaigns.

The second set of analyses was performed using the EUROCONTROL Collision Avoidance Fast-time Evaluator (CAFE) Revised Encounter Model for Europe (CREME) [14] with an appropriate selection of representative encounters for airspace classes D to E. CRÈME was adapted for RPAS by re-using closest miss distances of real European piloted aircraft encounters and combining them with trajectories generated outwards (backwards and forwards) from closest point of approach based on realistic RPAS performance models from Eurocontrol's BADA (Base of aircraft data). In this case the involved vehicles have variable (not straight) trajectories, and the encounters can be characterised by their probability of occurrence.

In both sets of analyses, only pair-wise encounters were considered and analysis was based on open-loop simulation of the corresponding encounters; that is, neither RPA nor intruder performed a manoeuvre to avoid the LoWC (at least not because of the RWC indications). Sensor errors were not considered.

A. *RWC Volume Definition*

Starting from reference works ([6],[9]) and considering particularities of the European operational scenario for airspace classes D to G, the WCV was quantified. The time criteria and related thresholds for generating the Caution Alert were taken into account.

The previous objectives were translated into the following quantified parameters as shown in Figure 3:

- *Horizontal Spatial Threshold* (HST), the horizontal protected distance.
- *Horizontal Temporal Threshold* (HTT), a threshold of τ_{mod} the modified time to closest point of approach (CPA) [6].
- *Vertical Spatial Threshold* (VST), the vertical protected distance.
- *Caution Alert Time* (CAT) is the time threshold for issuing the Caution Alert of RWC, and is defined as the time interval needed for the aircraft to violate the above defined thresholds.

The previous parameters were assessed by means of Monte Carlo simulations of uniformly distributed encounters, evaluating the following criteria:

- Time difference between the Caution Alert Time and the RWC last possible manoeuvre (i.e. the event for which horizontal and vertical manoeuvres would no longer avoid LoWC) greater than the latency of the RP/ATCo interaction and C2L;
- Time difference between the RWC last manoeuvre and TCAS-II resolution advisory alert greater than zero;
- Range of Caution alert below the surveillance sensor ranges;
- Time at Caution alert below the ATCo acceptable time for cooperative intruders in order to avoid overlapping between RWC and ATCo separation provision;
- Range of Caution alert below the visual range of non-cooperative intruders in order to allow an intruder that has only Visual Based Separation to see the own RPA

It is worth noting that, because the RWC software is aware of which type of transponder is installed onboard the intruder (Non-Cooperative, Cooperative without Airborne Collision Avoidance System (ACAS) and Cooperative with ACAS) and its altitude (below or above FL100), six sets of the above parameters have been found by the analysis. Two classes of vehicles for the RPA were considered. One with relatively low manoeuvring performance (i.e. Fixed Wing Tactical, TUAV, or Rotary, RUAV, unmanned vehicle) and a second one with higher manoeuvrability (i.e. Medium Altitude Long Endurance, MALE, unmanned vehicle).

In [12] are reported the tables summarizing the RWC parameters resulting from the performed analysis for both TUAV and MALE RPA.

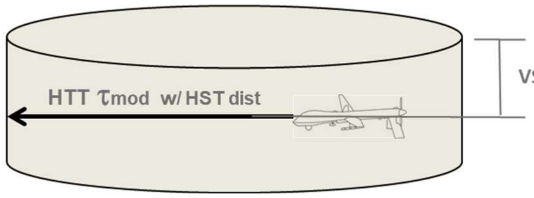

Figure 3. Well-Clear Volume Definition.

B. *Fast-Time Simulation Assessment of Validation Objectives*

The assessment of the validation objectives through FT simulations followed a specific analysis strategy. First, encounters were classified according to two main factors: the equipment of the intruder (i.e. ACAS equipped, cooperative non-ACAS equipped and non-cooperative) and the type of airspace in which the encounter occurred (i.e. below 10.000 ft and RPA speed below 100 kts and at any altitude for RPA speeds above 100 kts). Then a subset of CREME encounters were extracted fitting the given classification. Such a subset was used to execute open-loop simulations (i.e. neither RPA nor intruder manoeuvre to avoid the conflict) to evaluate the proposed solution comparing it also with other RWC selected volumes depicted in Figure 4.

