TOWARDS THE LOGIC OF AN AIRBORNE COLLISION AVOIDANCE SYSTEM WHICH ENSURES COORDINATION WITH MULTIPLE COOPERATIVE INTRUDERS

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ABSTRACT

This paper addresses the problem of coordination of avoidance action among multiple aircraft. We present a method based on the *symmetrical force fields* principle which defines a fully distributed and reactive coordination. In this method, each aircraft is capable of coordinating its own avoidance action autonomously with the other's, without any communication or negotiation. We have pointed out how the approach naturally matches the air traffic domain: parameters of conflict detection and specific strategies of conflict resolution can be easily incorporated within the method. This approach would therefore allow to define the basis of the logic of an airborne collision avoidance system ensuring the coordination with others. In addition, it would also allow to define the principle of a distributed air traffic control system. Some experiments are discussed.

1. INTRODUCTION

One of the most important issues of air traffic control(15) (ATC) is to ensure collision-free navigation for all controlled aircraft. Since aircraft collisions may be due to an unpredictable aircraft intrusion or ground control failure, a possible way to increase the level of safety is to fit the aircraft with an airborne collision avoidance system (ACAS). For this reason, TCAS II, the only existing ACAS, is to be mandatory in the USA for all commercial aircraft. TCAS II is able to detect conflicts involving *own* aircraft and surrounding intruders, and it provides the pilot with advisory of vertical avoidance maneuver when a threat of collision occurs, without any intervention of air traffic controllers(5) (19).

The implementation of such systems faces technical problems such as the physical means which are necessary to obtain the position and velocity of intruders, and it raises operational questions such as the impact of TCAS II on the ATC operating environment. It faces theoretical problems as well. An important one that will be addressed in this paper, is the coherence among multiple resolutions: how can multiple ACAS involved in a same conflict achieve a coherent resolution ? In other words: how can multiple ACAS coordinate their avoidance actions ? And the higher the number of equipped aircraft, the more this problem will become critical.

Although TCAS II provides an effective protection while remaining compatible with ATC environment (2)(17), the principle of coordination seems completely defined only for a couple of TCAS. However, since TCAS may be involved in a conflict with more than 20 intruders, it must be able to coordinate itself with 20 other TCAS.

The general problem of coordination among multiple mobile agents has been studied in Robotics and in Distributed Artificial Intelligence as well. Various techniques have been proposed. Most of these rely on a centralized approach(1)(6)(13)(22). The resulting centralized algorithms, however, cannot be distributed onto the aircraft in order to provide them with an autonomous avoidance mechanism. Some techniques used a decoupled approach allowing the robots to determine their own actions, one at a time and in order of priority(4)(8)(23). In the case of a high density of robots, however, this does not allow sufficient coordination speed, and furthermore the lower prioritized robots may be highly penalized. On the other hand, a few approaches implemented multiagent planning techniques in order to achieve distributed coordination(3)(10). However, since these approaches generally require communication protocols and negotiation mechanisms between the agents, they do not allow a reactive and resilient coordination.

In our previous work(24), we have developed a method that defines a fully distributed and reactive coordination among multiple robots. The purpose of this paper therefore is to highlight how the method matches the air traffic domain. This method would probably enable us to define the basis of an ACAS logic ensuring the coordination with multiple ACAS. However, our objective in this paper is neither to

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† This work has begun while the author was at ONERA.

propose an improvement of the TCAS II logic, nor to depict the implementation of a new ACAS.

Section 2 describes the principle of the symmetrical force fields method. Section 3 defines the conflict detection by a repulsive potential function which reflects a threat of collision. Section 4 defines the conflict resolution of a passive intruder by a sliding force which represents an avoidance direction. Section 5 defines the conflict resolution of an identical active intruder by symmetrical forces, representing two coherent avoidance directions. Finally, section 6 highlights some typical simulations and experiments.

2. BACKGROUND AND OUTLINES OF THE APPROACH

Our approach is based on the symmetrical force fields method(25)(26) which is a double extension of the potential field method(11)(12)(13)(21).

