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Article

RPAS Automatic ADS-B based Separation Assurance and Collision Avoidance System Real Time Simulation Results

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Abstract: Remotely Piloted Aircraft Systems (RPAS) are increasingly becoming relevant actors flying through the airspace and will assume much more importance in the future perspective. In order to allow their safe integration with manned conventional traffic in non-segregated airspaces, in accordance with the overall Air Traffic Management (ATM) paradigm, specific enabling technologies are needed. As well known, among the enabling technologies identified as crucial for RPAS integration into the overall ATM system, the Detect and Avoid (DAA) technology is fundamental. In the meantime, to support extended surveillance, the universal introduction on-board of aircraft of cooperative Automatic Dependent Surveillance – Broadcast (ADS-B) is increasingly implemented, having the potential to allow coverage of the whole airspace also in remote areas not usually covered by conventional radar surveillance. In this paper, the experimental results are presented and discussed that have been obtained through the real-time validation, with hardware and human in the loop (RTS-HIL) simulations, of an automatic ADS-B based Separation Assurance and Collision Avoidance System aimed to support RPAS automatic operations as well as remote pilot decision making. In the paper, after an introductory outline of the Concept of Operations (ConOps) of the system and of its architectural organization, while also providing basic information about the main system functionalities, the description is reported of the tests that have been carried out and the obtained results are described and discussed, in order to emphasize the performances and limitations of the proposed system. In particular, not only the quantitative performances obtained are reported and commented but also the feedbacks received by the pilots in order to improve the system are described, for instance in terms of preferred typology of conflict resolution manoeuver elaborated by the system.

Keywords: Remotely Piloted Aircraft Systems; RPAS; Unmanned Aerial Vehicles; UAV; Unmanned Aerial Systems; UAS; Detect and Avoid; DAA; Separation Assurance; Self Separation; Collision Avoidance; Situational Awareness; Drones; Aircraft; ADS-B; Real Time Simulations

1. Introduction

In the last decades, Remotely Piloted Aircraft Systems (RPAS) emerged as relevant and increasingly diffused new actors in the air traffic picture, covering flight levels that range from very low-level operations to higher flight levels. The first appearance of RPAS has been in the military framework, due to the inherent advantages deriving from the use of Unmanned Aerial Vehicles (UAVs) in dangerous operations in threat environments. Such advantages, as the possibility to use the full range of performances of the platform, not limited by the presence of humans on board, and the reduced costs associated to missions execution while at the same time eliminating the risk for the human pilots, motivated a significant effort towards the development of military RPAS [1]. After that, RPAS have started to be considered also in the civilian aviation framework, with the aim of achieving similar advantages in civil applications in terms of costs reduction and substitution of human pilots in performing repetitive tasks and long endurance operations that can be efficiently delegated to automation in the aircraft guidance. In addition, parallel development of concepts such as the ones of Small Air Transport (SAT) [2] and Personal Air Transport System (PATS) [3] is also linked to RPAS concepts and technologies.

The SAT concept is now addressed in terms of research and development of solutions allowing single pilot operations, having the potential to ease the introduction of this aviation transport paradigm as a relevant industry, especially for instance in the areas of Europe where surface transport infrastructures are not enough extensively implemented and the costs for implementation would be excessively high due to the presence of geographical barriers. In such a situation, a solution to increase the mobility capabilities in such areas would be the one of implementing extensive use of regional small airports, which in those areas are numerous, by wide number of SAT vehicles, which would be piloted under single pilot operations to reduce the flight costs and the needed number of qualified crew. In such framework, research activities are ongoing under the transversal SAT work package in Clean Sky 2 EU funded programme, such as the ones specifically devoted to design of enabling technologies for single pilot operations in SAT vehicles that are carried out in the COAST project [4-5]. In this framework, in order to reduce the single pilot workload the Detect and Avoid technologies are fundamental and are also more relevant in case of delegation of the separation responsibility to the flight segment, as envisaged under specific circumstances by the SESAR ATM Target Concept [6]. Based on that, specific design activities are ongoing in the COAST project addressing a, ADS-B based tactical separation system supporting the pilot in the separation task [7-8] and also addressing a step forward in terms of design of overall integrated mission management system automatically managing the flight, included self-separation tasks, in case of pilot incapacitation [9]. It is clear that these technologies represent a cross fertilization of the DAA technologies coming from the RPAS domain and from the unmanned vehicles automation domain in general.

For what concerns, then, the PATS approach intended to be implemented in this new and revolutionising aviation sector is the one of total autonomy of the vehicles, in case of both freight and passengers transport, motivating dedicated effort addressing the design of technologies such as the ones for 4D automatic navigation, situation assessment and supervision, swarms guidance, separation assurance and collision detection, fault detection and isolation [10]. To this aim, the RPAS technologies play a fundamental role as baseline for cross fertilization and further improvement towards the full autonomy in the PATS domain and a fundamental role is played, once again, by the DAA technologies.

Even if the RPAS domain is very relevant in terms of both current application and future further developments, as outlined above, the presence into the airspace of such new actors led to a new and very important issue in terms of safety: the safe integration of RPAS with conventional manned vehicles in the common airspace. This issue becomes also more relevant in view of the expected activation over the next few years or decade of the Urban Air Mobility (UAM) transport segment, which will start probably by using conventional rotorcraft with conventional pilots and will then evolve through RPAS paradigm towards fully automated vehicles for passengers (and freight of course) transport into wide urban areas. This motivates a double issue in terms of safety: (1) integration of RPAS with the conventional manned traffic in the usual airspace without using segregation and under the control of conventional Air Traffic Management (ATM) and Air Traffic Control (ATC) system; (2) integration of the RPAS and, as a perspective of UAM vehicles, into an overall ecosystem devoted to Unmanned Traffic Management (UTM) in the lower airspace (Very Low Level (VLL) operations), ecosystem that is now being designed and implemented according to the U-Space paradigm [11].

A considerable number of research and development activities have been undertaken worldwide in the last decades, aiming supporting and allowing the integration of RPAS in the unsegregated airspace. In Europe, for instance, the projects INOUI and ICONUS have been carried

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out as the first ones addressing the issue. ICONUS findings [12] indicated that there are several classes of obstacles in the RPAS integration in the unsegregated airspace: regulatory obstacles, such as common standards, interoperability and airworthiness; procedural obstacles, namely planning of operations, separation methods and minima, approach procedures, emergency procedures; social and organizational issues, namely human factors, public acceptance, liability insurance; and system limitations, notably the Detect and Avoid system, the Command and Control link and the safety, security and reliability aspects linked to those systems. Difficulties have further complicated due to the large number of RPAS type and dimension and the variability of missions. RPAS can range from few grams (and tendencies to further reduction of weight is a clear trend) to vehicles which can weigh as much as General Aviation aircraft; missions can vary from usual scheduled to unscheduled flights. Depending on such a large number of topics, a widespread kind of initiatives has been conducted all over the word, often in a non-coordinated fashion.

Based on that, in Europe the SESAR programme devoted effort to support the integration of RPAS together with conventional manned vehicles in non-segregated airspace. Starting from the roadmap for the integration of RPAS prepared by the European RPAS Steering Group (ERSTG), SESAR Joint Undertaking (SJU) completed the RPAS Integration Definition Phase, which identified the guidelines for the RPAS Integration topic to be included in the SESAR2020 program, driving the R&D development in ATM in Europe in these years. Consequently, SJU sponsored dedicated projects under the global program for RPAS Demo, in order to investigate and collect data from flight tests and experiences about RPAS integration issues. One of such projects was RAID (RPAS-ATM Integration Demonstration), which carried out both real-time validations and flight demonstrations for the integration of RPAS vehicles in ATM. A description of the real-time demonstrations carried out in RAID has been provided in the reference paper [14], which was aimed to represent an overview of the project contents but was not specifically devoted to the specification of the features of the integrated ADS-B based Automatic Separation Assurance Collision Avoidance System (ASACAS) designed by CIRA, the Italian Aerospace Research Center, that has been demonstrated in the project. The aim of this paper, therefore, is to report with more details and more specific focus the outcomes and findings from the real-time demonstrations carried out in the RAID project, so complementing and extending the previous reference paper [14]. Of course, being this paper limited to real-time demonstration results description and discussion, it does not cover the flight demonstration results, which will be addressed in future works.

