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Aircraft Automatic Collision Avoidance Using Spiral Geometric Approach

M. Orefice, V. Di Vito

Abstract**—**This paper provides a description of a Collision Avoidance algorithm that has been developed starting from the mathematical modeling of the flight of insects, in terms of spirals and conchospirals geometric paths. It is able to calculate a proper avoidance manoeuver aimed to prevent the infringement of a predefined distance threshold between ownship and the considered intruder, while minimizing the ownship trajectory deviation from the original path and in compliance with the aircraft performance limitations and dynamic constraints. The algorithm is designed in order to be suitable for real-time applications, so that it can be considered for the implementation in the most recent airborne automatic collision avoidance systems using the traffic data received through an ADS-B IN device. The presented approach is able to take into account the rules-of-the-air, due to the possibility to select, through specifically designed decision making logic based on the consideration of the encounter geometry, the direction of the calculated collision avoidance manoeuver that allows complying with the rules-of-the-air, as for instance the fundamental right of way rule. In the paper, the proposed collision avoidance algorithm is presented and its preliminary design and software implementation is described. The applicability of this method has been proved through preliminary simulation tests performed in a 2D environment considering single intruder encounter geometries, as reported and discussed in the paper.

Keywords**—**Collision Avoidance, RPAS, Spiral Geometry, ADS-B Based Application.

I. Introduction

DURING the lasts years, the development of Remotely Piloted Aircraft Systems (RPAS) has been characterized by an exponential growth, both in military applications and in civil and commercial environments. One of the major challenges related to the extensive use of RPAS is their integration into the civil airspace. The outcomes of researches, carried out both in Europe and in the US, individuate the Sense and Avoid technology as a key enabler for the RPAS integration into civil airspace while targeting suitable level of safety.

Pham et al. [1] present a review on collision avoidance systems (CASs) focusing on the sense and detection methods and on the collision avoidance manoeuver approaches.

One of the most recent and promising proposed solutions is based on the development of Sense and Avoid systems based on the use of Automatic Dependent Surveillance – Broadcast (ADS-B) technology, which will be mandatory from 2020, in the US [2] and in Europe, for all aircraft flying in Class A, B, and C airspaces. References [3]-[9] show CASs based on ADS-B technology. These methods differ for both the collision detection methods and the collision avoidance maneuver calculation approaches. The collision detection method proposed in [3] can be categorized as a worst-case method: a threat-region is computed considering an estimation of all possible intruder trajectories. The resolution maneuver is provided in terms of heading commands. The main drawback of this methodology for collision avoidance manoeuver calculation is that the computation of the threat-region could be inefficient, even if it assures that no collision can happen, so preventing the application in real-time systems.

Another method proposed in literature, presented in [4], computes the collision probability considering the uncertainties associated to the ADS-B measurements and by using Monte-Carlo simulations. Therefore, threat levels are defined and an avoidance maneuver is computed for each of them. Also in this case, the associated computational burden is huge, due to need of using Monte-Carlo Simulations for the computation of the collision probability.

The collision detection method based on geometric approach proposed in [5], then, considers a predicted violation of predefined separation minima. In this case, a heading command is imposed in order to increase the predicted distance at the closest point of approach. The method has not a huge processing computation but it is necessary the cooperation of involved threat aircraft.

Another method that considers the violation of a minimum safe horizontal separation threshold and the generation of a proper heading angle reference in order to restore the minimum allowed separation distance is presented in [6]. The collision resolution problem is considered as a phase of the overall path planning design.

Similar to the methodology proposed in [6], also the methods proposed in [7] and [8] formulate the collision avoidance problem as path planning task, with pre-assigned waypoints, space and separation constraints, height limit and geo-fences constraints.

Once again, in [9] a collision detection criterion, based on the violation of a safe separation threshold, is presented. In this case, the collision avoidance maneuver is obtained from the resolution of an optimization problem. In particular, a trajectory collision risk assessment is performed in order to create a function that assigns a collision potential to a given trajectory.

A promising approach based on monocular cameras, for the

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collision detection, is proposed in [10]. This method is considered very interesting due to the small size, light weight and low power consumption of the required sensor; nevertheless, the method may have a low velocity response due to blurry images especially in dark environments, so it may result not suitable for real-time applications.

The collision avoidance method, proposed by Bai et al. [11], is based on the partially observable Markov decision process (POMDP) and the collision avoidance resolution logic is generated automatically by solving the model that specifies the goal and the operating environment of the system. The collision detection is relatively simple and is based on a safe separation distance. Also this methodology, nevertheless, even if relatively simple involves very high computational complexity, so resulting not convenient for real-time applications.