Concerning the *RWC Nominal Performance* objective related to allowing the pilot enough time to perform the RWC manoeuvre, the FT simulation highlighted an average time of 40s and a minimum of 25-30s for slow manoeuvring vehicles (TUAV) and longer time allowance (average of 55s and minimum of 40s) for a larger vehicle with higher manoeuvre capability. The only exception is related to the minimum time obtained for encounters with cooperative ACAS-equipped aircraft above 10.000 ft that could be too short (14s), for which may be a higher Caution Alert time threshold would be needed. However, average and minimum times to manoeuvre from Caution Alerts are all well above the minimum time of 20s to manoeuvre from an alert, as provided by previous studies [15]. Therefore, this analysis confirms that the RWC defined setting gives enough time for the RP to react and perform the manoeuvre even when interacting with the ATCo. Advisory Alerts have been demonstrated to be a relevant addition to the RWC function. Two advantages have been identified. Firstly, they provide excellent situational awareness to detect close proximity intruders very close to becoming Caution Alerts. A significant proportion of those encounters have been identified. Secondly, they complement the Caution function for late alerts, providing early awareness of the incoming conflict.

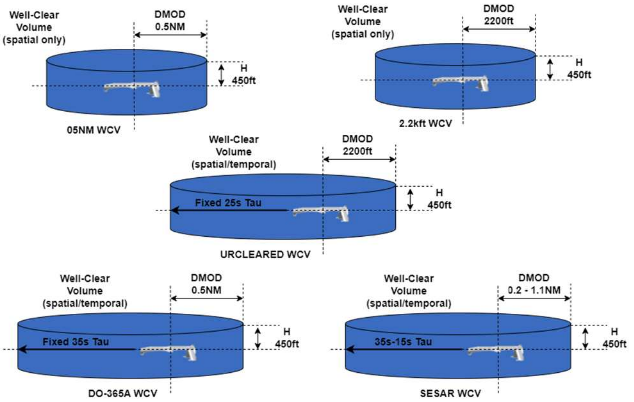

Figure 4. Selected Well-Clear Volume employed during the fast-time simulation.

Collision Avoidance interoperability cannot be performed correctly as no definition for such a function exists at this point for RPAS. In this analysis the considered CA function employs the same WC protection volume as the target avoidance volume but with a reduced prediction time window to raise a potential CA resolution advisory (set to 25s). In these conditions Caution activation to Warning alert exhibits a uniform probability distribution from 60s down to 0s for all non-cooperative and cooperative intruders. The average value of around 30s indicates that, generally, enough margin exists from a Caution Alert to CA.

Regarding *ACAS interoperability*, the Caution Alert is issued, on average, about 65s before the RA and between 7s to 26s from the end of the RWC phase (the RWC last point of manoeuvre) to the RA point. Therefore, if the RP performs their RWC manoeuvre in the allowed time then an RA on the intruder is very unlikely.

The analysis of the *Separation interoperability* has been performed using Short-Term Conflict Alert (STCA) [16] as a reference for the moment in which the ATCo may determine the course of action for a specific encounter, which generally occurs much earlier than any potential separation violation (between 5.5 to 6.5 NM). Results show that STCA alerts occur much earlier in time than Caution Alerts in all cases (25 to 60s), with wide margins except for ACAS encounters in higher airspace, where the margins are consistent but significantly reduced (around 10s).

Finally, for the *See and Avoid interoperability* both the active-surveillance system (for non-cooperative intruders) and the mode-S surveillance system (for cooperative intruders) provide sufficient horizontal range to cover a large proportion of encounters at all critical phases of the encounters. For lower airspace, active radar coverage almost reaches 100%, while in higher airspace, the value decreases to 80-90%. Note, however, that this reduction occurs at extreme ranges, which implies relatively long-time margins. Delayed Caution Alerts due to range limitations may only imply a slight protection reduction. The analysis has also showed that the Field of View of active-surveillance sensors may become the main bottleneck in the RWC function for non-collaborative intruders. At closer distances between RPAS and intruder, the elevation limits (set to ±15 degrees) become an obstacle to maintaining a continuous coverage of the intruder. At LoWC the coverage is reduced to a minimum of around 60-70%.

V. Real-Time Simulation Results

The RT simulations performed had humans-in-the-loop, thus the metrics were almost exclusively human performance based. Data results were used to evaluate the capability of RWC to avoid LoWC in nominal conditions accounting for the surveillance sensor accuracies, presence of other interfering traffic (even causing simultaneous predicted LoWC) and the manoeuvre performed by the RP. This was needed because the FT simulations (FTS) only concerned 'Open Loop' evaluations, in peer-to-peer encounters, without sensor errors.