The paper is organized as follows. Section 2 first reports a description of the applicable CIRA background and motivations that led to the design of the integrated ADS-B based Automatic Separation Assurance Collision Avoidance System (ASACAS), then provides an overview of the system concept of operation and of the implemented system architecture, while also providing basic information about the algorithms implemented in the main system functionalities. Section 3, then, describes some relevant tests that have been performed in the real-time simulations, with reference to both Collision Avoidance as well as Separation Assurance experiments, including the related test plan and the obtained results. The main findings are discussed in Section 4 and the conclusion from this paper are reported, finally, in Section 5 reports some relevant results of the real-time demonstration campaign and discusses the main findings emerged.

2. Materials and Methods

2.1. Background and motivations

In the last decades CIRA gained relevant expertise in the design of Detect and Avoid (DAA) systems, thanks to activities that have been carried out in both Italian national funded projects and in European international funded projects.

The integrated ADS-B based Automatic Separation Assurance Collision Avoidance System (ASACAS), whose real time simulation campaign is the subject of this paper, is indeed the result of many years of incremental research in this topic. The main motivation that led the design of such a system has been the one of capitalizing and extending the previous experience, related to single baseline systems for Collision Avoidance (radar based) and for Self-Separation, in order to achieve the design of a unique integrated system managing all the functions at the same time, according to properly designed overall system automation logic, and implementing the above indicate functions in the most appropriate way, taking into account requirements of compliance with the Rules of the Air [15] and self-compatibility.

Here in the following the evolutionary approach that led to ASACAS design is outlined. Baseline version of an Autonomous Collision Avoidance radar-based system was developed in the framework of the Italian national funded project TECVOL (Technologies for the Autonomous Flight), reaching TRL 6 as individual technology [16-19]. Baseline version of a Separation Assurance ADS-B based system was developed in the framework of the Italian project SEPARA (System for General Aviation Separation Support), reaching TRL 5 as individual technology [20-21].

Starting from these baseline individual systems, in the Italian national funded project MISE (Applications for unmanned aircraft avionics), the first and baseline version of ADS-B based integrated system ASACAS has been developed. The ASACAS first version has been evolved, then, in the Italian national funded project EATS (Efficient Air Transport System). The second (evolved) version of the system, then, has been demonstrated, both in real-time and in real live flight trials, in the SESAR JU funded project RAID (RPAS-ATM Integration Demonstration), completed in 2016, finally achieving TRL 6.

More in details, the Automatic Separation Assurance and Collision Avoidance System (ASACAS) development has been implemented through the incremental steps described in the following. The first version of the ASACAS (version 1p0) system has been designed in order to update the former Autonomous Collision Avoidance (ACA) system, developed in the framework of the project TECVOL. The rationale of this update was the need of adapting the collision avoidance functionality to the use of the cooperative surveillance sensor ADS-B IN as unique sensor for obstacle detection purposes, so replacing the radar-based non-cooperative sensor suite used in the application developed in TECVOL. This represented the first step towards the development of a fully integrated Automatic Separation Assurance and Collision Avoidance System (ASACAS version 2p0), including both Separation Assurance and Collision Avoidance functionalities based on ADS-B IN surveillance sensor, as well as integrating dedicated Situational Awareness functionality and overall ASACAS system logic. The ADS-B IN provided surveillance data are used as input for conflict and collision detection algorithms in order to support the Collision Avoidance and the Separation Assurance functionalities. These raw data are pre-processed by a.

In the ASACAS 1p0 version, the collision detection system for Collision Avoidance has been specifically modified, with respect to the former TECVOL application [16-19], and designed in order to allow it using ADS-B IN provided data, broadcasted by all ADS-B OUT equipped surrounding aircraft. The overall collision detection system architecture designed in ASACAS 1p0 aimed managing the ADS-B data in order to provide the collision avoidance resolution algorithm (which has not been changed with respect to the baseline version) with proper information about the surrounding traffic [22-23]. In this phase, also dedicated Surveillance Processing application, compliant with applicable RTCA standard DO-317 [24], has been designed and implemented in the system.

The ASACAS 2p0 version, then, improved the Collision Avoidance functionality, already implemented in the ASACAS version 1p0, and designed and integrated in the overall system the functionalities of Separation Assurance (modifying and evolving the baseline Self-Separation functionality from SEPARA [20-21]), TCAS Compatibility Check and Situational Awareness. Moreover, ASACAS 2p0 included suitable automation logic that has been specifically developed in order to properly manage the behavior of the whole integrated system.

The ASACAS system, therefore, provides the RPAS with the following automatic capabilities:

- assistance to Separation Assurance, to perform separation maneuver, when required, to remain well clear of other traffic aircraft;
- Collision Avoidance;

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- enhanced Situational Awareness, providing Traffic information to allow the RPAS pilot to build his situational awareness related to the surrounding traffic, as enhancement of the Remote Pilot traffic supervision;
- provision of compatibility information between the ASACAS system and the TCAS operations foreseen in case of proximity between the ownship and a TCAS-equipped aircraft;
- provision of an automation logic that coordinates and sequences all the functionalities, based on the risk associated to the surrounding aircraft, and processes the possible remote pilot inputs received through the dedicated HMI implemented in the Remote Pilot Station (RPS).

Further improvements of the ASACAS system are still ongoing in the framework of the EATS project [25-26], benefitting, in addition, from the additional experience and know-how gained by CIRA in several international projects, both completed (as for instance the EDA funded project MIDCAS, Mid-Air Collision Avoidance System [27-28]) and currently ongoing (as for instance the Clean Sky 2 funded project COAST, Cost Optimized Avionic System [4-5, 7-8]).

2.2. Concept of Operations

Based on what indicated above, three main capabilities are provided by ASACAS implementation: Separation Assurance (SA), Collision Avoidance (CA) and Situational Awareness (SitA). Here in the following, a description is reported of the interactions between the systema and the RPAS Remote Pilot, in order to outline the ASACAS intended application and benefits.

The RPAS remote pilot is aware of traffic information by means of the Human Machine Interface (HMI) that allows him to build his situational awareness related to the surrounding traffic, including the indication of the consolidated traffic tactical picture around the remotely piloted aircraft (ownship) and the associated level of severity of each surrounding aircraft in terms of loss of separation and collision risk with respect to ownship. To consolidate the traffic picture and evaluate the associated risks, the system uses ADS-B IN provided inputs as well as ownship navigation data provided by the onboard navigation sensor (GPS). The overall ASACAS concept of operations is represented in the following Figure **1**, where ATC indicates the Air Traffic Control service provision facility, GCC is the RPAS Ground Control Station where the Remote Piloted Vehicle station is located, and FCC indicates the Flight Control Computer hosting the on-board software ASACAS (as well as the additionally needed softwares for Autopilot and low-level aircraft control).