The potential field method has been developed to solve the real-time obstacle avoidance problem for mobile robots. The underlying idea is that the robot, represented as a point in its configuration space, is a particle moving under the influence of artificial potentials generated by the goal and by the obstacles. The goal produces an attractive potential which pulls the robot towards it, while the obstacles produce repulsive potentials which push the robot away from them. The repulsive potentials are defined so that the robot cannot get into contact with obstacles: the closer to an obstacle, the higher the repulsive potential. The negated gradient of the resulting potential defines the force applied to the robot, and therefore its acceleration, which is called its resulting action (Figure 1).

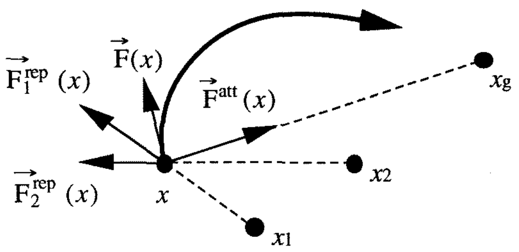


Figure 1. The robot (at x) is repelled by the obstacles at x_1 and x_2 while the goal (at x_g) attracts it. One can note that the forces are radial.

This approach is particularly efficient and well-suited to situations in which the robot senses obstacles while moving. The main drawback one has to deal with using this method is the presence of local minima of the potential function (other than the goal). Static minima may be caused by the topology of the environment: concave obstacles can easily trap the robot. On the other hand, dynamic minima may occur when several robots are moving in the same environment. Typically, two aircraft in a "tangent" encounter generate minima for each other (Figure 2).

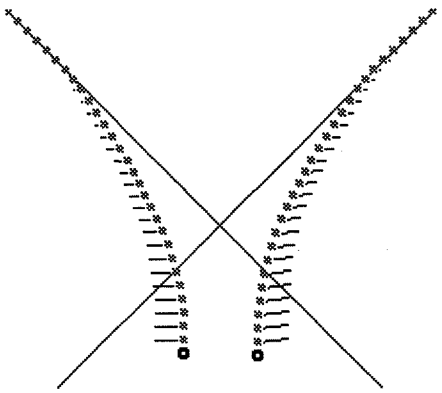


Figure 2. Dynamic steady state. The aircraft follow their flight plan (straight line). The repulsive forces are plotted at each point of the trajectories.

In our previous work, we have pointed out that these minima were due a wrong definition of the avoidance action. The attractive force defines a *convergence* action, i.e. an action that pulls the robots towards a goal location, while the repulsive force defines a *flee* action, i.e. an action that pushes away from an obstacle location. The *avoidance* action, however, is an action that moves the robot round an obstacle. This action cannot be obtained by the composition of these two previous actions: a third force was missing. We thus have determined the *sliding* force from a repulsive potential, as a force that leads to slide along the equipotentials; such a sliding force defines an avoidance action (section 4).

In addition, in order to define coordination of (resp. convergence, flee or avoidance) actions between two robots, we have shown that the two (resp. attractive, repulsive or sliding) forces must be *coupled.* And under certain conditions of the two potentials, the two forces must be *symmetrical* (section 5).

Therefore, this approach allows to define a fully distributed and real-time coordination, requiring neither communication nor negotiation among the robots. And futhermore, this approach naturally matches the air traffic: each aircraft A (using the method) flies in a field of attractive and sliding forces issued respectively from attractive and repulsive potentials. The attractive force is generated by the next beacon of the flight plan which pulls A towards it (this represents the effect of an autopilot). The sliding forces are produced by each surrounding intruder which move A round them. The norm of each sliding force reflects a threat of collision with the corresponding intruder, while its direction represents an avoidance direction.

If intruder I is cooperative (i.e. it uses the same principle), the sliding force generated by A on I and the sliding force generated by I on A are symmetrical. This condition of symmetry between the couple of sliding forces ensures the coordination of the couple of avoidance actions.