References [12] and [13] propose a collision avoidance method for more than two unmanned vehicles. The collision detection condition is verified if the distance between agents is lower than the sum of the radius computed around the aircraft involved in the conflict. The avoidance maneuver is obtained by overwriting a potential filed output by an ad hoc turning rate.

An optimized trajectory for the collision avoidance is presented in [14], where the convergence of the method has been proved through a Monte Carlo simulation.

A very interesting approach, for a collision avoidance maneuver elaboration, is proposed in [15] and [16]. The approaches are based on the theorems examined in [17] about spirals and conchospirals in the flight of insects. The state vector and the objective function are designed to simultaneously guide the aircraft along a safe spiral trajectory whilst providing an indication of an appropriate point to stop the avoidance manoeuver.

An image-based sense and avoid approach is reported in [18]. The approach provides lateral or vertical separation without range estimation and a simple termination criterion is used for the avoidance maneuver. Furthermore, the Air Force Research Laboratory and Lockheed Martin developed an Automatic Collision Avoidance System in order to perform aggressive maneuver to avoid collisions [19]. The maneuver is computed through an optimization tool that chooses, among a set of available maneuvers, the best one to be applied.

Finally, the Federal Aviation Administration (FAA) has formed a team in order to develop a new ACAS (Airborne Collision Avoidance System) technology, identified as ACAS X, intended to define the next international standards for collision avoidance. The ACAS X program has the goal of introducing a plug-and-play surveillance architecture based on GPS data and other sensors such as radar and electro-optical sensors. The logic is based on an optimization process and it takes as input a probabilistic dynamic model and a multi-objective utility model [20], [21].

For what concerns the collision avoidance problem, the Italian Aerospace Research Center (CIRA) is carrying out specific activities aimed to identify a new collision avoidance manoeuver calculation methodology that is suitable for real-time implementation, so constituting a promising technological enabler for the safe RPAS integration into the civil airspace. Based on the results of the above summarized literature analysis and taking into account the fundamental requirement above indicated, in this paper a collision avoidance methodology is proposed that is based on the findings emphasized in [17].

The paper is organized as follows. Section II introduces the overall sense and avoid system architecture where the proposed collision avoidance algorithm is expected to be implemented. Section III provides a description of the collision avoidance strategy in a 2D environment. The results of a preliminary numerical validation campaign, carried out through fast-time simulations considering typical 2D collision avoidance scenarios, will be presented in Section IV. Finally, in Section V the conclusions and the future works are described.

II. System Architecture

The functional architecture of the whole collision avoidance system in which the collision resolution module is implemented is shown in Fig. 1 [22]. The overall system comprises, in addition to the collision resolution, five propaedeutic main functionalities, which will be introduced in the following.

Provided that the system receives traffic data from the ADS-B IN on-board equipment, the Surveillance Processing module is aimed to implement the processing of the raw ADS-B IN data in order to allow their use by the system.

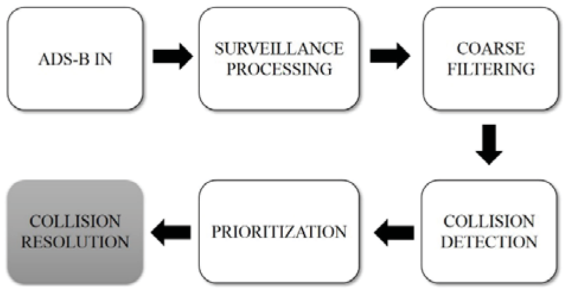

Fig. 1 Overall Collision Avoidance System architecture

Since the ADS-B IN equipment is intrinsically able to receive and provide as output traffic information including targets that may be located very far from ownship, up to even 40 nautical miles, a pre-selection of the traffic is needed. Therefore, the Coarse Filtering functionality aims excluding from the collision detection the targets whose range from the ownship is greater than a specified threshold. The Collision Detection module, then, performs the pairwise check about the collision condition between ownship and each considered aircraft. The criterion applied for conflict detection is the one usually adopted in literature, based on the consideration of both the predicted distance at the closest point of approach between ownship and the considered aircraft and the range rate.

The results of the check may include multiple conflicts, i.e. more than one surrounding aircraft may pose a threat to ownship; therefore, proper prioritization criterion is implemented by dedicated Collision Prioritization module in order to select the most dangerous vehicle.

Finally, the obtained information is sent to the Collision Resolution module in order to elaborate the calculation of the collision avoidance maneuvers.