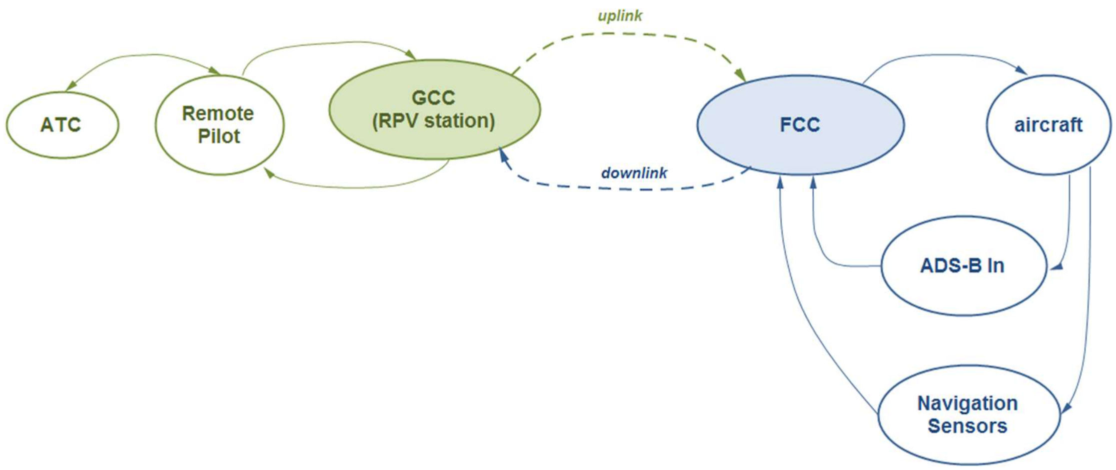

Figure 1. ASACAS Concept of Operations

From an operational point of view, the ASACAS system continuously performs the monitoring of the traffic in order to provide enhanced situational awareness to the Remote Pilot and in order to identify possible loss of separation and/or collision risks.

In presence of a predicted loss of separation with respect to one or more traffic vehicles, the system is expected to provide information to the Remote Pilot and to automatically elaborate a separation recovery manoeuver, to be proposed to the Remote Pilot. The Remote Pilot is then in charge of evaluating the feasibility of the manoeuver with respect to the constraints affecting the flight and not considered by the ASACAS system (it is worth to notice here that the system performs the elaboration of the separation recovery manoeuver without considering any constraint related for instance to existing no-fly zones, segregated areas, fixed obstacles, flight plan constraints and so on). If needed, based on the current tactical picture, the Remote Pilot can interact with the ATCo (Air Traffic Controller), in order to ask the clearance for the implementation of the proposed manoeuver or to negotiate it. Based on the outcomes of the Remote Pilot and/or ATCo evaluations, the manoeuver can be accepted and, in this case, the Remote Pilot can decide to delegate its automatic implementation to the aircraft Autopilot or to implement the manoeuver himself.

In presence of predicted risk of collision with respect to one or more surrounding traffic vehicles, the ASACAS system is expected to provide information to the Remote Pilot and to automatically elaborate collision avoidance manoeuver with respect to the most dangerous vehicle, according to proper prioritization criterion implemented. The collision avoidance manoeuver, due to its emergency nature, is expected to be automatically implemented by the automatic guidance system. Nevertheless, the Remote Pilot is provided with the possibility of aborting the manoeuver and taking the direct control of the vehicle, at any moment.

The ASACAS system is also continuously performing the TCAS compatibility check, aimed to provide a prediction, based on the current trajectory of ownship and traffic vehicles, of the Resolution Advisory activation in the surrounding traffic vehicles equipped with TCAS [29]. Based on the outcome of this check, the expected behavior of the ASACAS system with respect to identified loss of separation and collision risks is accordingly modified in order to assure that no maneuvers are generated by ASACAS that could create nuisance to the TCAS elaborated maneuver by the considered traffic vehicle.

2.3. Architecture

As outlined in the previous sections, ASACAS includes the functionalities of Separation Assurance (SA) and Collision Avoidance (CA) and provides enhanced Situational Awareness (SitA) to the Remote Pilot by classifying each surrounding vehicle based on the associated risk with respect to ownship. The SA and CA functions are allocated on two different logical levels, since CA is considered as an emergency function that is activated only when an emergency event is raised, whereas, in tactical operations, the SA function is in charge of guaranteeing safe separation among aircraft. The functional architecture of the ASACAS system is reported in Figure 2 [14].

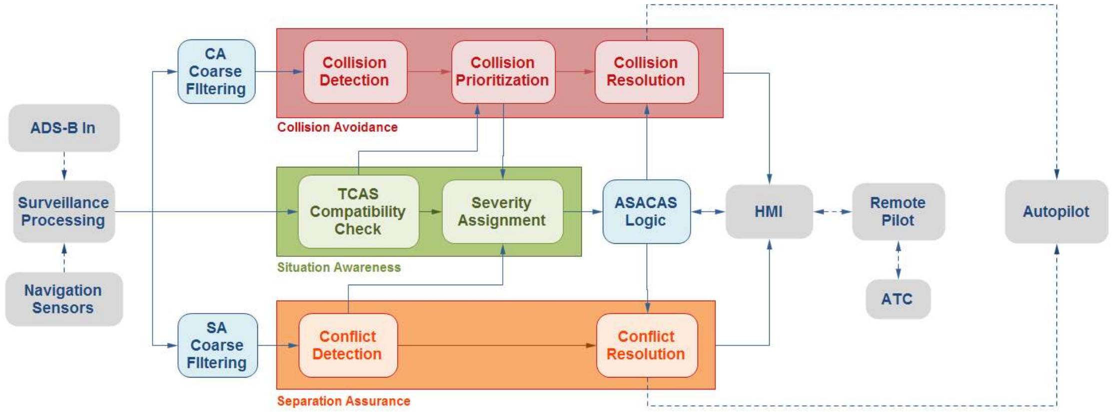

Figure 2. ASACAS functional architecture [14]

As indicated in Figure 2, the system receives, from the on-board ADS-B IN surveillance sensor, traffic position and velocity data about surrounding ADS-B OUT equipped aircraft, in order to predict future conflicts (intended as predicted loss of separation) and potential future collisions

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between ownship and surrounding traffic. The DAA system is supported by a DO-317 [24] Surveillance Processing application, aimed to perform the processing of the raw data provided by the ADS-B IN surveillance system, in order to allow their use by the conflict/collision detection system. Furthermore, the functional architecture comprises the following functionalities, which will be outlined in the following section:

- Coarse Filtering, both for Collision Avoidance and Separation Assurance functions,
- Conflict Detection for Separation Assurance function,
- Conflict Resolution for Separation Assurance function,
- Collision Detection for Collision Avoidance function,
- Collision Prioritization for Collision Avoidance function,
- Collision Resolution for Collision Avoidance function,
- TCAS Compatibility Check for Situational Awareness function,
- Severity Assignment for Situational Awareness function,
- ASACAS Logic.

The outputs of the system include the classification of the surrounding traffic in terms of conflicts (i.e. vehicles that constitute a potential loss of separation with respect to ownship), threats (i.e. vehicles that constitute a collision risk with respect to ownship), and traffic (i.e. vehicles that do not pose risks with respect to ownship). Furthermore, the DAA system elaborates suitable manoeuver to restore the separation minima with respect to all the detected conflicts (if any) and suitable maneuver to escape from the most dangerous collision vehicle detected (if any). The separation assurance manoeuver is proposed to the Remote Pilot, who is in charge of providing his/her clearance and may also request the automatic implementation of the manoeuver by the system. The collision avoidance maneuver is executed in automatic way, due to the emergency nature of such a manoeuver, and can be terminated by the Remote Pilot if needed.

2.4. Algorithms

The detailed description of the algorithms applied in the ASACAS system and of the related implementation in the dedicated functionalities is out of the scope of this paper, which is indeed focused on the real-time tests description. Nevertheless, in order to ease the comprehension of the system behavior, in the following a conceptual description is reported of each ASACAS system functionality and, therefore implicitly, of the implemented associated algorithms. Some details about the baseline versions of the Collision Avoidance individual algorithm and about the baseline version of the Separation Assurance individual algorithm can be found in the reference papers [16-19] and [20-21], respectively. As already described, these baseline versions have been then evolved for the integration in the overall designed ASACAS system as outlined in the previous section 2.1.