A. Real-Time Assessment of Validation Objectives

Three RTS campaigns were performed. Two with the operational scenarios mainly located in terminal manoeuvring areas of three Italian airports, namely: Bari as airspace class D, Brindisi as airspace class E and Grottaglie as airspace class G. The simulated RPA were a TUAV and MALE fixed wing. 71 encounters were performed resulting in almost 15 hours of RTS. The third RTS campaign operational scenario was located in Germany and the Czech Republic. A generic light MALE, a UAM vehicle similar to a Volocopter 2X and a smaller multicopter drone were used as RPA. 70 encounters were performed resulting in 12 hours of RTS. All the sessions involved expert ATCos and UAV pilots.

The RTS scenarios were chosen to encompass all airspace classes D, E and G, involving realistic encounter situations that may involve coordination of the remote pilot with ATC. The situations were selected to model realistic use cases involving existing aircraft and drone builds.

The architecture of the RTS trials is shown in Figure 5, together with the roles of human participants in the tests. Specifically, two different remote pilots, six controllers, one manned pilot, three human factor experts and about eight engineers were involved in the execution of the test runs.

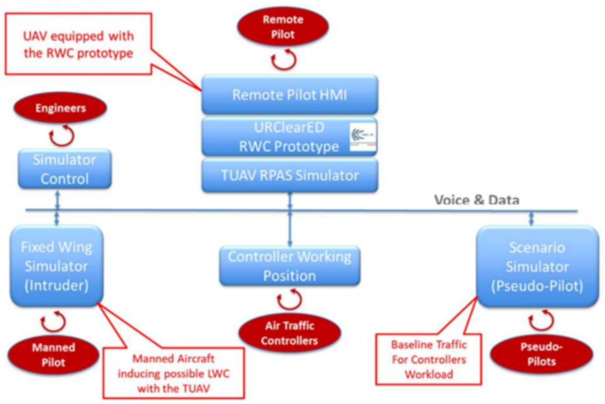

Figure 5. Real time simulation functional architecture

Two Pseudo-Pilot stations were used to manage the traffic in the flight test areas and one Controller Working Position station was used by controllers to perform ATCo tasks. A piloted HW-in-the-loop simulation facility of a manned aircraft of the general aviation class (i.e. 500 kg maximum take-off weight, 100 m/s max speed, 12000 m ceiling altitude) was used mainly as a VFR intruder in order to create conflict situations. To set and modify on-line the testing scenarios as scheduled, the facilities were connected to dedicated Simulation Control stations managed by test engineers. Finally, data and voice were shared through a local area network emulating the airspace with the radio communications among pilots and controllers.

In the tests performed the LoWC situations occurred due to: contingencies (e.g. failure of the RWC system or the RP had difficulties in the execution of the RWC manoeuvre through the autopilot system); limited field-of-view of the radar sensor (i.e. the non-cooperative intruders appear suddenly near the ownship or disappear during an encounter determining the LoWC); accelerated encounters (i.e. the intruder executes a manoeuvre towards the ownship at relatively low distance and/or high speed). In encounters in which only an Advisory Alert was issued the RP never executed a manoeuvre except for the cases in which the ATCo asked them to execute a separation manoeuvre to avoid IFR aircraft in airspace classes D and E and in a few cases in which they had autonomously decided to manoeuvre fearing a turn of the intruder toward the RPA direction in airspace class G.

In general, a RP manoeuvre was needed in those encounters in which one of the following events occurred:

- the ATCo provided separation;
- the RP requested the ATCo for a clearance to perform a well-clear manoeuvre after the activation of the RWC Caution Alert (mainly in airspace class E in encounters with VFR intruders);
- the RWC Caution Alert was issued (mainly in airspace class G).

The mean distance between the RPA and the intruder at the CPA in the previous cases is reported in Figure 6. It highlights how the ATCo separates long before the other two cases the aircraft is involved with in the encounter. In cases in which the RP has to ask for a clearance to the ATCo, the distance to the CPA is smaller with respect to that in which the RP can directly operate to keep well-clear (i.e. in airspace classes G) due to the interaction time with the ATCo.

Figure 7 shows the time to CPA at the Caution Alert activation. The reported values depend on the intruder equipment, namely: cooperative with ACAS, cooperative without ACAS and non-cooperative.