Reference [22] provides a detailed description of the modules mentioned above, that are out of the scope of this paper. The algorithm implemented in the Collision Resolution module, which is the specific scope of this paper, is described in the following Section III.

III. Collision Avoidance Approach

This section describes the calculation methodology proposed for the elaboration of the collision avoidance maneuver to be followed by the ownship if a collision condition with another aircraft is detected. At the present stage of the algorithm design, only the planar geometry is considered, so the problem is here described with reference to a 2D framework. The collision detection is performed considering a safety circular region around the intruder aircraft and a prediction of the intruder trajectory, under the hypothesis of straight-leveled flight with uniform motion. The collision detection criterion consists in verifying if the predicted distance at the closest point of approach, over the considered time horizon, is lower than the predefined safety radius. The collision detection is out of the scope of this document; more information can be found in [23]. In the following, the collision avoidance maneuver calculation methodology will be described.

A. Spiral Planar Low of Motion

The avoidance trajectory generation problem is here addressed using a Cartesian reference frame with origin located in an arbitrary point. As reported in [17], if a light source is placed in the origin of the assumed reference frame, a flying insect would describe an approaching spiral trajectory towards the light source keeping constant the angle $0 < \alpha < \pi/2$ between the direction of the flight and the direction towards the source.

Considering a 2D geometry, in polar coordinates the law of motion is:

$$\begin{aligned} x(t) &= r(t)\cos(\theta(t)) \\ y(t) &= r(t)\sin(\theta(t)) \end{aligned} \tag{1}$$

where *t* is the time, *r* and θ are the radial and angular polar coordinates, respectively.

Setting $r(0) = r_0$ and $\theta(0) = \theta_0$, it is possible to obtain:

$$r(t) = -(V\cos\alpha)t + r_0 \tag{2}$$

and

$$\theta(t) = \theta_0 - \ln\left(1 - \frac{Vt}{r_0}\cos\alpha\right)\tan\alpha \tag{3}$$

under the natural assumption that the insect flies with a constant speed *V* and that $0 \le t \le r_0/(V\cos\alpha)$.

It is worth noticing here that the flight will end at $t = r_0/(V\cos\alpha)$, although $-\ln\left(1 - \frac{Vt}{r_0}\cos\alpha\right) \to +\infty$ when $t \to r_0/(V\cos\alpha)$.

Substituting (2) and (3) in (1), the low of motion turns into:

$$\begin{aligned} x(t) &= (r_0 - Vt\cos\alpha)\cos\left[\theta_0 - \ln\left(1 - \frac{Vt}{r_0}\cos\alpha\right)\tan\alpha\right] \\ y(t) &= (r_0 - Vt\cos\alpha)\sin\left[\theta_0 - \ln\left(1 - \frac{Vt}{r_0}\cos\alpha\right)\tan\alpha\right] \end{aligned} \tag{4}$$

The relations (4) will be used in order to define the collision avoidance maneuver, where:

- r_0 is the initial distance between the ownship and the intruder aircraft;
- θ_0 is the initial angular polar coordinate of the ownship in the reference frame with origin in the target point, which is the final destination point towards which the ownship aircraft has to fly in order to avoid the collision;
- *V* is the velocity of the ownship, assumed as constant.

The hypothesis of uniform motion is here assumed not only for the ownship but also for the considered threat aircraft.

Once posed the collision avoidance trajectory generation problem in that form, the following parameters need to be defined:

- target point position;
- approaching angle α.

The methodologies used to set the values of these parameters are described in the following.

B. Target Point Position Definition

The computation of the target point position assumes a fundamental role in the definition of the collision avoidance maneuver. In fact, as mentioned above, this point will be the final destination point towards which the ownship aircraft has to fly.

In order to define the target point position, a 2D encounter geometry is here considered with the ownship and one intruder aircraft both in straight-leveled flight with uniform motion.

A local reference frame is here considered, with origin in the ownship, *x* axis along the ownship velocity vector, and *y* axis defined considering a counterclockwise rotation of *pi/2* rad with respect to the *x* axis.

In this reference frame, only the *x* coordinate identifies the closest point of approach. Therefore, the target origin point will be characterized by the same *x* coordinate and by a *y* coordinate necessary to exit the safety bubble constructed around the intruder. In fact, if a collision is detected, certainly the predicted closest point of approach is expected to be located inside the safety bubble. The *y* coordinate of the target origin point is chosen on the perpendicular straight line to the *x* axis and the sign is evaluated based on the Rules Of the Air.