For the specific application in the real-time testing addressed in this paper, in addition, it is worth to emphasize here that the considered Separation Volume is a cylinder centered in the conflicting intruder, whose planar radius is 0.5 Nm and whose semi-altitude is 500 ft. The size of the cylinder is properly incremented in order to take into account the uncertainties affecting mainly the position and velocity data of the intruder. The considered Collision Volume, then, is a sphere centered in the colliding intruder, with 500 ft radius. The radius of the sphere is properly incremented in order to take into account the uncertainties affecting mainly the position and velocity data of the intruder.

2.4.1. SA and CA Coarse Filtering

In order to provide a pre-selection of the traffic, due to the ADS-B IN equipment capability of detecting traffic located very far and therefore *a priori* not representing a risk for the ownship, a suitable coarse filtering function is needed, able to select the surrounding aircraft to be processed by the CA and SA functionalities, so reducing the computational burden. The basic principle proposed for the coarse filtering consists in excluding from the conflict/collision detection the aircraft whose distance from the ownship is greater than a specified threshold. The thresholds set for conflict and collision detection shall be different, due to the different nature of risk associated to SA and CA

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functionalities. Therefore, two different coarse filtering have been implemented, one for each functionality.

2.4.**2**. SA Conflict Detection

Once received traffic information about aircraft resulting from the SA coarse filtering processing, the conflict detection function shall check potential loss of separation between ownship and each considered aircraft. The conflict detection is based on the calculation of possible breach of cylindrical separation volume by the ownship with respect to all the surrounding traffic vehicles: pair-wise check is implemented for each and all the surrounding traffic vehicles that have been provided by the dedicated SA coarse filtering functionality and the cylindrical separation volume breach is considered only if occurring within the specified tactical time horizon considered as separation assurance look ahead time by the ASACAS. The output of this functionality is the list of conflicting vehicles with associated conflict geometry relevant data.

2.4.**3**. SA Conflict Resolution

The conflict resolution function is activated once one or more conflicting aircraft have been identified by the conflict detection function and, therefore, a separation maneuver is automatically elaborated by this function, assuring the ownship separation from all the aircraft detected as conflicts. The function, therefore, calculates multi-conflict separation maneuver, aimed to avoid the cylindrical separation volume infringement for the considered conflict geometry and using a separation and proper prioritization of the channels (longitudinal, lateral, speed) in which the maneuver is proposed, in order to not generate excessive workload for the pilot in evaluating and implementing the maneuver. In addition, in order to allow integration of the proposed system in regular conventional traffic and to inherently guarantee self-compatibility among aircraft equipped with the ASACAS SA functionality, the maneuver is elaborated in such a way as to comply with the Rules of the Air.

2.4.4. **C**A Collision Detection

Once received traffic information about aircraft of interest as resulting from the CA coarse filtering processing, the collision detection function shall check potential collision conditions between ownship and each considered aircraft. The collision detection is based on the calculation of possible breach of spherical collision volume by the ownship with respect to all the surrounding traffic vehicles: pair-wise check is implemented for each and all the surrounding traffic vehicles that have been provided by the dedicated CA coarse filtering functionality and the collision volume breach is considered only if occurring within the specified emergency time horizon (greater than the tactical time horizon of SA functionality) considered as collision avoidance look ahead time by the ASACAS. The output of this functionality is the list of potentially colliding vehicles with associated collision geometry relevant data.

2.4.5. **C**A Collision Prioritization

Based on the check performed by the collision detection function, multiple collisions may be detected, i.e. more than one surrounding aircraft may pose a threat to ownship. Therefore a dedicated prioritization criterion is proposed in order to individuate the most dangerous collision risk. To perform the prioritization the most relevant collision geometry parameters are considered and particular importance is associated to the resulting time-to-go (i.e. the range over range rate ratio between the considered aircraft).

2.4.6. **C**A Collision Resolution

The collision resolution function shall elaborate a modification of RPAS vehicle trajectory, aimed to avoid the predicted collision with respect to the only threat aircraft considered as highest priority by the prioritization logic. The function, therefore, elaborates a single-collision avoidance maneuver, aimed to prevent the spherical collision volume infringement for the considered collision geometry.

The maneuver does not implement any separation and prioritization of the channels (longitudinal, lateral, speed), being it inherently calculated as 4D (four dimensional) manoeuver. Of course, based on the specific collision geometry the elaborated maneuver may affect only one of the control channels (i.e. a purely collision avoidance maneuver can be elaborated, for instance), but this is not pre-determined or selected by specific design of the functionality and is purely determined by the collision geometry among generally 4D maneuvers available. It is also worth noticing that, due to the emergency nature of the maneuver, it does not consider any requirement in terms of Rules of the Air.

2.4.7. TCAS Compatibility Check

In order to manage the compatibility of the ASACAS system implemented on ownship with the potential TCAS-equipped surrounding aircraft, the TCAS Compatibility Check function shall predict when one or more of them will trigger a RA due to the ownship proximity. This information allows guaranteeing the compatibility between the ASACAS and the TCAS, because based on the predicted RA alerted aircraft, the expected behavior of the ASACAS with respect to identified loss of separation and collision risks is accordingly modified in order to assure that no nuisance maneuvers are generated by ASACAS disturbing the TCAS maneuver elaborated by the considered traffic vehicle.

2.4.8. Severity Assignment

The severity assignment function bases its elaboration on the data provided by the SA and CA functions, in order to support the remote pilot by means of visual depiction on a dedicated CDTI of the whole traffic scenario. Once all the aircraft have been processed by the CA and SA functions, all the detected surrounding aircraft shall be managed and classified basied on:

- the conflict status provided by the conflict detection function;
- the collision status provided by the collision detection function and suitably prioritized by the collision prioritization one;
- the RA alerted status provided by the TCAS compatibility check function.

To this aim, the Severity Assignment function shall identify which is/are the surrounding aircraft with respect to which a Separation or Collision Avoidance maneuver is needed, taking into account also the RA alerted aircraft. From a practical point of view, the Severity Assignment functionality provided output is the data source for the visualization, on a dedicated display implemented on the HMI, of all the relevant information related to the surrounding traffic, collected and elaborated by the CA and SA functions and suitably classified and prioritized according to the associated severity level of risk, in order to individuate and differentiate all the aircraft represented on the CDTI (Cockpit Display of Traffic Information).

2.4.9. ASACAS Logic

The assignment of a severity risk to each surrounding aircraft shall be processed by a suitable ASACAS logic in order to establish which the ASACAS system operational status is. The ASACAS Logic function processes the information about the aircraft detected as conflicts/collisions and those ones provided by the TCAS compatibility check, in order to:

- coordinate and sequence the two functionalities of Separation Assurance and Collision Avoidance, based on the risk associated to the surrounding aircraft;
- process the Remote Pilot commands to the ASACAS (for instance, separation assurance or collision avoidance maneuver termination), issued through HMI.

3. Results and Discussion

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3.1. Test Plan

In the following four exemplary tests of the Real-Time Simulation (RTS) campaigns are detailed, two used as representative cases of Separation Assurance tests and two used as representative cases of Collision Avoidance tests. The considered exemplary tests address:

- Tests 1 and 2 – Separation Assurance automatically implemented by the ASACAS system once received proper clearance by the Remote Pilot;
- Tests 3 and 4 – Collision Avoidance automatically implemented by the DAA system.

In all the tests, the ownship is flying inside a defined Operational Maneuvering Area in presence of multiple vehicles as surrounding traffic and one of these represents a conflict (i.e. potential loss of separation) in tests 1 and 2 and a threat (i.e. potential collision) in tests 3 and 4.

In the description of all the RTS, here only the vehicle of interest is represented in the figures, even if other traffic has been also simulated and managed by the ATCo during the RTS. The intruder and ownship positions are reported with respect to a local reference frame centered in the initial position of ownship at the simulation start. In the real time tests here described, conventionally, the origin of the local reference frame corresponds to the point where the handover procedure between the Safety Pilot and the Remote Pilot has been completed and, therefore, the Remote Pilot is operating the RPAS ownship [14].

3.1.1. Test 1 Plan

The initial conditions for ownship and intruder of interest are reported in Table 1.

