Conflict detection and resolution algorithms for UAVs collision avoidance

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ABSTRACT

Collision-avoidance is a safety-critical requirement to operate UAVs in non-segregated airspaces. In case of communication problems between a UAV and the corresponding pilot-in-command, a technology is required onboard the UAV to implement a capability to detect and avoid collision-hazards even autonomously. After an introduction to the problem of developing a so-called sense-and-avoid system and its avoid-function, this work presents a solution in terms of algorithms to implement the above capability. To detect and resolve potential mid-air conflicts, a geometric deterministic approach has been utilised: an intruder is modeled trough a moving-ellipsoid and a four-dimensional approach in the time-space domain provides the solution. The approach makes use of kinematics information to detect potential conflicts and to provide actions for conflict resolution, such as speed-changes in intensity and/or direction. The proposed solution also enables the UAV to meet the applicable vertical and horizontal minima of separation and to comply with real-time constraints.

NOMENCLATURE

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
ATC	Air Traffic Control
ATM	Air Traffic Management
FOR	Field Of Regard
ICAO	International Civil Aviation Organization
PIC	Pilot In Command
SAA	Sense And Avoid
SAAS	Sense And Avoid System
TCAS	Traffic alert and Collision Avoidance System
UAV	Unmanned Aerial Vehicle

1.0 INTRODUCTION

Traffic separation and collision avoidance are requirements that an aircraft must meet to be operated within non-segregated airspaces; unmanned aerial vehicles (UAVs) also need to meet these requirements to be integrated in such environments(1-5).

Recent investigations have pointed out an increasing interest in using UAVs within civil environments and a wide diffusion of their operations is foreseen by 2025(1,2,6). However, the routine integration of UAVs into non-segregated airspaces is not a simple matter and presents regulatory and technical issues. For example, requirements state that an aircraft shall not be operated in such a proximity to other aircraft as to create a collision hazard(7). In addition, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained […] so as to see and avoid other aircraft(8).

A main technical issue to operate UAVs into non-segregated environments is the lack of an onboard capability to see and avoid potential collision hazards. To achieve this operational capability a UAV must demonstrate a so-called sense-and-avoid function at least equivalent to the see-and-avoid capability of a human onboard a manned aircraft(3,4).

The term sense-and-avoid has been coined by the aeronautical community to refer to the capability to remain well clear from and avoid collisions with other traffic. A Sense-And-Avoid System (SAAS) should implement this capability through two fundamental functions: a sense-function should acquire information from the environment, while an avoid-function should assess the risk of potential collisions and avoid them either by providing information to a so-called Pilot-In-Command (PIC) or by implementing actions in an autonomous way.

Over the years different approaches have been proposed to automate the process of avoiding potential collisions; reviews on several methods and different evolving philosophies can be found in the literature(9,10). General methods to solve different problems can be based on cost-optimisation approaches. However, depending on the problem, these methods could involve a computational effort that is unsuitable for real-time applications(9). Other diffused approaches involve geometric considerations to define conditions for conflict-detection and directions for conflict-resolution(9-12). The latter can be used to develop control commands to drive a reference aircraft to avoid its obstacles. In addition, geometric solutions can usually be formulated to require a computational effort that can comply with real-time constraints.

This paper proposes a geometric approach. It is based on a schematisation of possible encounter scenarios and utilises kinematics information to identify whether or not an aircraft is predicted to violate a safety region around an intruder. Over the years several approaches have been considered: for example, there exist two-dimensional methods with safety regions like circles(10), while other methods utilise three-dimensional spheres(11) or cylinders(12).

The solution proposed in this paper utilises a moving ellipsoid to delimit the region of an intruder within which an aircraft must not enter. The resulting method enables the UAV to identify three-dimensional situations of conflict and to generate three-dimensional actions of conflict resolution (such as speed changes in intensity and/or direction) in real-time.

This paper is organised as follows. First, an insight into the sense-and-avoid problem is given. Then, the discussion is focused on the main objective of the present research, i.e. the avoid-function (reference architectures and requirements are illustrated). An introduction to common approaches to conflict-detection-and-resolution is also given. Finally, a solution is proposed (in terms of algorithms) to implement the capability of avoiding potential conflicts, along with some results from preliminary simulations.

2.0 SENSE AND AVOID

The Sense-And-Avoid (SAA) problem involves the development of solutions to enable the UAVs to meet the requirements for traffic separation and collision avoidance, considering co-operative and non-co-operative intruders, into non-segregated airspaces. The final objective is to develop a so-called SAA standard as a method for a UAV to demonstrate the compliance to the regulations for the operations within non-segregated airspaces. Worldwide agencies, through their dedicated working groups (such as EUROCAE WG73 or RTCA SC203), industries and research centres are working to address issues and to propose solutions(3-5,11-19).

To obtain a solution several factors should be considered, such as the environment in which an aircraft operates, the applicable regulations and procedures and the capability of an aircraft to manoeuvre. Main studies should involve sensors to acquire information, algorithms to detect and resolve conflicts, systems of communication and how/when humans may have a real-time role in making decisions(16). Finally, it is also important to understand how handling a conflict situation within a system of Air Traffic Management (ATM).