The complete list of the Rules Of the Air can be found in [24]; nevertheless, in the algorithm here considered only a proper subset of them has been implemented, according to Fig. 2. In particular, four sectors of interest have been identified:

- If the intruder aircraft is approaching from Sector I or II, the ownship shall turn on the right. Therefore, the target origin point shall be, outside of the safety radius, on the right of the ownship. It shall have a negative *y* coordinate.
- If the intruder aircraft is approaching from Sector III, the ownship shall turn on the left. Therefore the target origin point shall be, outside of the safety radius, on the left of the ownship. It shall have a positive *y* coordinate.
- If the intruder is approaching from Sector IV, i.e. it is overtaking, no maneuver is needed.

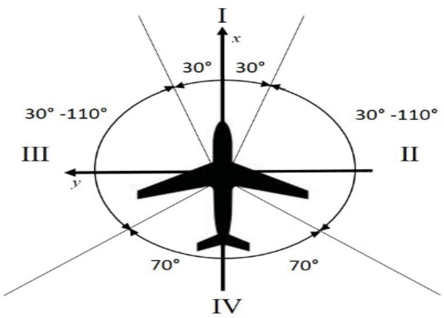

Fig. 2 Definition of sectors for encounter geometry

This scheme is based on the analysis presented in [25]. Therefore, the intruder approaching sector identifies the ownship turn side for the collision avoidance maneuver. The *y* coordinate value is set in order to move the target origin point on the safety bubble edge plus a conservative additional distance, here estimated as the 10% of the safety bubble radius. This conservative value has been evaluated based on the analysis of a set of a typical encounter geometry, in order to be sure that the whole collision avoidance calculated trajectory will be located outside the safety region.

C. Computation of the Angle α

In order to define the approaching angle α, a sensitivity analysis of the relation between θ and α has been carried out.

The angular polar coordinate of the ownship at the end of the flight computed on the edge of existence domain of the function (3), i.e. excluding the singularity, in the reference frame with origin in the target point is here indicated as θ_f. It is assumed that $\Delta\theta = \theta_f - \theta_0$. It is possible to verify that, once $\Delta\theta$ has been defined, the angle α is uniquely set, independently from θ_0, r_0 and *V*. In Fig. 3 the typical curve $\Delta\theta$ vs. α is shown, assuming $\theta_0 = 0$ deg, $r_0 = 4000$ m, and $V = 50$ m/s. Therefore, in order to obtain the angle α, it is necessary to define the angle θ_f. In order to facilitate the return to the route of the ownship, it is advantageous to align, at the end of the collision avoidance maneuver, the ownship to the direction it was flying before the collision avoidance maneuver was started. Considering that the angle θ_f is always defined in the reference frame with origin in the target point, it shall be equal to the ownship inertial speed orientation, in the same reference frame, before the collision avoidance maneuver was started.

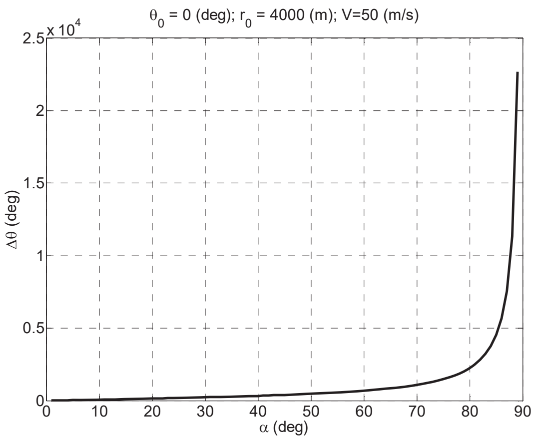

Fig. 3 Sensitivity analysis $\Delta\theta$ vs. α

Once the angle θ_f has been defined, it is possible to compute $\Delta\theta$ and, so, α.

An extensive simulation campaign has shown that the interval of interest, according to the typical approaching geometries, can be reduced to the interval $\alpha \in [0,42]$ deg (Fig. 4) or $\alpha \in [-42,0]$ deg with a specular behavior.