Table 1. Ownship RPAS and intruder starting position in local reference frame for test 1

	x [m]	y [m]	z [m]	TAS [m/s]	Track wrt x [deg]
Ownship	0	0	1000	35	0
Intruder	16000	500	1000	35	180

Both the aircraft are performing straight and level flight towards their selected destination waypoints, so the geometry here considered leads to a loss of separation according to head-on encounter (to be noticed that, indeed, a lateral displacement of 500 m exists between the vehicles, which in any case leads to loss of separation condition, due to the circumstance that the nominal separation volume centered in the intruder has 0.5 Nm radius, so it is greater than the 500 m displacement). This Separation Assurance test has been preliminarily examined in the reference paper [14] and is here addressed once again in order to provide its deeper analysis, also with respect to the additional exemplary Separation Assurance test 2 here reported.

3.1.2. Test 2 plan

The initial conditions for ownship and intruder of interest are reported in Table 2.

Table 2. Ownship RPAS and intruder starting position in local reference frame for test 2

	x [m]	y [m]	z [m]	TAS [m/s]	Track wrt x [deg]
Ownship	0	0	1000	35	0
Intruder	17000	500	1000	35	180

Both the aircraft are performing straight and level flight towards their selected destination waypoints, so the geometry here considered leads to a loss of separation according to head-on encounter.

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3.1.3. Test 3 plan

The initial conditions for ownship and intruder of interest are reported in Table 3.

Table 3. Ownship RPAS and intruder starting position in local reference frame for test 3

	x [m]	y [m]	z [m]	TAS [m/s]	Track wrt x [deg]
Ownship	0	0	1000	35	0
Intruder	16000	0	1000	35	180

Both the aircraft are performing straight and level flight towards their selected destination waypoints, so the geometry here considered leads to a loss of separation and, then, to a collision condition, according to head-on encounter. It is worth noticing here that, in order to allow the activation of the Collision Avoidance functionality, the maneuver proposed by the Separation Assurance functionality is voluntarily ignored by the Remote Pilot, so allowing the ownship RPAS continuing its flight plan, until the distance threshold set for the activation of the Collision Avoidance functionality is reached. This Collision Avoidance test has been preliminarily examined in the reference paper [14] and is here addressed once again in order to provide its deeper analysis, also with respect to the additional exemplary Collision Avoidance test 4 here reported.

3.1.4. Test 4 plan

The initial conditions for ownship and intruder of interest are reported in Table 4.

Table 4. Ownship RPAS and intruder starting position in local reference frame for test 4

	x [m]	y [m]	z [m]	TAS [m/s]	Track wrt x [deg]
Ownship	0	0	1000	35	0
Intruder	13000	0	1000	35	180

Both the aircraft are performing straight and level flight towards their selected destination waypoints, so the geometry here considered leads to a loss of separation and, then, to a collision condition, according to head-on encounter.

3.2. Test Results

In the following, the results of the tests whose plan is detailed in section 3.1 are reported and discussed in order to provide indications and examples about the ASACAS system performances and limitations.

3.2.1. Test 1 results

The evolution of the flight is represented in Figure 3 and in Figure 4.

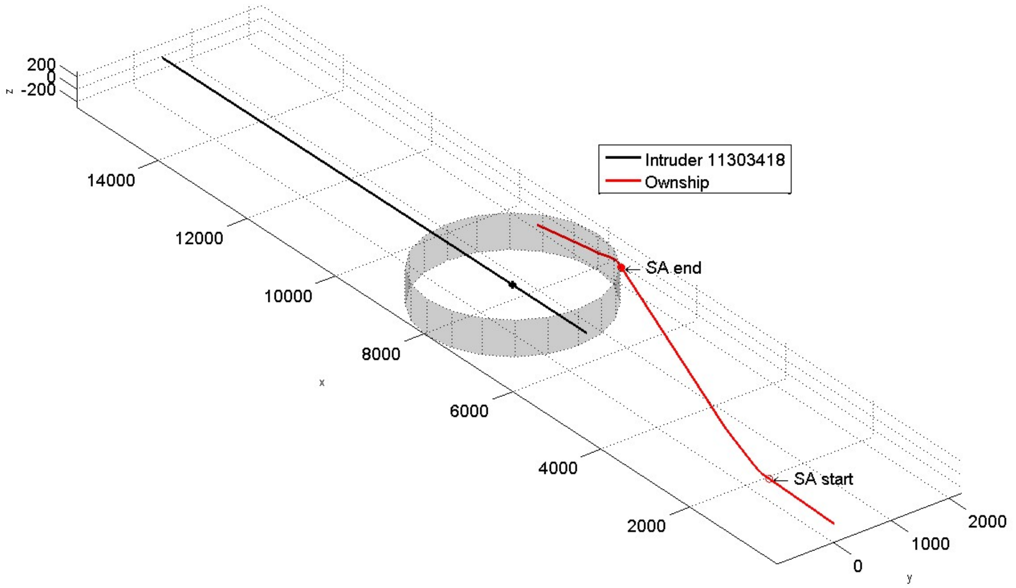

Figure 3. Test 1, automatic separation assurance manoeuver, 3D trajectory of ownship and conflicting intruder

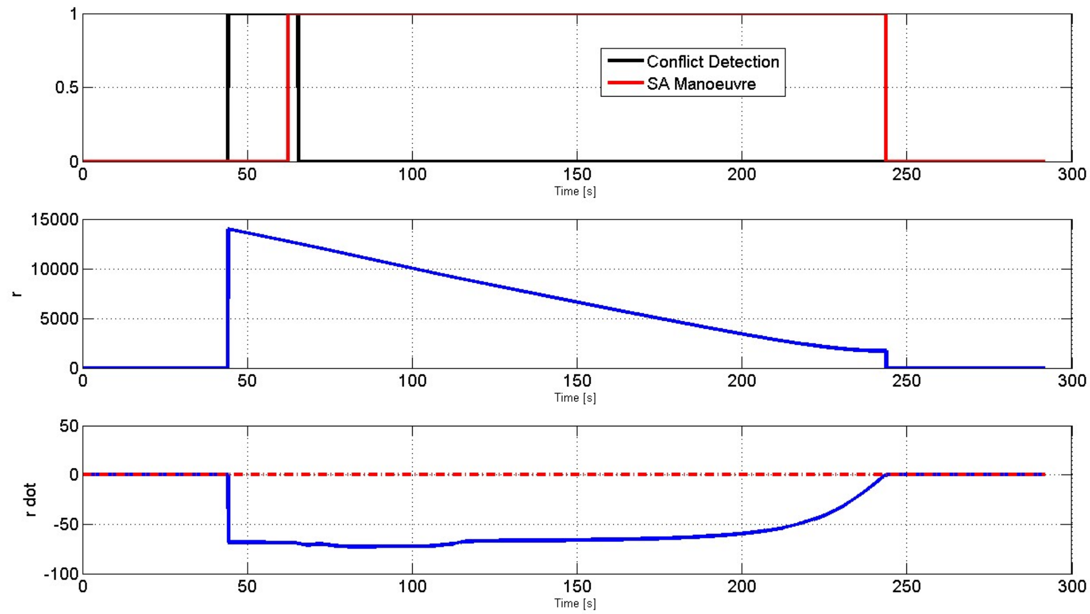

Figure 4. Test 1, automatic separation assurance manoeuver, parameters of interest

When the distance threshold set for the activation of the Separation Assurance function is reached, the system indicates to the Remote Pilot the predicted loss of separation condition and, at the same time, it starts proposing suitable Separation Assurance manoeuver to be implemented by the ownship. The Remote Pilot, once analyzed the proposed maneuver (that is updated at a proper rate by the ASACAS system), provides his clearance for the activation and, in this specific test, requests the automatic implementation of the manoeuver by the Autopilot, i.e. requests to ASACAS to automatically send the Separation Assurance maneuver reference commands to the Autopilot. The Separation Assurance manoeuver for this head-on encounter geometry consists in about 20 deg track

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variation and in a simultaneous ownship altitude reduction of about 200 m, as represented in Figure 3.