The ATM system is already organised to limit the risk of collisions between aircraft under a target level of safety, but a modernisation of such a system is required. An interesting publication also deals with this topic and presents the vision of ICAO on how a modern ATM system should deliver services to the airspace users by 2025(6). It details how the ATM should act on the flight trajectories of manned and unmanned aircraft to avoid potential hazards. It also defines a future ATM system based on the integration of seven main independent concept components: one of them is the ‘conflict management’ component.

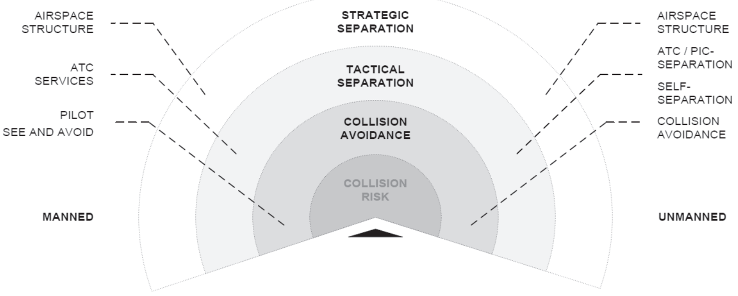

Figure 1. Conflict management layers.

The conflict management should limit the risk of collisions between aircraft. It should be implemented through three different layers(6), that is: strategic conflict-management, separation-provision and collision-avoidance, see Fig. 1.

A strategic management of a conflict should limit the application of tactical changes to aircraft flight trajectories. If a failure occurs in such a process, then tactical actions should be implemented to avoid imminent collisions and to ensure an adequate separation(6).

Instead, a tactical management of a conflict (which involves the separation-provision and collision-avoidance layers) should be implemented through some fundamental steps to be sequentially executed: the conflict detection, the formulation and the implementation of a solution and finally the monitoring of the evolution of the situation.

For what concerns a UAV, a degree of autonomy can be required to implement tactical actions (for example, when latencies or communication problems between the PIC and the corresponding UAV are such to prejudice the safety). Thus, the following discussion focuses on how to develop an avoid-function to detect and resolve conflicts even autonomously.

3.0 AVOID FUNCTION

This section briefly discusses how an avoid-function should behave and which main sub-functions, interfaces and constraints it should have; see Figs 2, 3 and 4.

An avoid-function is part of a complex system that is a SAAS. Such a system should be able to gather information from the environment (sense function), process the information for assessing the risk of potential collisions, and either provide assistance to a PIC or operate autonomously the corresponding UAV for avoiding potential conflicts (avoid function).

A SAAS should involve different integrated sensors solutions to meet 'all-whether-all-time' and 'co-operative/non-co-operative' requirements. A solution may be based on radars and electro-optical/infrared cameras for non-co-operative requirements, while transponders and ADS-B may provide additional information for co-operative intruders(17). Such sensors may implement a suitable sense-function to produce information for an avoid-function.

An avoid-function should be able to implement separation and collision-avoidance capabilities. Separation actions should primarily be provided by an ATC (in such a case, a PIC has to implement ATC indications); anyway, a PIC is also responsible of implementing actions to avoid conflicts if an ATC did not provide the due indications (in such a case, a PIC could be assisted by a SAAS to decide when and how to operate); finally, where all the previous actions cannot take place, a SAAS should be able to act autonomously to avoid imminent conflicts.

An avoid-function could be located between the sensors and the auto-pilot system of an aircraft, in order to acquire information about potential hazards before providing guidance actions (see Fig. 2). To develop an avoid-function different constraints should be considered, such as the capabilities of an aircraft to execute a manoeuvre and the existing flight rules (see Fig. 3). In addition, different modes of operation should also be considered (see Fig. 4). For example, during normal conditions of operation/communication, a PIC just has to implement ATC indications; instead, when ATC does not provide indications and the PIC is able both to identify a conflict and to provide commands to the UAV, then the PIC can utilise the available information to avoid the conflict either manually (manual mode), or by setting an automatic manoeuvre (semi-automatic mode), or also by providing clearance to a SAAS to drive the UAV (fully-automatic mode); finally, when the PIC is not able to communicate with the UAV, then an onboard SAAS should be able to operate the UAV autonomously (autonomous mode).

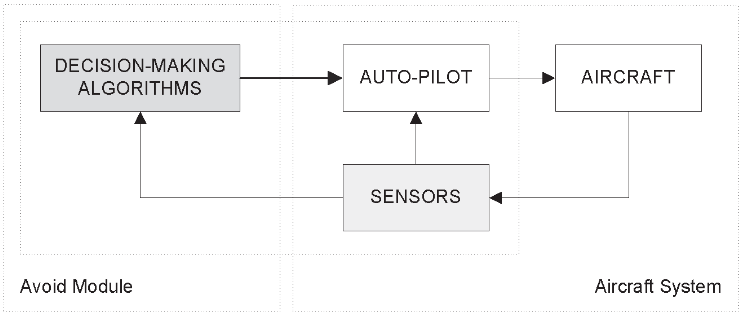

Figure 2. Allocation of a decision-making system to implement an avoid-function.