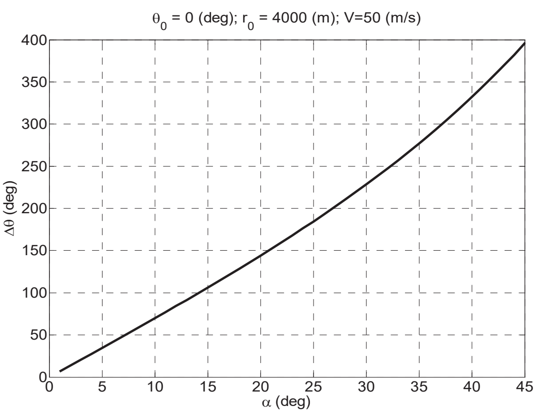

Fig. 4 $\Delta\theta$ vs. α interval of interest

IV. Numerical Validation

The proposed approach has been tested by means of fast-time numerical simulations, representing some relevant collision scenarios, aimed to assess the effectiveness of the proposed collision resolution methodology.

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Both the intruder and the ownship have been simulated by using simple point-of-mass kinematic model, with constant velocity, in a 2D environment.

Four typical scenarios are here reported, always including an encounter geometry involving one single intruder and the ownship, flying at the same altitude and speed in a planar environment. The scenarios have been designed so that the considered collision detection criterion is always verified; therefore, the intruder aircraft will be labeled as a threat. The four scenarios are listed below:

- *Scenario 1*: The threat aircraft and the ownship are in head-on geometry, flying at the same speed and altitude. Since the threat aircraft is approaching from Sector I (Fig. 2), the collision avoidance module shall recommend a right-turn maneuver.
- *Scenario 2*: A lateral collision geometry, with a 90 deg beam from the ownship right side, characterizes this scenario. The two aircraft fly at same speed and altitude. Since the threat aircraft is approaching from Sector II (see Fig. 2), the collision avoidance module shall recommend a right-turn maneuver.
- *Scenario 3*: A lateral collision geometry, with a 90 deg beam from the ownship left side, characterizes this scenario. The two aircraft fly at same speed and altitude. Since the threat aircraft is approaching from Sector III (see Fig. 2), the collision avoidance module shall recommend a left-turn maneuver.
- *Scenario 4*: A lateral collision geometry, with a 30 deg beam from the ownship left side, characterizes this scenario. The two aircraft fly at same speed and altitude. Since the threat aircraft is approaching from Sector I (Fig. 2), the collision avoidance module shall recommend a right-turn maneuver.

A. Scenario 1

In the first scenario, the ownship and the threat aircraft are flying at the same altitude in a head-on geometry. Referring to a fixed reference frame, with origin in the start point of the ownship trajectory, the initial input variables values are reported in

TABLE I.

TABLE I
SCENARIO 1 – INPUT PARAMETERS VALUES

	Threat Aircraft	Ownship
x position (m)	4000	0
y position (m)	0	0
velocity (m/s)	40	40
track angle (deg)	180	0

Fig. 5 shows the trajectories followed by the two aircraft in the fixed reference frame. Since the aircraft are in a collision geometry, the ownship implements the collision avoidance maneuver. The threat is approaching from Sector I (see Fig. 2) and, therefore, the ownship turns on the right side in order to avoid the collision. The safety region is represented, in Fig. 5, when the aircraft are at the closest point of approach.

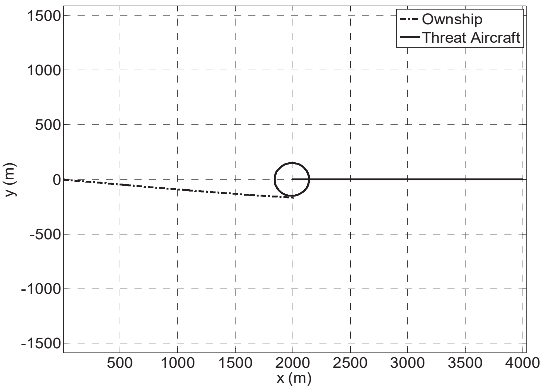

Fig. 5 Scenario 1 - Aircraft trajectories

Fig. 5 shows, according to Fig. 6, that the collision avoidance maneuver ends when the relative distance is minimum and the closure rate is null, i.e. at about 50 s of the simulation time. In fact, starting from this point, the two aircraft will start diverging and this condition represents the collision manoeuver termination criterion.