This leads to a trajectory of ownship (the conflicting intruder is continuing its straight-levelled flight undisturbed) that is tangent to the separation volume centered in the intruder and whose size is increased with respect to the nominal one based on the closure rate between vehicles at the moment where the maneuver has been frozen by the system. It is worth noticing here that the Separation Assurance maneuver is the one cleared by the Remote Pilot; nevertheless some fine tuning of it is still possible and automatically implemented by the ASACAS system during the manoeuver execution, if needed based on the current traffic picture. The updates of the maneuver are indicated by the signal "Conflict Detection" raising to 1 in Figure 4**,** whereas the implementation of the manoeuver is indicated by the signal "SA Manouvre" maintaining the level 1 in the same figure.

The analysis of Figure 4 then, allows observing that, in this real time simulation test, the conflict condition has been detected by the ASACAS system at about 44 s and so the self-separation manoeuver started to be proposed to the pilot few moments after that time (due to elaboration time and transmission latency). The Remote Pilot examined the manoeuvers real-time updated by the system at proper frequency and, at about 62 s, cleared the automatic execution of the proposed manoeuver by the system.

The minimum distance between vehicles (i.e. the distance at the Closest Point of Approach, CPA) is about 1700 m, coherently with the set dimension of the Separation Volume and so the ownship trajectory is tangent to the Separation Volume. The Separation Assurance manoeuver has been completed at about 243 s, when the range rate between vehicles became positive (the vehicles started diverging). It is worth noticing here that the range and range rate indicated in Figure 4 are calculated only during the Separation Assurance function execution, i.e. from about 44 s to about 243 s, and, therefore, the null values indicated outside this time interval have no meaning in the figure.

The Separation Assurance functionality of the ASACAS system, therefore, showed to perform as expected in the real time simulation test here described.

3.2.2. Test 2 results

The evolution of the flight is represented in **Figure 5** and **Figure 6**.

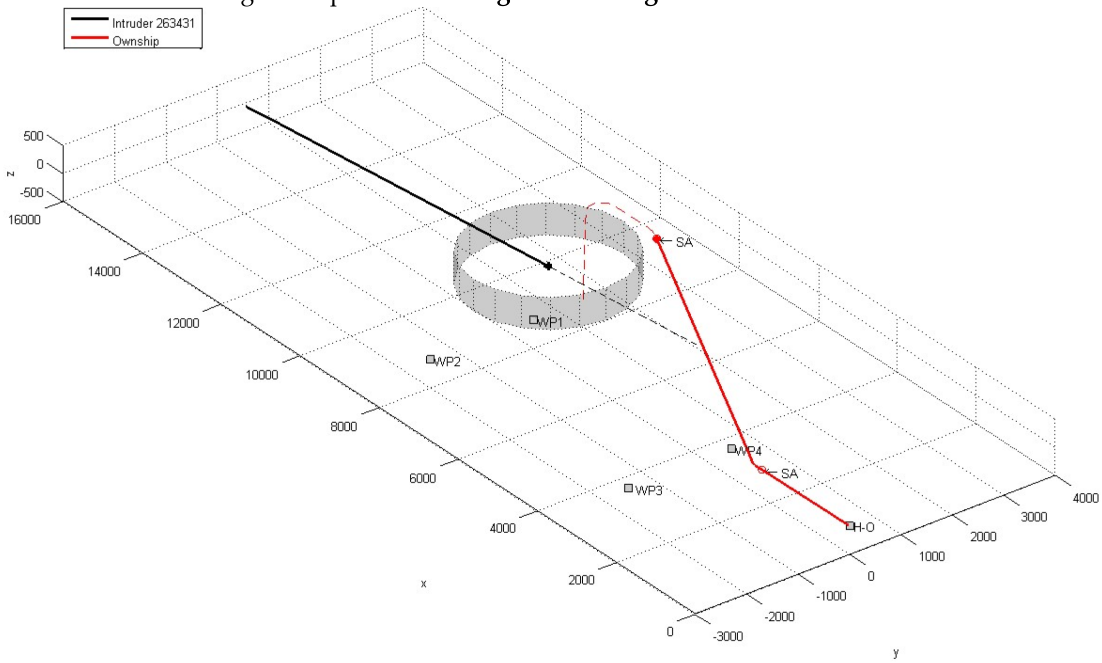

Figure 5. Test 2, automatic separation assurance manoeuver, 3D trajectory of ownship and conflicting intruder

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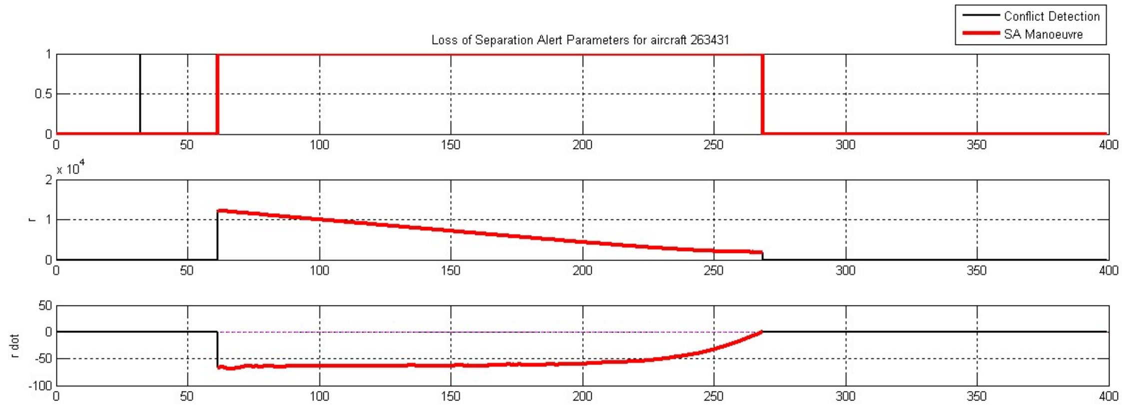

Figure 6. Test 2, automatic separation assurance manoeuver, parameters of interest

When the distance threshold set for the activation of the ASACAS Separation Assurance function is reached, the DAA system indicates to the Remote Pilot the predicted loss of separation condition and, at the same time, it starts proposing suitable self-separation manoeuver to be implemented by the ownship. The Remote Pilot, once analyzed the proposed maneuver (that is updated at a proper rate by the system), provides his clearance for the activation and, in this specific test, requests the automatic implementation of the manoeuver by the ASACAS system itself through the remotely piloted vehicle Autopilot. The self-separation manoeuver for this head-on encounter geometry is represented by about 25 deg track variation and by a simultaneous ownship altitude reduction of about 300 m, as represented in **Figure 5**. The ownship trajectory does not seem to be tangent to the separation volume; this is due to the unavailability of some recorded data and, then, the need of approximate computation offline of the separation volume dimensions.

The analysis of Figure 6, then, allows observing that, in this real time simulation test, the conflict condition has been detected by the ASACAS system at about 30 s and so the self-separation manoeuver started to be proposed to the pilot few moments after that time (due to elaboration time and transmission latency). The Remote Pilot examined the manoeuvers real-time updated by the DAA system at proper frequency and, at about 65 s, cleared the automatic execution of the proposed manoeuver by the system through the aircraft Autopilot.

The minimum distance between vehicles (i.e. the distance at the Closest Point of Approach, CPA) is about 1800 m, coherently with the set dimension of the Separation Volume. The self-separation manoeuver has been completed at about 270 s, when the range rate between vehicles became positive (the vehicles started diverging). It is worth noticing here that the range and range rate indicated are calculated only during the Separation Assurance function execution; therefore the null values indicated outside this time interval have no meaning in the figure.

The Separation Assurance functionality of the ASACAS system, therefore, showed to perform as expected in the real time simulation test here described.