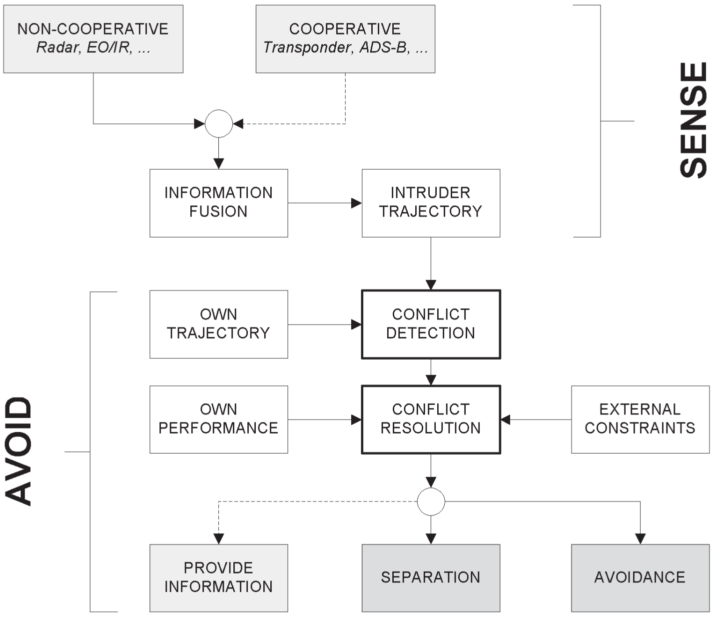

Figure 3. Reference architecture for sense-function and avoid-function.

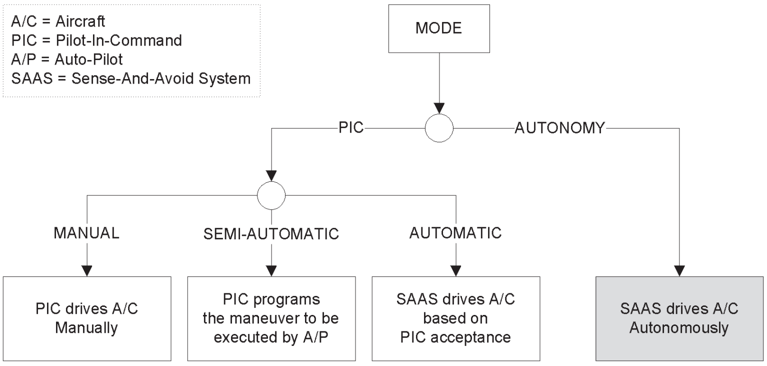

Figure 4. Reference modes of operation to implement an avoid-function.

4.0 AVOID REQUIREMENTS

This section deals with separation and collision avoidance requirements gathered from the literature(4,5,14). The final objective is to identify the main constraints to develop a first prototype of an avoid-function. The latter, in its turn, should provide a UAV with a capability to avoid collisions (even autonomously) during en-route flight phases.

Generally speaking, UAVs operations in non-segregated airspaces shall not increase the risk to other airspace users. Accordingly, UAVs should be equipped with a SAAS which should comprise components to detect and avoid collision hazards in real-time. More specifically, a SAAS should implement a sense function (to acquire information from environment) and an avoid function (to identify and avoid potential conflicts). The latter should implement two main functions: a separation-provision function and a collision-avoidance function.

The separation-provision function has to separate UAVs from other aircraft whenever ATC is not providing separation. It has to warn the PIC of a loss of separation, so that the PIC may manoeuvre as required. Then, it has to inform a PIC as soon as a separation is restored and should seek approval for returning to a reference course, unless another loss of separation is detected. In addition, this function has to separate UAVs from other aircraft by a minimum distance of 0.5 nm in the horizontal plane or 500ft in the vertical plane.

The collision-avoidance function should not rely on ATC to protect a UAV from a potential collision. It should inform a PIC (if possible) on pending manoeuvres and implement an override capability. Also, it has to inform a PIC (if possible) as soon as a conflict is resolved before returning to a reference course (unless another conflict is detected). Anyway, it has to provide UAVs with a capability to operate even autonomously to resolve imminent collision hazards. In addition, this function has to ensure that other aircraft are avoided by a minimum distance of 500ft in the horizontal plane and 350ft in the vertical plane.

In addition, other constraints should also be considered. For example, the capability of an aircraft to actually execute a manoeuvre is a fundamental constraint. Also, at least for what concerns separation-provision, a UAV should comply with the flight rules as they apply to a manned aircraft(7,20). Moreover, the definition of a conflict-avoidance manoeuvre should take into account that UAVs with the same type of SAAS have to operate in a compatible way and a SAAS should be interoperable with systems like an ACAS(22) (Airborne Collision Avoidance System) and the TCAS II(21) (Traffic alert and Collision Avoidance System).

Finally, for what concerns the region of space each aircraft should be able to monitor, this should comprise a field of regard (FOR) of ±110° in azimuth and ±15° in elevation(14).

5.0 CONFLICT DETECTION AND RESOLUTION

Before illustrating the developed solution, this section briefly introduces the problem of conflict detection and resolution. Actually, several methods have already been proposed to automate the process of detecting and resolving potential conflicts(10-12); a review also exists, which discusses, compares and classifies different approaches(9).

The problem presents different aspects that should be considered. For example, it can be important to identify whether a situation involves the horizontal plane, the vertical plane, or both. The definition of methods for trajectory predictions, conflict detection and conflict resolution are also critical(9).