It highlights the different behaviour of the system depending on the intruder on-board equipment. Reduced time and distance of the Caution Alert are associated with non-cooperative intruders in order to allow the visual acquisition of the RPAS by the Visual Flight Rule (VFR) aircraft.

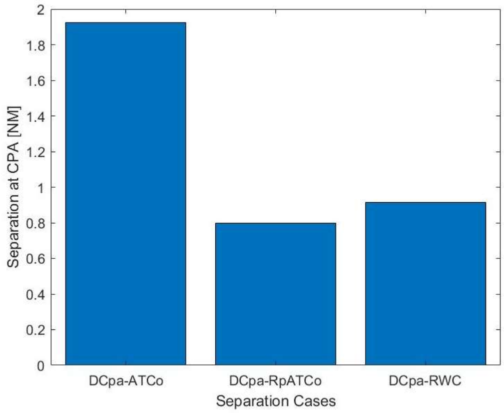

Figure 6. Mean distance between ownship and intruder at CPA in the case in which: the ATCo gave separation provisions (*DCpa-ATCo*), the RP requested an ATCo clearance for a well-clear manoeuvre (*DCpa-RpATCo*) and the RP directly executed a manoeuvre after a RWC Caution Alert (*DCpa-RWC*).

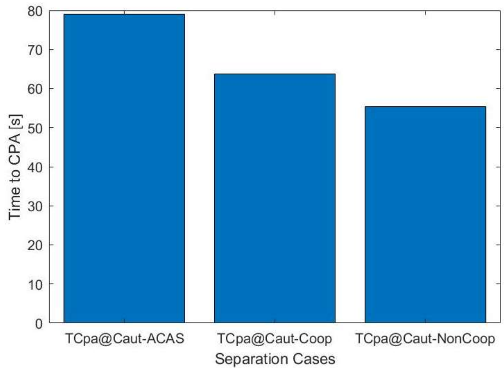

Figure 7. Time to CPA at the Caution Alert activation depending on the intruder equipment, namely: cooperative with ACAS (*RCpa@Caut-ACAS*), cooperative without ACAS (*Tcpa@Caut-Coop*) and non-cooperative (*Tcpa@Caut-NonCoop*).

Concerning the *RWC nominal performance* objective:

- In all the cases analysed the timing of the alert issuing was sufficient to coordinate with the ATCo, if needed, and to avoid the loss of well-clear for all types of intruder equipment and encounter geometries, and tested airspace classes.
- The measured impact on RWC performances of traffic sensor measurement errors, during RTS, was limited to very rare cases when there was a temporary unwanted flickering of the RWC alerts. LoWC conditions were induced by the intrinsic bearing and azimuth field of view limitations of non-cooperative traffic sensors.
- The measured performance of the RWC system during RTS was not compromised by the C2 link delay in line-of-sight (LOS) and beyond-line-of-sight (BLOS) conditions. In BLOS conditions, difficulties in the use of the autopilot for the execution of the separation manoeuvre were experienced. The RP tried to bypass such problems pre-setting the autopilot in potential encounters identified on the CDTI through advisory alerts.

Regarding the *ACAS interoperability* objective, in the cases in which no LoWC had occurred in encounters with ACAS equipped intruders, an RA was not triggered in the time interval from the Caution Alert activation up to the execution by the RP of the well-clear manoeuvres. The RP executed the well-clear manoeuvre with a mean time of 62 s to CPA at a mean distance of 3.6 NM following the RWC caution activation which occurred at a mean time of 75 s to CPA at a mean distance of 4.4 NM.

Concerning the *Separation Interoperability* objective, in airspace classes D and E, the measured ATCo separation provisions were well in advance of the RWC Caution Alert. The mean distance to CPA associated with the events of ATCo separation provision is about 7 NM while the Caution Alert is issued at about 3.2 NM. The ATCo gave separation provisions to the aircraft involved in the encounter with a mean time of 124 s before the CPA whereas encounters in which the ATCo did not intervene (i.e. uncontrolled airspace or controlled airspace in presence of VFR intruders or off-nominal conditions) the Caution Alert was issued with a mean of 66 s before the CPA. The RP initiated the manoeuvre before asking the clearance, only in a few cases in which the high-density traffic delayed the ATCo actions or in encounters where non-cooperative intruders were not visible on the controller working position.

In the case of *See and Avoid Interoperability*, during encounters with VFR intruders, the Caution Alert activation always occurred below the threshold of 5NM, giving the possibility for the intruders to visually detect the RPA and perform a separation manoeuvre. In cases where the manned aircraft did not separate, the RP had the time to execute a well-clear manoeuvre.