3.2.3. Test 3 results

The evolution of the flight is represented in Figure 7 and Figure 8.

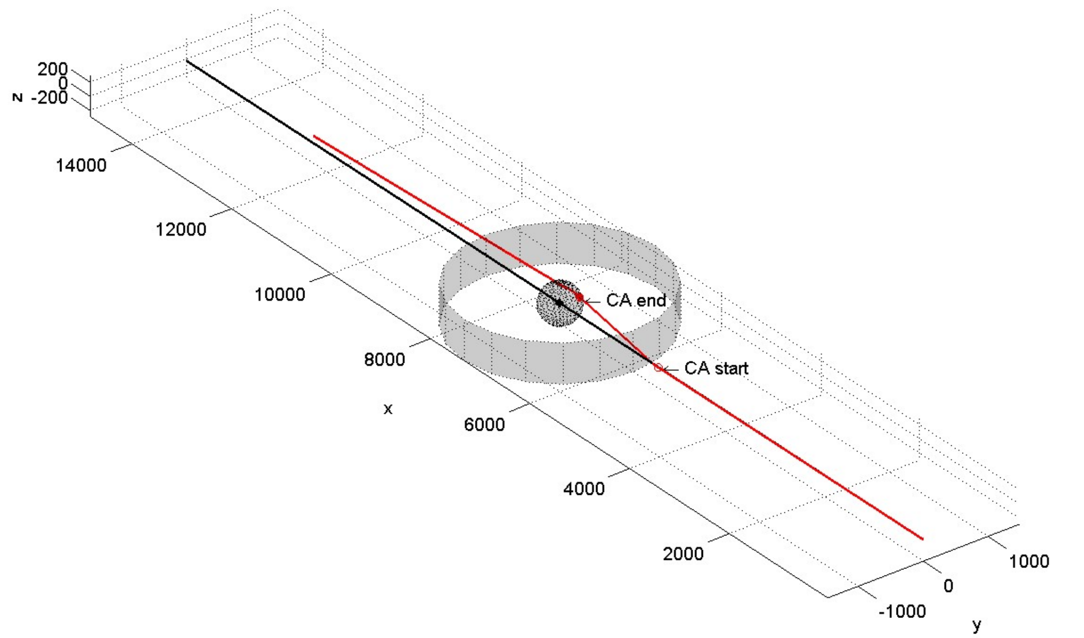

Figure 7. Test 3, automatic collision avoidance manoeuver, 3D trajectory of ownship and colliding intruder

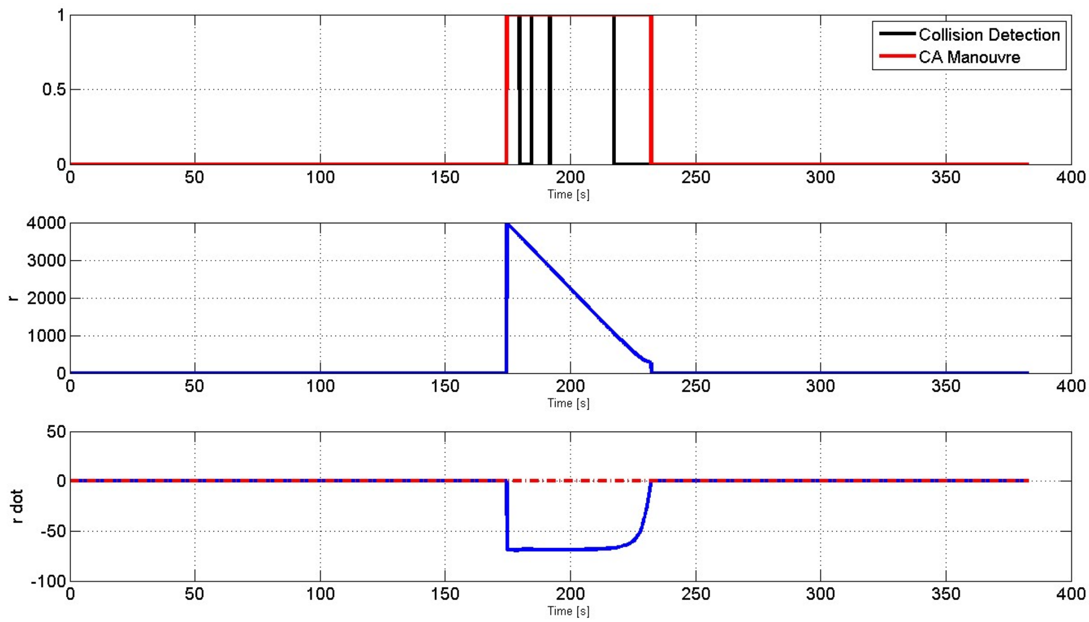

Figure 8. Test 3, automatic collision avoidance manoeuver, parameters of interest

When the distance threshold set for the activation of the ASACAS system Collision Avoidance function is reached, the DAA system indicates to the Remote Pilot the predicted collision condition and automatically starts executing suitable collision avoidance manoeuver allowing the ownship to avoid the collision. The Remote Pilot monitors the collision avoidance manoeuver executed by the system and he has the possibility to abort it and take the control of the RPAS, if desired.

The Collision Avoidance manoeuver for this head-on encounter geometry consists in a planar only maneuver with about 10 deg track variation, as represented in Figure 7. This leads to a trajectory of ownship (the colliding intruder is continuing its straight-levelled flight undisturbed) that is tangent to the collision volume centered in the intruder and whose size is increased with respect to

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the nominal one above indicated based on the closure rate between vehicles at the moment where the collision avoidance maneuver has been frozen by the ASACAS system. It is worth noticing here that the collision avoidance maneuver can be automatically updated by the DAA system during its execution, if needed based on the current traffic picture. The updates of the maneuver are indicated by the signal "Collision Detection" raising to 1 in Figure 8, whereas the implementation of the manoeuver is indicated by the signal "CA Manouvre" maintaining the level 1 in the same figure.

The analysis of Figure 8, in addition, allows observing that in this real time simulation test the collision condition has been detected by the DAA system at about 175 s and at the same time the collision avoidance manoeuver started to be automatically executed by the system (after the proper very small elaboration time) through automatic transmission of the maneuver reference commands to the aircraft Autopilot.

The minimum distance between vehicles (i.e. the distance at the Closest Point of Approach, CPA) is of about 280 m, coherently with the set dimension of the Collision Volume and so the ownship trajectory is tangent to the Collision Volume. The collision avoidance manoeuver has been completed at about 232 s, when the range rate between vehicles became positive (the vehicles started diverging). As in the previous tests, the range and range rate indicated are calculated only during the Collision Avoidance functionality execution, so from about 175 s to about 232 s; therefore the null values indicated outside this time interval have no meaning in the figure.

The Collision Avoidance functionality of the ASACAS system, therefore, showed to perform as expected in the real time simulation test here described.

3.2.4. Test 4 results

The evolution of the flight is represented in Figure 9 and Figure 10.