Conflict detection conditions could be based on range criteria, time criteria or both and should be used to trigger a conflict resolution method. Over the years, several methods have been proposed to resolve potential conflicts. For example, common methods deals with optimisation of functions, potential fields and geometric analysis. Optimisation methods combine system-models and cost-metrics to find an optimal strategy, i.e. the trajectory with the lowest expected cost(9). Depending on the problem, optimisation methods can have high computational costs, especially when compared to other methods. As an alternative, potential field methods treat an aircraft as a charged particle: they utilise modified electrostatic equations to generate continuous manoeuvres for moving an aircraft far away from an intruder (a repulsive point) while pointing to a goal (an attraction point). Finally, a third method can be based on geometric considerations only. Geometric approaches utilise kinematics information to define conflict detection conditions and conflict resolution directions. They are widely used in many fields and several works can be found in the literature(9-12).

For what concerns the present research, a kinematic approach has been considered to develop a solution (in terms of algorithms) that is able both to detect potential conflicts and to define actions of conflict resolution. Such a solution is discussed in the following section.

6.0 MATHEMATICAL FORMULATION OF AN AVOID PROBLEM AND SOLUTION

A conflict-detection-and-resolution solution is now proposed. To achieve this purpose, a reference conflict scenario is considered and the main assumptions are illustrated. Then, a mathematical formulation of the reference problem is provided. Finally, a solution is proposed in terms of a condition for conflict detection and algorithms for conflict resolution.

In the considered scenario, B is the reference aircraft that is assumed to manoeuvre to avoid a conflict, while A represents a moving (but not manoeuvreing) intruder, see Fig. 5.

There, let $V_A\mathbf{u}_A$ and $V_{B0}\mathbf{u}_B$ be the velocities of the intruder A and the reference aircraft B, where $\mathbf{u}$ is a unit vector. Also, let $v_0\mathbf{u}_r$ be the velocity of B relative to A, while $\mathbf{x}_0$ represents the position vector of B with respect to A, see Fig. 5. Both the intruder A and the aircraft B are assumed to initially move at constant velocities.

The space region around A is modeled through an ellipsoid, with semi-major axes R_1, R_2 and R_3, which represents the prescribed separation region. Thus, a conflict situation occurs if and only if B is predicted to violate the safety ellipsoid around A.

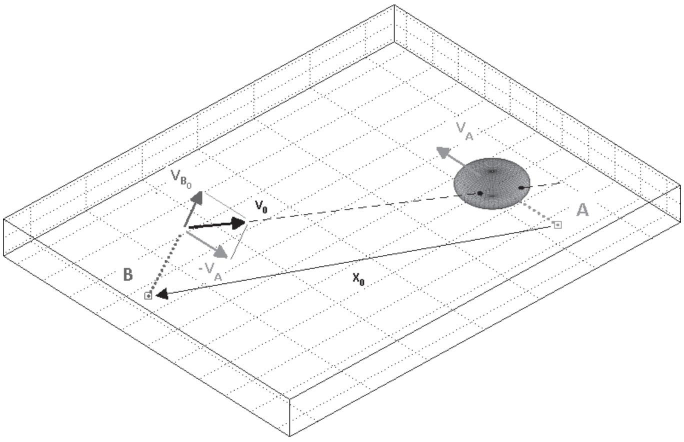

Figure 5. Schematisation of a predicted conflict in a 3D scenario.

To prevent possible conflict situations, the reference aircraft B must perform a suitable manoeuvre, which is initially modeled as an impulsive velocity change. After the manoeuvre, the aircraft B is assumed to maintain a new constant velocity whose modulus is V_{BF}.

To formalise the problem, it is useful introducing some mathematical definitions. To begin, the quadratic form associated to the ellipsoid that represents the intruder is modeled through a positive definite matrix $\sigma \in R^3 \times R^3$ whose eigenvalues are:

$$\mathrm{eig}_{\mathrm{i}}(\sigma) = 1/\mathrm{R}_{\mathrm{i}}^2 \quad \mathrm{i} = 1,2,3 \qquad \text{. . . (1)}$$

Now, let S be a vector space associated to the three-dimensional physical space, where $\mathbf{p}_1$ and $\mathbf{p}_2$ are two homogeneous vectors, but $\mathbf{p}$ and $\mathbf{q}$ need not to be homogeneous; in such a vector space, consider the inner-product, norm and distance defined as:

$$s(\times,\times): S \times S \rightarrow R \,|\quad s(\mathbf{p},\mathbf{q}) = \mathbf{p}^T \sigma \mathbf{q} \qquad \text{. . . (2)}$$

$$n(\times): S \rightarrow R^+ \,|\quad n(\mathbf{p}) = \sqrt{s(\mathbf{p},\mathbf{p})} \qquad \text{. . . (3)}$$

$$d(\times,\times): S \times S \rightarrow R| \quad d(\mathbf{p}_1,\mathbf{p}_2) = n(\mathbf{p}_2 - \mathbf{p}_1) \qquad \text{. . . (4)}$$

It is worth noting that if $\mathbf{r}$ is a generic vector centred at A, then a point $\mathbf{r}_{\mathbf{e}}$ belonging to the ellipsoid boundary will satisfy the relationship $d(\mathbf{r}_e,\mathbf{0}) = 1$; thus, the conflict region can be mathematically characterised by the inequality $d(\mathbf{r},\mathbf{0}) < 1$.