B. Human Performance

The Human Performances of both ATCo and RPs were assessed using a mixed approach of qualitative and quantitative methods (interviews and questionnaires). Most of the data collected during the RTS were qualitatively analysed using standard research practices (i.e., *Thematic Analysis Methodology*). The qualitative data collected (from observations and debriefings) were compared and integrated with the quantitative ones (both “post-run” and “post-session” questionnaires) with the final goal to support the HP validation objectives and to enhance data reliability.

Concerning the roles and responsibilities, operating methods and tasks the following results were found:

- All test RPs, reported that RWC provides good situational awareness, coherent with the actual dynamic evolution of traffic, and provides added value with respect to the ATCo information in all airspace classes D-E-G.
- Both RPs and ATCo did not perceive any changes in their role and responsibilities in relation to the RWC module compared to current operations in all the airspace classes D-E-G. However, in the first RTS campaign a general tendency was observed for the RPs to act in advance in order to avoid possible conflicts, resulting in the RPs performing separation manoeuvres against the traffic before calling ATC.
- The tasks of the ATCo did not change with the introduction of the RWC module, and the overall level of workload of the ATCo remained acceptable also considering high traffic scenarios. The same happened for the RP. In the second RTS campaign the perceived workload values were below that of the first RTS because of the greater familiarity with the RWC function of both the main actors.

Regarding the consistency of information between the RWC and that provided by the ATCo, feedback from the RPs returned positive results in all the RTSs. However, in some runs of the second session the RPs answered with low ratings (Figure 8) due to off-nominal conditions. This was the case in Run 2 where the RWC module failed to detect an intruder, and for this reason the information provided by the RWC module and the one from ATC were not consistent. Regarding Run 3 the RP experienced radio congestion with ATC. For this reason, no communication between the RP and the ATCo occurred during operations, which affected the manoeuvres that had to be carried out in order avoid the traffic.

Concerning the HMI Design the RPs reported positive results, especially for the ease to notice and interpret the RWC alerts. Some concerns were expressed relating to the position of the CDTI integrated in the overall HMI. The RPs suggested to place it nearer to the autopilot panel in order to set it more rapidly having the view of the conflict bands in its proximity.

Regarding the ATCo’s acceptance of the RWC module, the debriefing indicated that they judged the solution to be positive. This result was due to the majority of the ATCos not perceiving a significant change in their usual working practice when controlling RPAS with the RWC module. In general, it was identified that RPs and ATCOs’ acceptability of the RWC module depends on three important points:

- Training for the RPs on the RWC module usage and related procedures.
- How the limitations of the RWC prototype used during the simulations will be addressed and further developed (i.e., time thresholds for the alerts, reliability of the distance of the traffic displayed by the RWC module HMI).
- Mitigations over the RPs and ATCOs’ safety concerns regarding a possible usage by the RPs of the RWC to act in advance to avoid traffic without informing ATC.

In general, both RPs and ATCo judged that RWC can increase flight safety and can help avoiding traffic disruptions due to collision avoidance activation, not only in class G, but also in class D and E where VFR aircraft without transponders can be present (Figure 9).

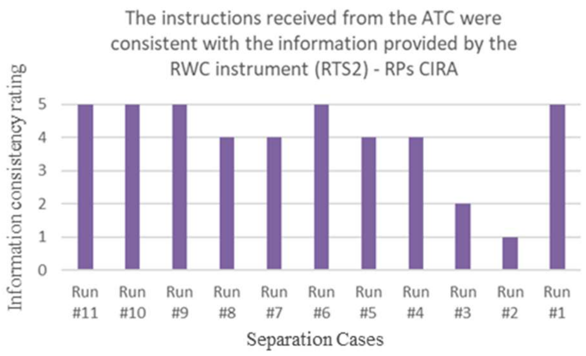

Figure 8- Ratings regarding the consistency of information provided by the RWC module with the information provided by ATC during the second RTS. (1= Strongly Disagree, 2=Disagree, 3=Neither agree nor disagree, 4=Agree, 5=Strongly Agree).

Figure 9- Perceived level of safety by ATCOs during the different runs of the second RT session (1: Very Low; 5: Very High)

VI. Conclusions

This paper addresses the definition of the RWC function for RPAS flying under IFR into European airspace classes from D to G. Such work has been carried out in the framework of the URClearED project [4], co-founded by SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation program.