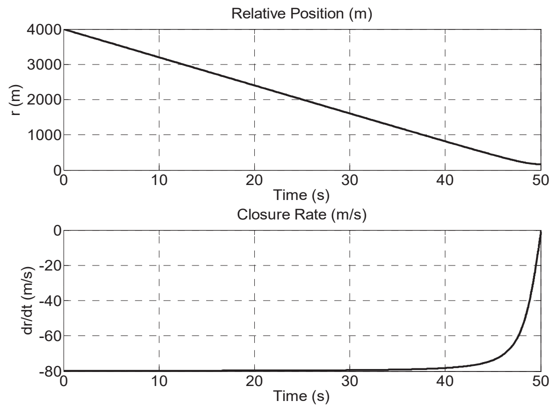

Fig. 6 Scenario 1- Relative distance and closure rate

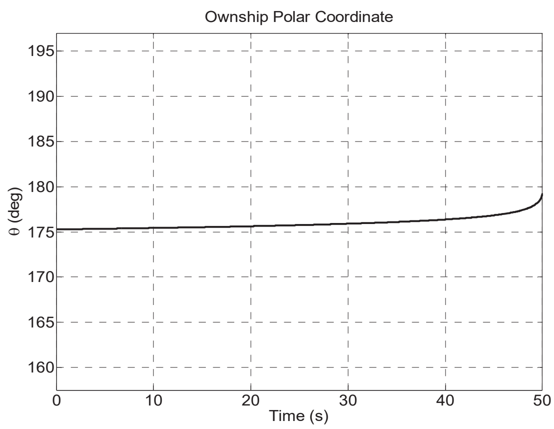

Fig. 7 Scenario 1 - Ownship polar angular coordinate

Finally, Fig. 7 shows the evolution of the angle θ in the reference frame with origin in the target point.

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Starting from the initial value $\theta_0 \approx 175$ deg, the ownship reaches the final value $\theta_f = 180$ deg at the end of the simulation. According to Fig. 4, the value of α is about 0.7 deg.

B. Scenario 2

The two aircraft, which characterize the second scenario, are in a lateral geometry approach. In particular, the threat aircraft is approaching from the right side of the ownship, with a beam angle of 90 deg. The initial input variables values are summarized in

TABLE II.

TABLE II
SCENARIO 2 – INPUT PARAMETERS VALUES

	Threat Aircraft	Ownship
x position (m)	2000	0
y position (m)	-2000	0
velocity (m/s)	40	40
track angle (deg)	90	0

Fig. 8 represents the trajectories followed by the aircraft in the second scenario.

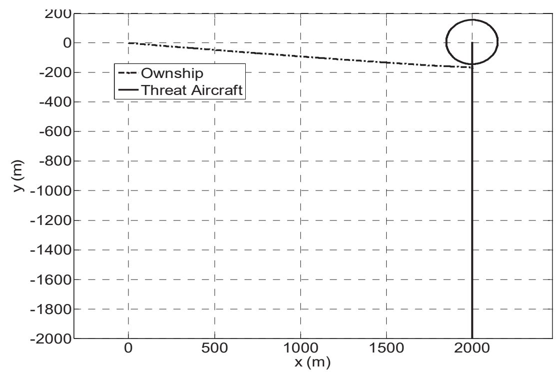

Fig. 8 Scenario 2 - Aircraft trajectories

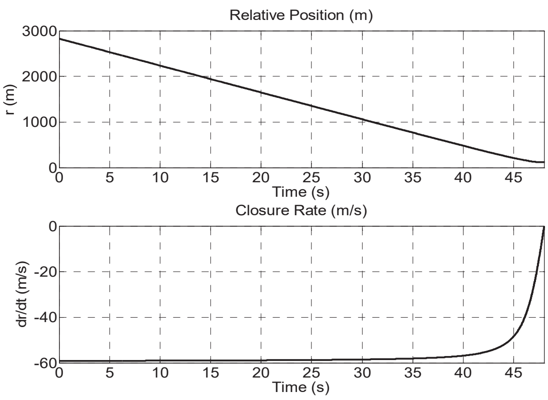

Fig. 9 Scenario 2 – Relative distance and closure rate

The threat aircraft is approaching from Sector II (see Fig. 2) and the collision resolution module suggests a turn on the right side, according to the rules of the air.

As in scenario 1, the evasive maneuver execution requires a duration of about 50 s, after which the aircraft start diverging (Fig. 9).

Even though the geometries of scenario 1 and scenario 2 are very different, the computed evasive maneuvers are very similar, as it can be seen in Fig. 10, with the value of α about 0.7 deg.

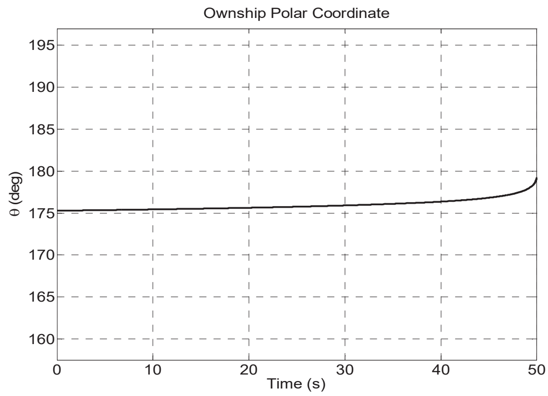

Fig. 10 Scenario 2 - Ownship polar angular coordinate

C. Scenario 3

The third scenario considers two aircraft in a lateral geometry. In particular, the threat aircraft is approaching from Sector III (see Fig. 2) and, hence, the ownship shall turn on the left side to avoid the collision.