Now, define the position of B with respect to A at a generic time instant τ

$$\mathbf{x}_{\tau} = \mathbf{x}_0 + \mathbf{v}_0 \tau \qquad \text{. . . (5)}$$

Also, the (dimensionless) initial distance of B with respect to A can be defined by:

$$d_0 = d(\mathbf{x}_0, 0) \qquad \text{. . . (6)}$$

In addition, let $d_m = d(\mathbf{x}_{\mathbf{m}},0)$ be the minimum (dimensionless) distance of B with respect to A, where $\boldsymbol{x}_m = \boldsymbol{x}_0 + \boldsymbol{v}_o \tau_m$. It may be shown that the time τ_m corresponding to d_m is given by:

$$\tau_{\mathrm{m}} = -s(\mathbf{x}_0, \mathbf{v}_0)/s(\mathbf{v}_0, \mathbf{v}_0) \qquad \text{. . . (7)}$$

Finally, assuming that the initial relative velocity of B with respect to A is not zero, define a time parameter τ_v as follows:

$$\tau_{\mathrm{v}} = 1/n(v_0) \qquad \text{. . . (8)}$$

We are now in a position to approach the problem of conflict detection. Assume that the reference aircraft is initially outside the conflict region and moves with a non-zero relative velocity with respect to the intruder. A conflict situation is predicted to occur, within a time τ_c, if and only if the following condition holds:

$$d_0 > 1 U \tau_m > 0 U \mathrm{d}_m < 1 \qquad \text{. . .(9)}$$

The time instant τ_c at which *B* is predicted to enter the safety ellipsoid may be shown to be:

$$\tau_c = \left[\sqrt{d_0^2 - d_m^2} - \sqrt{1 - d_m^2}\right]\tau_v \qquad \text{...(10)}$$

The condition of Equation (9) is deduced by studying the real solutions of the equation $d(\mathbf{r}_e, \mathbf{x}_\tau) = 0$; note that a conflict situation is associated to the existence of two real solutions for '$\tau > 0$'.

It remains now to provide a solution to lead the reference aircraft *B* to manoeuvre to avoid a conflict with intruder *A*. It is therefore useful to look for a condition (involving relative position and velocity of *B* with respect to *A*) that can guarantee that *B* will not collide with *A*.

To achieve this, note that if **x** and **v** represent the generic relative position and velocity vectors of *B* with respect to *A*, the general condition of collision avoidance is given by:

$$D(\mathbf{x}, \mathbf{v}) \leq 0 \qquad \text{...(11)}$$

where:

$$D(\mathbf{x}, \mathbf{v}) = s(\mathbf{x}, \mathbf{v})s(\mathbf{v}, \mathbf{x}) - s(\mathbf{v}, \mathbf{v})[s(\mathbf{x}, \mathbf{x}) - 1] \qquad \text{...(12)}$$

The condition of Equation (11) is again deduced by studying the solutions of the equation $d(\mathbf{r}_e, \mathbf{x} + \mathbf{v}\tau) = 0$, but examining in which situation there will be no real solution.

Note that Equation (11) can be used in a constructive way to calculate the velocity variations to avoid a collision between aircraft *B* and intruder *A*. In particular, we will now concentrate on a set of trajectories that are tangent in a time-space domain to the safety ellipsoid of *A*.

To achieve this, we will consider an (impulsive) velocity change $\Delta\mathbf{v}$ such that

$$\mathbf{v} = \mathbf{v}_0\, \mathbf{u}_r + \Delta\mathbf{v} \mid \quad D(\mathbf{x}, \mathbf{v}) = 0 \qquad \text{...(13)}$$

Two special solutions of Equation (11) are now discussed; the first one (when applicable) involves a velocity change parallel to the initial velocity of the reference aircraft *B* (case 1); the second solution involves a velocity change in both modulus and direction (case 2).

Case 1

Consider a speed increment in the form:

$$\Delta\mathbf{v} = k\, v_0 \mathbf{e} \mid \quad \mathbf{e} = \pm\mathbf{u}_B \qquad \text{...(14)}$$

where *k* is a real number. Solving Equation (13) with respect to this $\Delta\mathbf{v}$ yields:

$$\Delta\mathbf{v} = \left[\frac{\mathbf{e}^T\mathbf{M}\mathbf{u}_r}{-\mathbf{e}^T\mathbf{M}\mathbf{e}} + \sqrt{\left(\frac{\mathbf{e}^T\mathbf{M}\mathbf{u}_r}{-\mathbf{e}^T\mathbf{M}\mathbf{e}}\right)^2 + \frac{\mathbf{u}_r^T\mathbf{M}\mathbf{u}_r}{-\mathbf{e}^T\mathbf{M}\mathbf{e}}}\right] v_0\mathbf{e} \qquad \text{...(15)}$$

where (in Equation (15) and also in the following):

$$\mathbf{M}(\mathbf{x}) = \boldsymbol{\sigma}\mathbf{x}\mathbf{x}^T\boldsymbol{\sigma} - (\mathbf{x}^T\boldsymbol{\sigma}\mathbf{x} - 1)\boldsymbol{\sigma} \qquad \text{...(16)}$$

and **x** is the relative position of *B* with respect to *A* at which one wants to calculate $\Delta\mathbf{v}$.

