Conflict detection and resolution algorithms for UAVs collision avoidance

G. Migliaccio
giovanni.migliaccio.it@gmail.com

G. Mengali
g.mengali@ing.unipi.it

R. Galatolo
r.galatolo@ing.unipi.it

University of Pisa
Pisa, Italy

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.

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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.

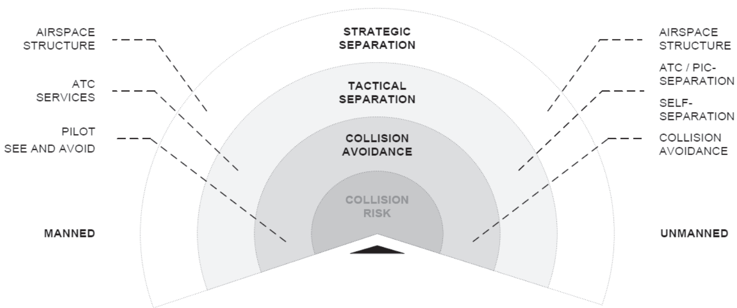

Figure 1. Conflict management layers.

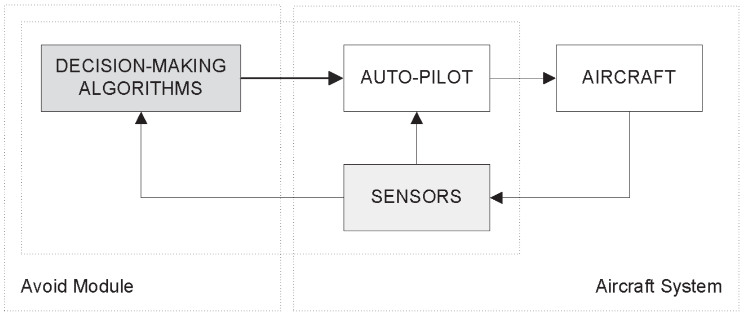

Figure 2. Allocation of a decision-making system to implement an avoid-function.

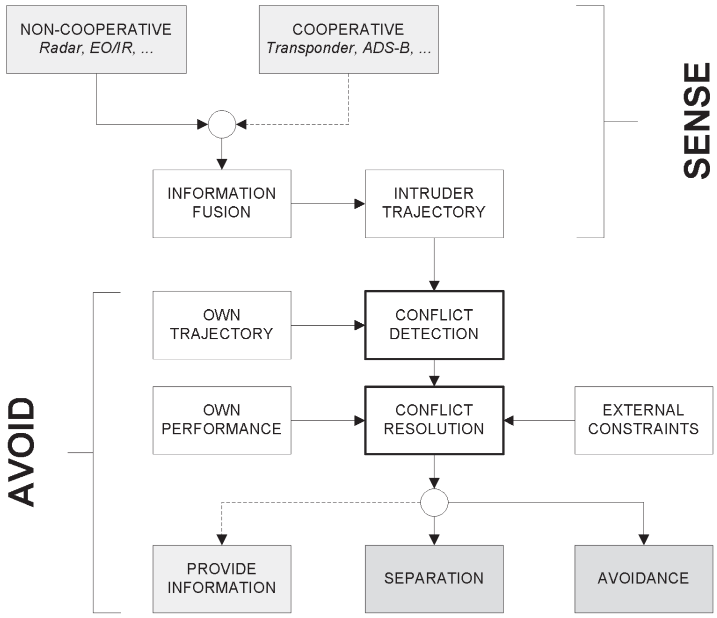

Figure 3. Reference architecture for sense-function and avoid-function.

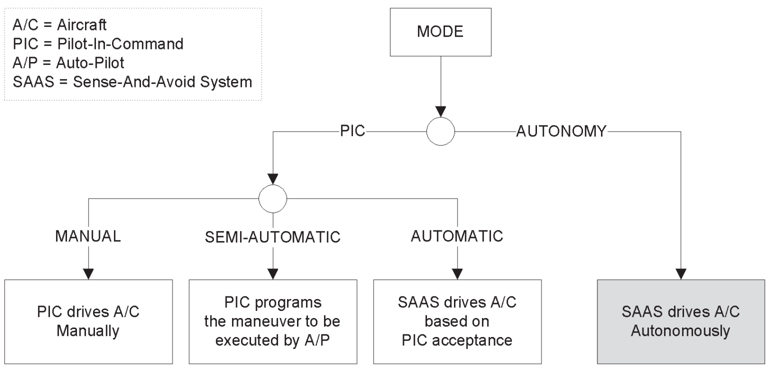

Figure 4. Reference modes of operation to implement an avoid-function.