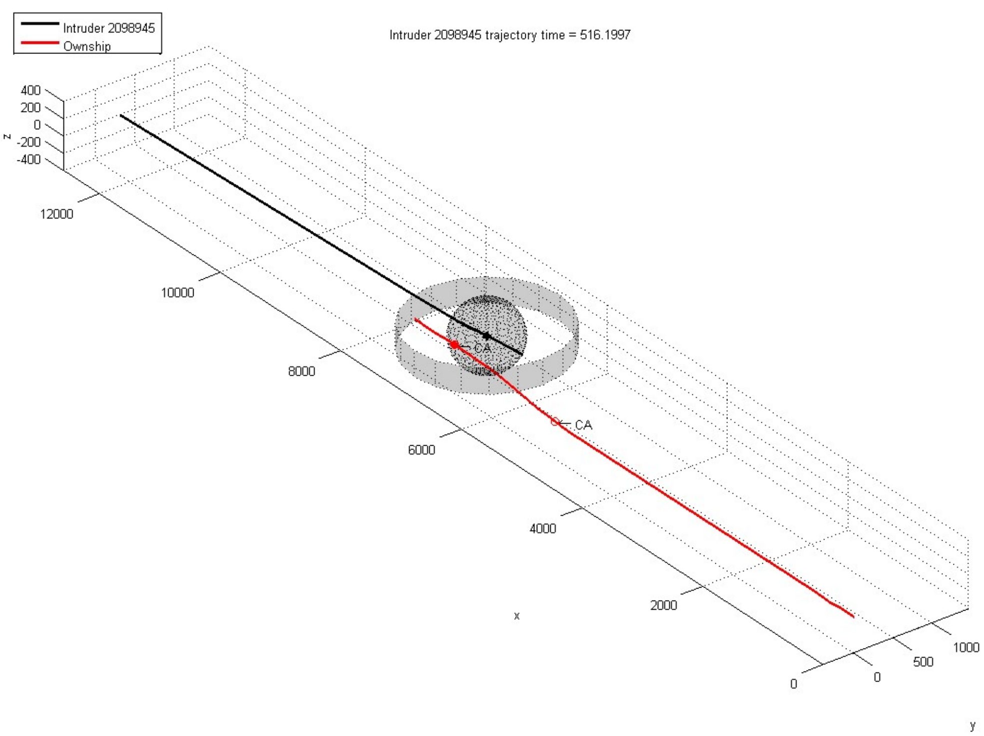

Figure 9. Test 4, automatic collision avoidance manoeuver, 3D trajectory of ownship and colliding intruder

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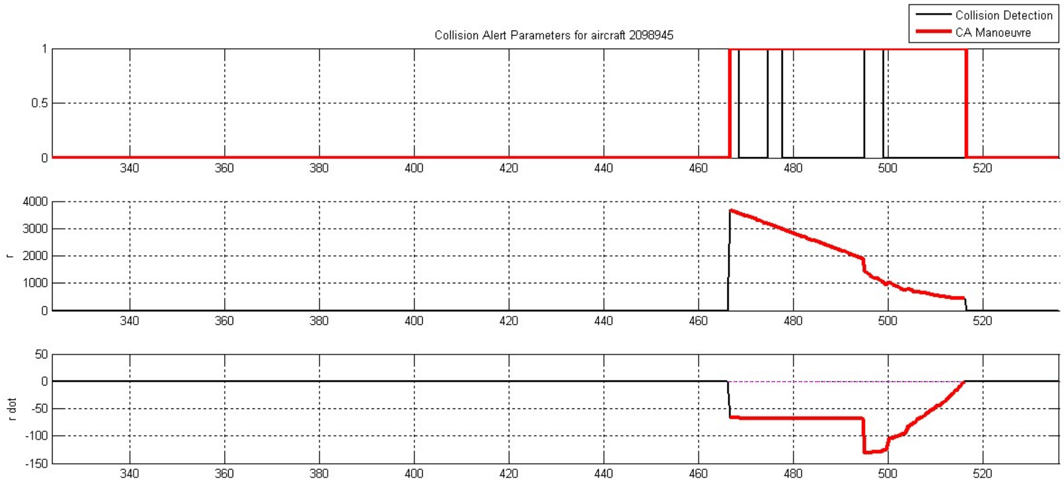

Figure 10. Test 4, automatic collision avoidance manoeuver, parameters of interest

When the distance threshold set for the activation of the ASACAS system Collision Avoidance function is reached, the DAA system indicates to the Remote Pilot the predicted collision condition and automatically starts executing suitable collision avoidance manoeuver allowing the ownship to avoid the collision. The Remote Pilot monitors the collision avoidance manoeuver executed by the system and he has the possibility to abort it and take the control of the RPAS, if desired.

The collision avoidance manoeuver for this head-on encounter geometry leads to a 3D variation of the ownship trajectory (the colliding intruder is continuing its straight-levelled flight undisturbed) that leads this modified trajectory to be tangent to the collision volume centered in the intruder. Its size is increased with respect to the nominal one above indicated based on the closure rate between vehicles at the moment where the collision avoidance maneuver has been frozen by the ASACAS system. It is worth noticing here that the collision avoidance maneuver can be automatically updated by the DAA system during its execution, if needed based on the current traffic picture. The updates of the maneuver are indicated by the signal “Collision Detection” raising to 1 in Figure 10, whereas the implementation of the manoeuver is indicated by the signal “CA Manouvre” maintaining the level 1 in the same figure.

The analysis of Figure 10 then, allows observing that in this real time simulation test the collision condition has been detected by the DAA system at about 465 s and at the same time the collision avoidance manoeuver started to be automatically executed by the system (after the proper very small elaboration time).

The minimum distance between vehicles (i.e. the distance at the Closest Point of Approach, CPA) is of about 460 m, coherently with the set dimension of the Collision Volume and the computed extra-size, so the ownship trajectory is tangent to the Collision Volume. The collision avoidance manoeuver has been completed at about 515 s, when the range rate between vehicles became positive (the vehicles started diverging). As already indicated in the previous tests, the range and range rate are calculated only during the Collision Avoidance functionality execution; therefore, the null values indicated outside this time interval have no meaning in the figure.

The Collision Avoidance functionality of the ASACAS system, therefore, showed to perform as expected in the real time simulation test here described.

5. Conclusions

The paper reported some exemplary experimental results obtained through the real-time validation, with hardware and human in the loop (RTS-HIL) simulations, of an automatic ADS-B based Separation Assurance and Collision Avoidance System (ASACAS) aimed to support RPAS automatic operations as well as remote pilot decision making. The paper described the background, motivation and design steps that led to the development, implementation and testing of the ASACAS system. In addition, the paper provided a description of the Concept of Operations of the system and of its architectural organization and summarized the main concepts implemented in the system, identifying its main functions and their mutual connection in the overall integrated system.

From the description of the exemplary real-time simulation with hardware and pilot in the loop tests, which are referred to both Separation Assurance and Collision Avoidance test scenarios, and from the analysis and discussion of the related results, it emerged that the ASACAS systems behave as expected in the tests: it demonstrated to be able to support the Remote Pilot in performing the separation management task, at tactical level, and to be able to perform automatic collision avoidance, at emergency level.

The elaborated maneuvers, both for self-separation and for collision avoidance, are able to minimize the deviation from the original flight path while being able to prevent the infringement of the assigned safety volumes.

The self-separation maneuver has been designed according to the early feedbacks and suggestions provided by the very experienced test pilots that acted as Remote Pilot: in particular, the Separation Assurance functionality of the ASACAS has been designed to provide maneuver that preferably acts on only one flight dimension (longitudinal, lateral, speed), with assigned priority to lateral changes (track deviation), priority that is in any case a parameter that can be set as desired. This design choice changed the initial implementation of the functionality, where the design was aimed to obtain 4D maneuver, and has been motivated by the need of providing the pilot with the minimum amount of workload in evaluating and implementing the proposed maneuver. Under such perspective, indeed, it is much more convenient for the pilot to manage a suggested maneuver affecting only one flight dimension than a while 4D maneuver. Therefore, the Conflict Resolution functionality assigns specified priority to the possible resolution maneuvers so as to select the one that minimizes the workload for the Remote Pilot and only in case this is not possible, due to the particular conflict scenario, the system increases the maneuver complexity, up to a full 4D maneuver. This is a relevant added value of the system.

Future work will address many possible improvements of the system. It is currently designed to be used in en-route phase of the flight and its extension to TMA (Terminal Maneuvering Area) operations is a future improvement of the system. In addition, the collision avoidance functionality of the system is limited to sequential single-collision management and does not specifically take into account the Rules of the Air and self-compatibility requirements. Therefore, future improvements will be needed to address these important aspects.

Finally, as indicated in the introductory part of the paper, the system has been also validated in real flight trials, which will be the subject of future publications.

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Conflicts of Interest: The authors declare no conflict of interest.

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