Case 2

Consider now a speed increment in the form:

$$\Delta \mathbf{v} = k v_0 \mathbf{w}(\delta,\theta) \qquad \text{. . . (17)}$$

in which **w** is a unit vector defined as:

$$\mathbf{w}(\delta,\theta) = \mathrm{Sin}\theta\mathbf{u}_\mathbf{r} + \mathrm{Cos}\theta[\mathrm{Cos}\delta\mathbf{u}_\mathbf{s} + \mathrm{Sin}\delta\mathbf{u}_\mathbf{r} \times \mathbf{u}_\mathbf{s}] \qquad \text{. . . (18)}$$

where $\delta \in [0,2\pi]$ and $\theta \in [-\pi/2,\pi/2]$ are generic angles and the unit vector $\mathbf{u}_\mathbf{s}$ is orthogonal to $\mathbf{u}_\mathbf{r}$. Algebraically solving Equation (13) with respect to the velocity variation of Equation (17) yields:

$$\Delta \mathbf{v} = \frac{\mathrm{Cos}(\theta_1)}{\mathrm{Sin}(\theta_1 - \theta_2)} v_0 w(\delta,\theta_1) \qquad \text{. . . (19)}$$

To calculate the path-deviations of Equation (19), the parameters of Equations (20)-(27) have to be preliminary calculated in their correct order. Also, note that V_{BF} has to be chosen to calculate the parameter of Equation (26); for example, if a manoeuvre at a constant speed (intensity) can avoid a conflict, a choice can be $V_{BF} = V_{B0}$, otherwise a change in speed intensity is also required.

$$\rho_1 = \frac{\mathrm{w}^\mathrm{T}(\delta,0)\mathrm{M}\mathrm{w}(\delta,\pi/2)}{-\mathrm{w}^\mathrm{T}(\delta,0)\mathrm{M}\mathrm{w}(\delta,0)} \qquad \text{. . . (20)}$$

$$\rho_2 = \frac{\mathrm{w}^\mathrm{T}(\delta,0)\mathrm{M}\mathrm{w}(\delta,\pi/2)}{-\mathrm{w}^\mathrm{T}(\delta,0)\mathrm{M}\mathrm{w}(\delta,0)} \qquad \text{. . . (21)}$$

$$\theta_1 = \mathrm{Cot}^{-1}\left[\rho_1 + \sqrt{\rho_1^2 + \rho_2}\right] \qquad \text{. . . (22)}$$

$$\rho = v_0 / V_{\mathrm{B}_0} \qquad \text{. . . (23)}$$

$$\rho_3 = \rho\,\mathrm{Sin}\theta_1 - \mathbf{u}_\mathrm{B}^\mathrm{T}\mathbf{w}(\delta,\theta_1) \qquad \text{. . . (24)}$$

$$\rho_\mathrm{A} = V_\mathrm{A} / V_{\mathrm{B}_0} \qquad \text{. . . (25)}$$

$$\rho_\mathrm{B} = V_{\mathrm{B}_\mathrm{F}} / V_{\mathrm{B}_0} \qquad \text{. . . (26)}$$

$$\theta_2 = \mathrm{Tan}^{-1}\left(\mathrm{Tan}\theta_1 - \frac{\rho/\mathrm{Cos}\theta_1}{\rho_3 + \sqrt{\rho_3^2 + \rho_\mathrm{B}^2 - \rho_\mathrm{A}^2}}\right) \qquad \text{. . . (27)}$$

The proposed instantaneous path-deviation of Equation (19) is only a first approximation of the real trajectory of *B* because the reference aircraft *B* cannot change its velocity vector with an impulsive manoeuvre. A possible strategy to face this problem is proposed hereafter.

First of all, note that the ideal trajectory of *B* can be schematised by a broken-line, see Fig. 6. Then, the actual trajectory should follow such a broken-line as closely as possible.

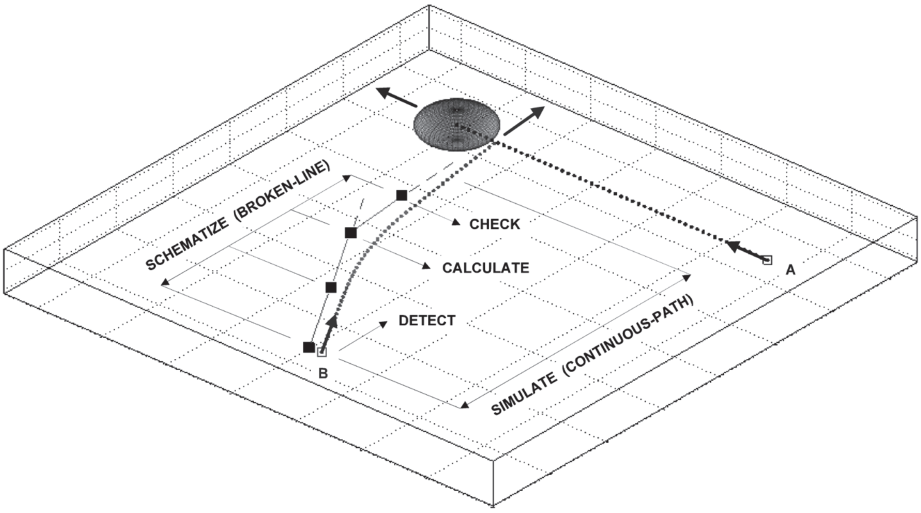

Figure 6. The proposed avoid-strategy through a broken-line and some key-actions.

With reference to Fig. 6, the broken-line is identified by the two segments P0-P2 and P2-P3. P0 coincides with the initial position of *B*, P2 represents the point corresponding to the ideal (impulsive) manoeuvre, while P1 and P3 represent points that the reference aircraft *B* is expected to reach at the beginning and the end of a real manoeuvre. In particular, P1 coincides with a position of *B* after a time-delay from P0, while P2 is not actually reached by *B*. Also, the time between P0-and-P1 and the length of P1-P2 are chosen depending on the automatic-pilot system delays and on the manoeuvreing capability of the reference aircraft *B*.