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.

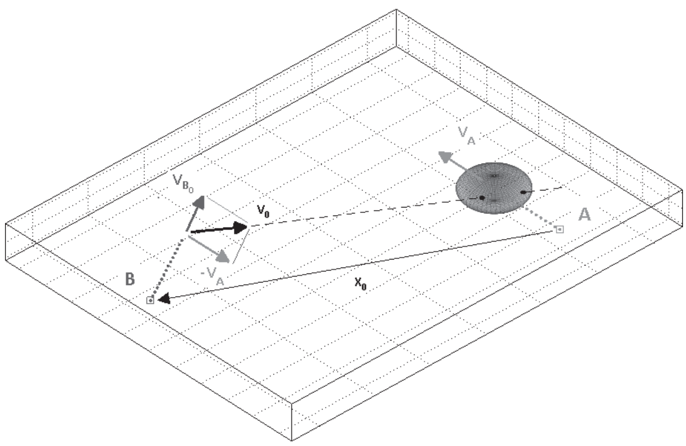

Figure 5. Schematisation of a predicted conflict in a 3D scenario.

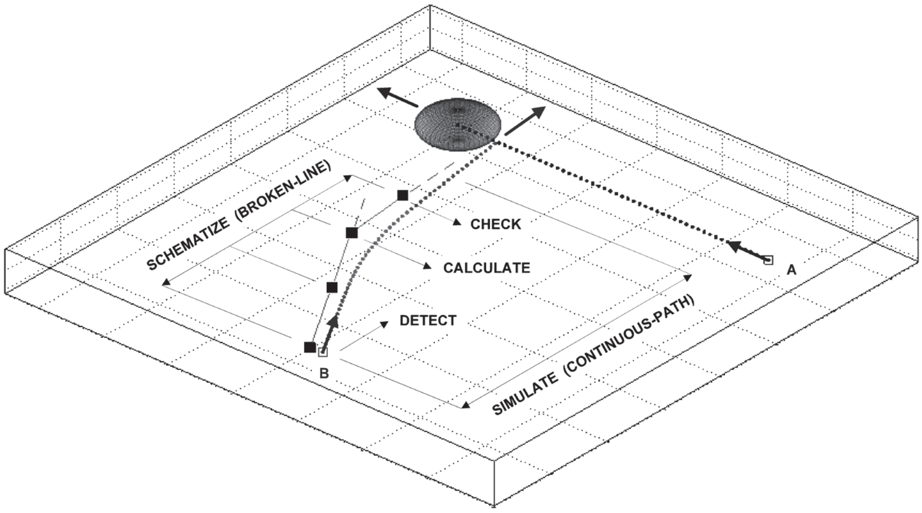

Figure 6. The proposed avoid-strategy through a broken-line and some key-actions.

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.

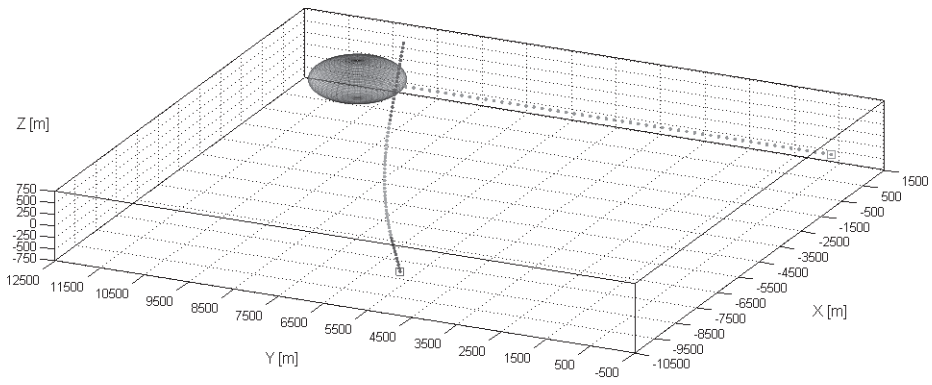

Figure 10. Aircraft-B performs a turn and climb 3D to avoid collision with Intruder-A.

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.