The resulting force exerted on A is defined by the sum of the attractive force and the sliding forces generated by each intruder. The acceleration issued from this resulting force is the resulting action of the aircraft.

In this paper, however, we will only focus on the coordination of avoidance actions among multiple cooperative aircraft. For this purpose, we make the following assumptions:

- each aircraft is either passive, i.e. it follows its flight plan without trying to avoid collision, or cooperative, i.e. it uses the same principle (the case of an intruder using a different principle of avoidance is discussed in[26]).
- for each aircraft using the principle, 3D relative position and velocity vectors of each surrounding intruder are available. This can be carried out by using transponder (ATCRBS, Air Traffic Control Radar Beacon System) which broadcasts the position obtained by a global navigation satellite system such as GPS (Global Positioning System).
- the type (passive or cooperative) of each intruder is available as well.

The method does not require point to point (selective) communication between aircraft.

3. CONFLICT DETECTION

The purpose of the conflict detection is to assess a risk of collision, and more generally a risk of conflict, between two aircraft. The threat of collision can be expressed as a repulsive potential.

3.1. Significant Parameters

Depending on the geometry of the encounter involving two aircraft A_i and A_j, three typical encounters can be isolated:

- *head-on* encounter, characterized by velocity vectors in nearly opposite orientations and nearly parallel to the aircraft axis (Figure 3). The significant parameter which allows to predict a risk of collision in such encounter is the *virtual collision time* (τ): it corresponds to the time before attaining the closest point of approach (TCPA, used in TCAS). It corresponds also to the time before the collision of two virtual mobiles moved by the projection (onto aircraft axis) of the two aircraft velocity vectors. Precisely:

$$\tau_{ij} = \frac{d_{ij}}{\dot{d}_{ij}}$$

where d_{ij} represents the distance between A_i and A_j, and $\dot{d}_{ij}$ the derivative of d_{ij}.

- *overtaking* encounter, characterized by velocity vectors in nearly identical orientations and nearly parallel to the aircraft axis (Figure 3). The significant parameter is the *time spacing* (s) between the two aircraft. Precisely:

$$s_{ij} = \min_{>0}\left(\frac{d_{ij}}{\dot{d}_j}, \frac{d_{ij}}{\dot{d}_i}\right)$$

where $\dot{d}_i$ represents the derivative of d_{ij} if A_i were static.

- *tangent* encounter, characterized by velocity vectors nearly perpendicular to the aircraft axis (Figure 3). Since the components of velocity vectors on the aircraft axis is low, the two previous criteria are no longer significant enough. The distance (d_{ij}) between A_i and A_j, however, allows to predict the risk of collision in this type of encounter.

3.2. Threat of Collision

The threat of collision between the two aircraft A_i and A_j is represented by a repulsive potential U_{ij} issued from a combination of three repulsive potentials, each of them corresponding to a parameter (τ, s or d). The potential U_{ij} is thus expected to reflect the threat of any encounter, whatever its geometry and the current maneuvers of the two aircraft, and furthermore without any explicit look-ahead analysis.

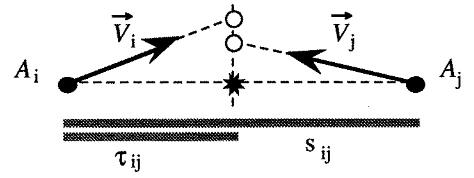
The potential U_{ij} can be defined by the following combination:

$$U_{ij} = \max\left(U^{\tau}_{ij}, U^{s}_{ij}, U^{d}_{ij}\right)$$

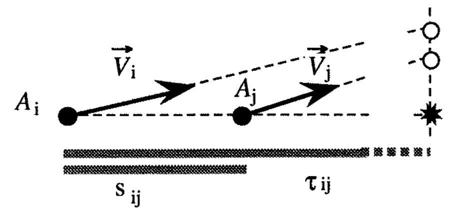
In order to create a potential barrier around the intruder, the repulsive potential U^{p}_{ij} (when p stands for τ, s or d) can be defined by a decreasing function, such as:

$$U_{ij}^p = \eta_p \frac{1}{p_{ij}} \qquad p_{ij} > 0$$

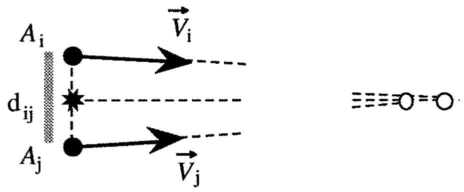
where η_p represents a positive scaling factor allowing to weigh the corresponding parameter.