Stated this, the strategy can be summarised through some key-actions to be executed sequentially, see Fig. 6. The first phase (*Detect*) is performed through the conflict detection condition of Equation (9). It follows the definition (*Schematise*) of an ideal path (a broken-line) for aircraft *B*. Here, the algorithm of Equation (19) can provide a path-deviation to avoid the predicted conflict (*Calculate*). The next step is to simulate a manoeuvre that is close enough to the ideal path of *B* and also represents a feasible turn from P1 to P3 (*Simulate*). A final check on the simulated manoeuvre verifies its effectiveness to avoid the predicted conflict (*Check*). If such a manoeuvre is declared effective, then the ideal path-deviation can actually be implemented.

7.0 RESULTS FROM SIMULATION

A number of preliminary simulations are now illustrated. Their aim is to demonstrate that the proposed solution is able to generate effective conflict avoidance trajectories that are also three-dimensional and kinematically-feasible paths; also, because the solution is based on algorithms that require a finite and low number of operations, such a solution is expected to perform well within real-time constraints (as verified by simulation).

The proposed simulations start from the same reference initial condition; Intruder-A is initially at the origin of a frame, with a velocity of 90ms^{-1}; the initial position of Aircraft-B is 10,000m on the port side and 5,000m in front with respect to Intruder-A (see Fig. 7); the initial velocity of Aircraft-B is 100ms^{-1}, it is rotated 60º from the velocity of Intruder-A (see Fig. 7), and its magnitude is kept constant during the manoeuvres illustrated hereafter.

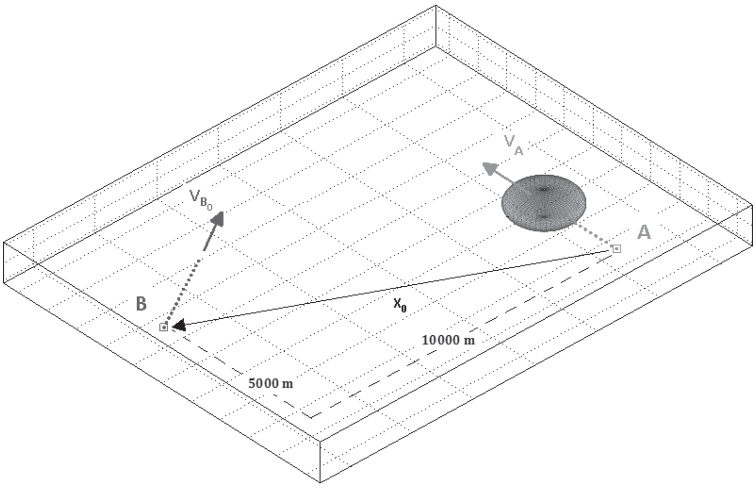

Figure 7. Intruder-A and Aircraft-B reference initilal condition.

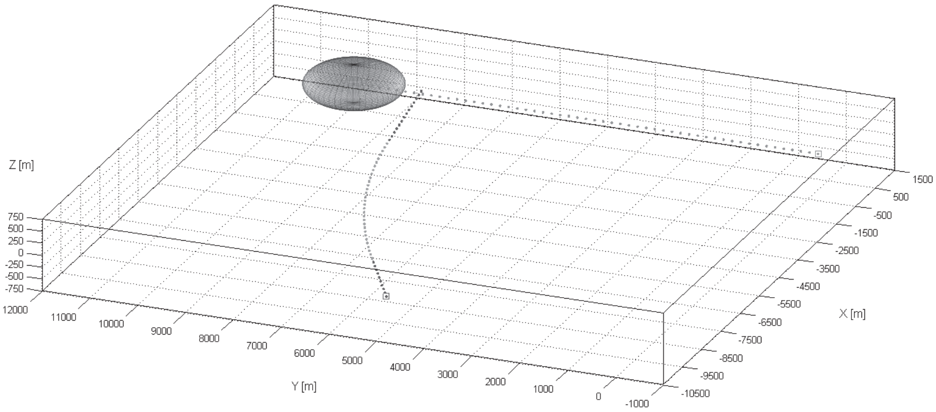

Figure 8. Aircraft-B performs a horizontal turn to avoid collision with Intruder-A.

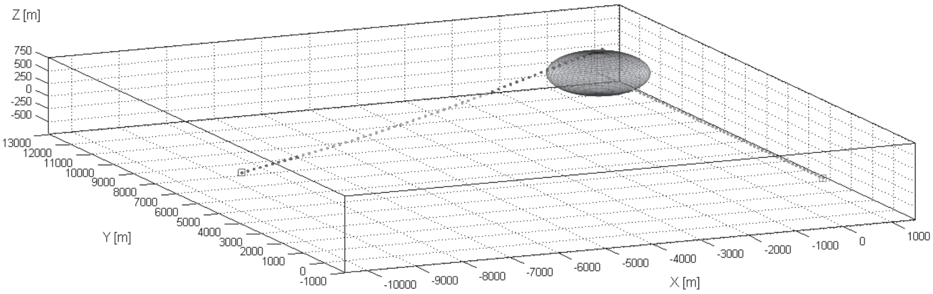

Figure 9. Aircraft-B performs a vertical climb to avoid collision with Intruder-A.