An operational concept for the RWC function is described, specifying its alerting and guidance functionalities to support RP decisions in the resolution of potential conflicts. Analyses made to define the WCV and the alerting times, based on Monte Carlo simulations, are presented. Finally, validation objectives focused on RWC nominal performance and its interoperability with ATCo separation provisions, ACAS equipped intruder and manned See and Avoid are detailed and validated by means of FT and RT simulations.

The main results achieved were:

- Based on FTS analysis, the RP has always the margins to manoeuvre when the encounter is with straight or low manoeuvring trajectories (40s on average). However, in encounters with manoeuvring aircraft, there are several cases (at least 30% using the CREME model) in which the RWC cannot alert the pilot in time to avoid the condition of LoWC. Those are the cases in which the intruder is manoeuvring mainly vertically, with less than 20 seconds remaining from Caution Alert to LoWC. In RTS, the measured RWC alert timing was sufficient to coordinate with the ATCO, if needed, and to avoid the loss of well-clear for all types of intruder equipment and encounter geometries, supporting the RP in the resolution of conflicts in all the tested airspace classes.
- Concerning nuisance alerts, no quantitative evaluation of this aspect was performed. FTS was only open loop (i.e. without a RP model in the loop) with a correlated encounter model, i.e. at least one of the aircraft involved is in contact with ATCo that gives at least information about the traffic conflict likely triggering an action. With this kind of model, we found a high number of encounters with manoeuvring aircraft due to ATCo separation provisions issuing intermittent Caution Alerts (i.e. Caution Alerts that are activated/deactivated in a short sequence) but never causing a real condition of LoWC. For the previous motivations these were not considered nuisance alerts. In RTS, nuisance alerts did not occur in any run.
- The FTS analysis shows that there are situations in which the Caution Alert is very late and these would lead to direct activation of the onboard CA function or activation of the CA function that is very close to the Caution. However, considering the analysis using only encounters with straight trajectories, there is enough time from a Caution Alert to a TCAS-II RA (typically more than 30s).
- The FTS analysis shows good interoperability with ACAS intruders (with TCAS-II). The Caution Alert is raised from 65s to 40s before the RA on the other aircraft and the last point to manoeuvre to avoid the RA is, on average, 25s to 30s from the RA. During the RTS, in all the cases in which no LoWC occurred in encounters with ACAS-equipped intruders, no RAs were triggered in the time interval from the Caution Alert activation up to the execution by the RP of the well-clear manoeuvre.
- From FTS, a typical margin between the ATCo intervention (either with STCA or without, based on an available study [17]) and the Caution Alert activation is, on average, about 20s in higher airspace and 15s in lower airspace (below FL100). This was confirmed by the RTS, in which the ATCo separation provisions, when available, were well in advance with respect to the RWC caution alert activation. The ATCo gave separation provisions to the aircraft involved in the encounter with a mean time of 124 s before the CPA. In encounters in which the ATCo did not intervene (i.e. uncontrolled airspace or controlled airspace in presence of off-nominal conditions) the Caution Alert was issued with a mean of 66 s before the CPA.

- In the FTS analysis, the average range at which a non-cooperative aircraft was detected (below FL100) was about 5NM, which is within the typical radar and visual ranges. However, a certain percentage of the encounters can have a higher range as the standard deviation is about 3NM. Therefore, in some cases, the visual or radar acquisition might happen later. In the RTS encounters with VFR intruders, the Caution Alert activation always occurred below the threshold of 5NM, giving the possibility for the intruders to visually detect the RPAS.

- All test RPs, reported that the RWC provides good situational awareness, coherent with the actual dynamic evolution of traffic, and provides added value with respect to the ATCo information in all airspace classes D-E-G.

- The tasks of the ATCo did not change with the introduction of the RWC module, and the overall level of workload of ATCo remained acceptable also considering high traffic scenarios. The same happened for the RP.

The RWC benefits are not always guaranteed, as is evident from some reported results. Therefore, a Collision Avoidance function shall always be present onboard the RPAS to manage situations that the RWC and RP have not been able to resolve in time.

Further work should focus on more evaluation of the trade-offs between the Caution Alert time margins taking into account limitations of non-cooperative sensor's field-of-view. The effect of manoeuvrability of intruders on the RWC alerting function should be investigated (including applicability of past experience with STCA [16]). Finally, specific procedures to mitigate the risk of RPs executing separation manoeuvres against traffic before calling ATC should be defined.

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