head-on encounter



overtaking encounter



tangent encounter

● *aircraft* ✱ *virtual collision point* ○ *closest point of approach*

Figure 3. The three typical encounters. One can note that τ is lower — hence, more significant — than s in a head-on encounter, unlike an overtaking one.

These scaling factors may depend on the type of intruder. Roughly speaking, since a cooperative intruder acts to avoid collision as own aircraft acts, the avoidance of a passive intruder is twice more intensive than the avoidance of a cooperative one. The scaling factors corresponding to a passive intruder are therefore greater than for a cooperative one; for instance:

$$\eta_p\ (\text{passive}) = 2\eta_p\ (\text{active})$$

Scaling factors may also depends on problem that the intruder has to cope with (technical problems on board, etc...).

3.3 Protection Volume

The potential has been defined so that the two aircraft cannot get into contact: the potential is infinite if the distance is zero. However, since in air traffic minimal separations are required†, a *protection* volume must be specified.

To incorporate minimal safety separations within the potential, allowing to define this volume, U_{ij}^p can be defined by:

$$U_{ij}^p = \begin{cases} \infty & \text{if } 0 \leq p_{ij} < p_0 \\ \eta_p \dfrac{1}{p_{ij} - p_0} & \text{if } p_0 < p_{ij} \end{cases}$$

where p_0 denotes the minimal authorized value of the parameter p.

Since vertical and horizontal minimal separations are different, the distance (d) between aircraft A_i and A_j is defined as a combination of vertical (v) and horizontal (h) distances:

$$d_{ij}^2 = h_{ij}^2 + \rho^2 v_{ij}^2$$

with:

$$\rho = \frac{h_0}{v_0}$$

where v_0 and h_0 represent vertical and horizontal minimal separations.

Minimal separations must be specified and may depend on flight conditions (e.g. lower in airport approach and in low altitude). For instance, in normal conditions v_0 and h_0 can be lower by half compared with ATC minimal separations, while τ_0 and s_0 can be set to 1 min

3.4. Reaction Volume

As a protection volume has been specified, a *reaction* volume must be specified as well. Indeed, since the potential is strictly positive, all the intruders are threatening and therefore induce an avoidance reaction from own aircraft. If an intruder is located beyond a certain limit (in particular beyond the range of the radar) it should be considered not threatening, so that own aircraft will no longer be influenced unnecessarily.

For this purpose, U_{ij}^p can be defined by (Figure 4):

$$U_{ij}^p = \begin{cases} \infty & \text{if } 0 \leq p_{ij} < p_0 \\ \eta_p \left(\dfrac{1}{p_{ij} - p_0} - \dfrac{1}{p_1 - p_0} \right) & \text{if } p_0 < p_{ij} \leq p_1 \\ 0 & \text{if } p_{ij} > p_1 \end{cases}$$

where p_1 is a positive constant corresponding to the threshold of the criterion p ($p_0 < p_1$).

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† Aircraft must generally be separated with 5 nautical miles (NM) in horizontal or 1000 feet (ft) in vertical.

The thresholds can be deduced from both the range of the radar and the minimal separations, so that 1) no threshold is greater than the range and 2) the ratio between thresholds and corresponding separations are identical. For instance, the range of a transponder Mode S is about 35 NM, and if the maximal velocity of own aircraft and intruders are about 8 NM / min, the maximum look-ahead time is 35 / (8 + 8) ≈ 2 min. The threshold τ_1 can thus be set to 2 min. The corresponding ratio is $\tau_1 / \tau_0 = 2$, and therefore $s_1 = 2$ min, $h_1 = 5$ NM and $v_1 = 1000$ ft.