TABLE III provides the initial parameters values for the considered approach geometry.

TABLE III
SCENARIO 3– INPUT PARAMETERS VALUES

	Threat Aircraft	Ownship
x position (m)	2000	0
y position (m)	2000	0
velocity (m/s)	40	40
track angle (deg)	270	0

The aircraft flight evolutions are represented in Fig. 11.

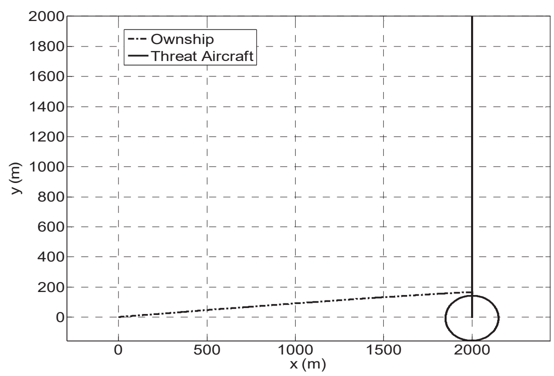

Fig. 11 Scenario 3 - Aircraft Trajectories

The evasive maneuver execution requires a duration of about 50 s, as reported in Fig. 12.

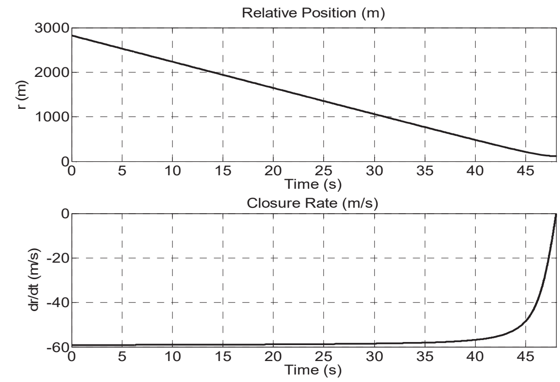

Fig. 12 Scenario 3 – Relative Distance and Closure Rate

As mentioned before, the avoidance maneuver requires a turn on the left side and, consequently, the $\Delta\theta$ shall be negative as well as α, which results of about -0.7 deg. The θ evolution during the flight is, therefore, reported in Fig. 13.

D.Scenario 4

Two aircraft in a lateral conflict geometry characterize the last scenario. Even though the threat aircraft is approaching from the left side of the ownship, the collision avoidance maneuver, according to the rules of the air, requires that the ownship turns on the right side. This is because the threat aircraft is approaching from Sector I (Fig. 2), being the approaching beam angle equal to 30 deg.

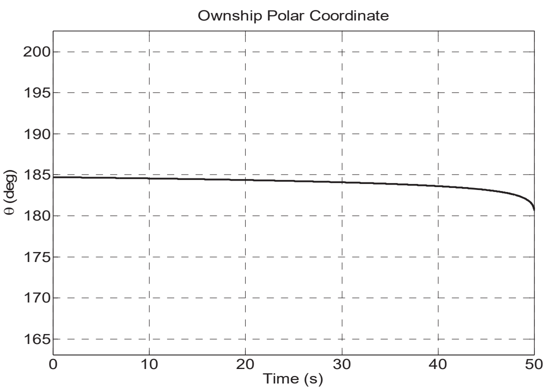

Fig. 13 Scenario 3 - Ownship angular polar coordinate

The initial flight conditions are reported in TABLE IV.

TABLE IV
SCENARIO 3– INPUT PARAMETERS VALUES

	Threat Aircraft	Ownship
x position (m)	3732	0
y position (m)	1000	0
velocity (m/s)	40	40
track angle (deg)	210	0

The trajectories followed by the two aircraft are represented in Fig. 14.