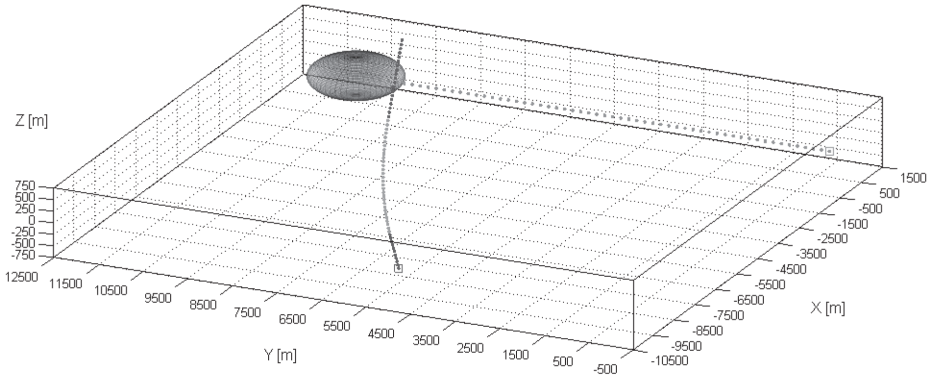

Figure 10. Aircraft-B performs a turn and climb 3D to avoid collision with Intruder-A.

A diagonal matrix σ is used in these simulations. This can be assumed to be a general choice because a moving intruder can be represented through a moving point (three-degree of freedom with no attitude orientation). For what concerns the proposed simulations, the ellipsoid (centred in *A*) is assumed having semi-major axes $R_1 = R_2 = 1{,}000$m and $R_3 = 400$m.

Concluding, the proposed method can provide horizontal turns (Fig. 8), vertical climbs or descends (Fig. 9), speed-variations, and fully three-dimensional manoeuvres (Fig. 10).

For example, Fig. 8 illustrates a solution in which the reference aircraft identifies that a conflict is predicted to occur (within 100sec), calculates the trajectories tangent (in the time-space domain) to the intruder moving ellipsoid and implements a horizontal turn.

Figure 9 shows another possible solution in which the reference aircraft implements a tangent solution corresponding to a vertical climb and avoids the predicted conflict.

Finally, Fig. 10 illustrates that the proposed solution is able to provide also a generic three-dimensional manoeuvre (in such a case, a turn to the right while climbing is executed) to avoid a predicted potential conflict between a reference aircraft and an intruder.

Preliminary simulations (like those illustrated in this section) have demonstrated what follows: the conflict detection condition is able to predict potential conflicts; the resolution algorithms and the avoidance strategy are able to generate effective avoidance trajectories; the algorithms have been implemented and the computation time to generate a set of 362 trajectories has been less than 0·095 seconds (as such, it can meet real-time constraints).

Thus, the proposed solution provides a new general approach to automate the collision avoidance capability, in a three-dimensional space, in real-time. Such an approach represents a first step to design control laws and provide autonomous navigation capabilities.

However, until now only kinematic constraints have been considered to define conflict avoidance trajectories. Other constraints have also to be considered, such as the aircraft performance during its manoeuvres and the flight rules that apply in the specific situation.

Additional analysis should also be conducted to assess the effects of uncertainties that come from realistic measurements of positions and velocities; also, other simulations have to be conducted with higher fidelity models of aircraft and intruders.

All these aspects (and possibly others) need to be considered, but are outside the scope of this paper and are left to future work.

8.0 CONCLUSIONS

UAVs that operate into non-segregated airspaces similarly to manned aircraft require an onboard system for collision-avoidance to meet the sense-and-avoid requirement.

This paper has first introduced the sense-and-avoid problem and then focused on the avoid-function which is the main objective of the research. This approach has been useful to introduce the main concepts and constraints that must be considered in the development of a conflict-detection-and-resolution solution to provide assistance to a human-pilot (if possible) or to operate a reference aircraft in an autonomous way (when required). Then, a solution has been illustrated along with a set of preliminary simulations.

The proposed solution has been shown to be able to detect the existence of potential conflicts through a conflict detection condition; also, the corresponding resolution algorithms and avoidance strategy are able to generate effective avoidance trajectories; those algorithms have been proved to require a computational effort that can meet real-time requirements.

The conclusion is that the proposed solution provides a new approach to automate a collision avoidance capability in a three-dimensional space and in real-time.

However, the proposed solution takes into account only kinematic constraints to define conflict avoidance trajectories. Of course, other constraints have also to be considered, such as the aircraft performances and the flight rules that shall be applied in a specific situation.

Additional simulations have also to be conducted, which involve higher fidelity models of aircraft and intruders. Also, additional analysis should consider possible uncertainties from a Sense-Function and the robustness of the proposed 'nominal' solution.

Another consideration involves the possibility that two conflicting aircraft can have the same collision avoidance system; in such a case, a general avoidance logic must be designed to ensure that both aircraft will manoeuvre in a compatible way. Also, additional strategies should be investigated to deal with multiple intruders.

Finally, the possibility of manoeuvreing intruders should also be considered. To achieve this, the monitoring of the evolution of a situation can be very important to take into account unforeseen or unpredictable changes to the trajectories of the aircraft, with the final objective to provide additional feedbacks to the avoid-function.

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