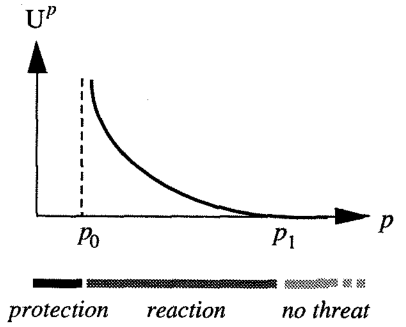

Figure 4. Potential function of the parameter p and the corresponding "slices" of volume.

To summarize:

- if one of the four parameters (τ, s, h or v) falls under its minimal authorized value, the intruder is located within the protection volume: a *conflict* occurs. The potential — hence, the threat of collision — is infinite.
- if all the parameters are greater than their threshold, the intruder is considered distant enough and therefore not threatening. The potential is zero.
- otherwise, the intruder is located within the reaction volume of own aircraft.

The size and the shape of the reaction and protection volumes would have a strong impact on the ATC environment. A large and hard reaction volume would generate unnecessary and perturbing avoidance reactions*. On the other hand, a small and soft reaction volume combined with a small protection volume would not prevent conflict occurrences. Only tests and evaluations would allow to determine and adjust the overall parameters.

4. CONFLICT RESOLUTION WITH A PASSIVE INTRUDER

The objective of the conflict resolution is to provide an avoidance direction. This direction can be defined as the direction of a sliding force of a repulsive potential. In this section we only consider the case of a passive intruder.

4.1. Set of Avoidance Direction

So far, in the potential field principle, the force that determines the so-called avoidance action has been defined as the negated gradient vector. To be precise, a repulsive force $\vec{F}$ at point x of a repulsive potential U has been defined by:

$$\vec{F}(x) = -\vec{\nabla}U(x)$$

This repulsive force induces the decreasing of the potential, and therefore leads the aircraft to descend along the lines of force. The corresponding action, in fact, is a flee action (Figure 5).

An avoidance action, however, has to induce a move round motion. The underlying idea is to define a force that just maintains the potential constant. This force leads the aircraft (if it has no inertia) to slide along the equipotential surface, and therefore, moves round the intruder. The acceleration issued from this *sliding* force is called an avoidance action (Figure 5).

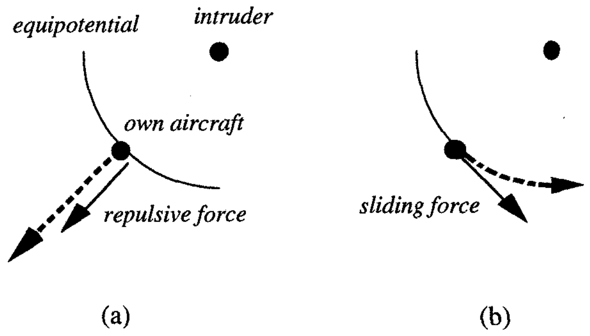

Figure 5. The two forces.

A sliding force $\vec{F}$ at point x of a repulsive potential U is defined by:

$$\vec{F}(x) \cdot \vec{\nabla}U(x) = 0$$

and unlike the repulsive force, its norm reflects the threat of collision represented by the potential U:

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[*] Since the resulting potential is defined as the maximum of the three partial potentials, our protection volume may be more restrictive than the ATC: a 1000 ft separation may be prohibited for level flight aircraft if the τ criterion is lower than its minimal value. The combination should probably be refined in order to include the defined volumes within the ATC.

$$||\vec{F}(x)|| = U(x)$$

The definition implies that a sliding force must be located within the tangential plane to the equipotential surface.

One can note (Figure 6) that, unlike repulsive fields, the sliding field is a circulating one, i.e. its rotational is not zero, and therefore a sliding field does not derive from a scalar potential[†].