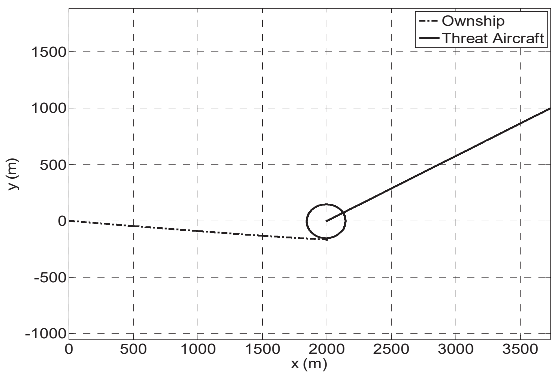

Fig. 14 Scenario 4 - Aircraft Trajectories

As in the previous scenarios, the avoidance maneuver execution requires a duration of about 50 s. After this time, the aircraft start diverging and the return to the route maneuver should be implemented. Fig. 15 represents the relative distance and the closure rate. Also in this case, the imposed $\Delta\theta$ (Fig. 16) determines an α angle of about 0.7 deg.

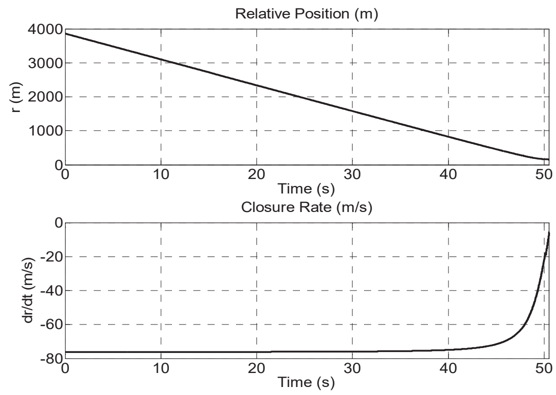

Fig. 15 Scenario 4 – Relative distance and closure rate

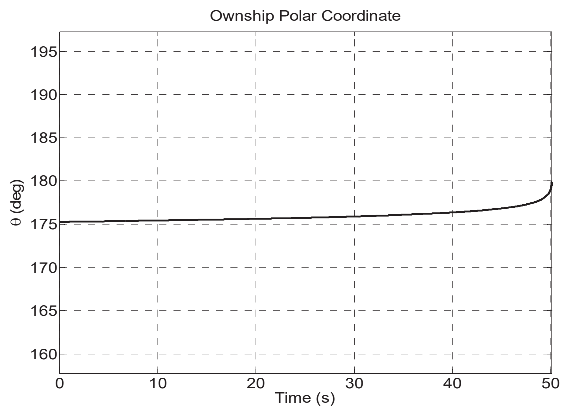

Fig. 16 Scenario 4 - Ownship polar angular coordinate

V. CONCLUSIONS

In this paper, a methodology for the real-time elaboration of a proper collision avoidance manoeuver, based on a spiral geometric approach, has been presented and discussed. The methodology has been developed, up to date at a preliminary design stage, by the Italian Aerospace Research Center (CIRA) in order to be proposed for the implementation in future Detect and Avoid systems, constituting technological enabler for the safe RPAS integration into the civil airspace.

After describing the mathematical modeling of the proposed algorithm, as well as the functional architecture of the overall collision avoidance system where this algorithm is expected to be implemented, in the paper also the results of a preliminary numerical assessment campaign have been reported and commented. These results, even if referred to simplified fast-time simulation environment considering 2D point-of-mass models, shown the effectiveness of the proposed algorithm and provided promising outcomes for the prosecution of the design activity.

The main advantages of the proposed methodology are its suitability for real-time application, being it based on closed form mathematical formulation of the elaborated collision avoidance manoeuver, and the capability of elaborating the whole collision avoidance manoeuver in a single computation step, once the collision resolution module is activated.

Up to date, the methodology has been developed by considering only the horizontal plane and one single intruder. In this design work, some limitations of the proposed methodology have been emphasized, which will be addressed in the design activity prosecution. In particular, the limitations to be overcome refer to the need of developing a mathematical procedure to set the target point of the collision avoidance manoeuver, which is now set based on the consideration of typical encounter geometries. Furthermore, the extension of the methodology to a complete 3D framework needs to be studied. The addition of a proper return to course algorithm, then, needs to be implemented, in order to obtain a complete collision avoidance module covering the whole collision avoidance mission phase, involving both the avoidance and the return to course tasks. The above indicated issues will be addressed in the near term prosecution of the design work. After that, the extension of the proposed methodology to multi-threat conditions consideration will be addressed. Indeed, another limitation of the proposed methodology is that, up to date, it is able to consider only single-threat avoidance manoeuvers, even if it is worth to emphasize that the overall collision avoidance system architecture here considered properly manages this limitation and allows the sequential consideration of multiple threats.

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