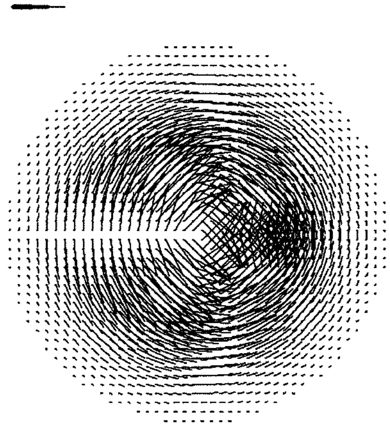


Figure 6. The sliding field. The intruder (not represented) is located at the center of the field. The upper arrow represents the acceleration (or velocity) vector of own aircraft. One can note the "switch line“ which delimits the frontier between left and right passage.

4.2. Specific Avoidance Direction

The definition of the sliding force leaves the avoidance direction incompletely defined. This indetermination, however, allows to incorporate specific strategies of avoidance in order to define what particular direction should be selected.

Although numerous considerations can be introduced, we only focus on four simple criteria constraining the resolution (and therefore reducing the set of sliding forces) which seem relevant to the air traffic.

- Since the addition of an horizontal and a vertical avoidance maneuvers may be difficult to monitor by the pilot (and by the controller as well) and may be uncomfortable for passengers, the avoidance should take place within either the horizontal plane or the vertical one.
- A horizontal avoidance should generally be preferable to a vertical one. Indeed, a horizontal maneuver does not require any increasing of the power regime and in addition, it seems generally better tolerated by passengers. The avoidance leaves own aircraft at the same altitude. To achieve this, the underlying idea obviously is to select an horizontal sliding force.
- However, when own aircraft is climbing or descending towards the intruder, it should return to a level flight before avoidance. In other words, any vertical component of the velocity vector leading to the intruder level should be cancelled before selecting a horizontal maneuver. The reason being the cancellation may be sufficient to ensure avoidance. For this purpose, the idea is to select an opposite force to the current vertical acceleration vector of own aircraft (or by default its velocity vector if it is zero).
- Finally, the deviation related to the nominal trajectory should be minimized. This is expected to induce a certain stability of the traffic, which is important in terms of cost, comfort and safety. Indeed, intensive maneuvers would stress the pilot, and furthermore, the large resulting deviations would prevent the controller from handling the traffic as well as possible after an external intervention (i.e. an avoidance maneuver from the pilot)[*]. The (horizontal) acceleration vector, or by default the velocity vector if it is zero, seems to reflect such a relevant direction. The sliding force therefore is defined by the projection of the acceleration (or velocity) vector onto the tangential plane.

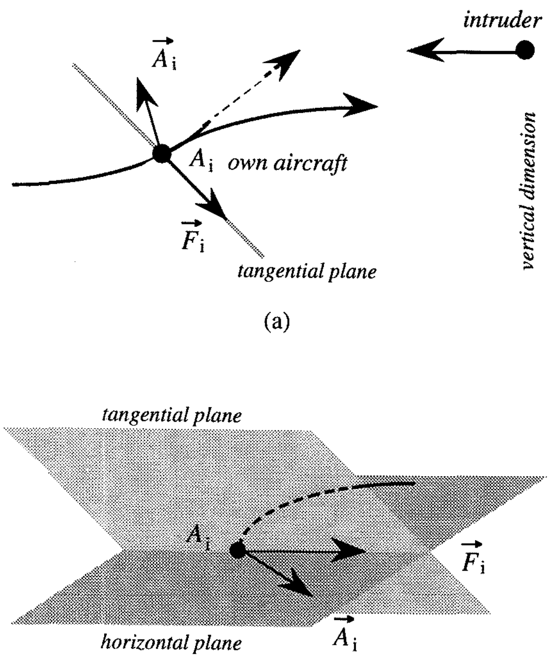
Taking into account these considerations in this order, the effective sliding force is defined:

- as the negated projection of the vertical acceleration (or velocity) vector onto the tangential plane, if own aircraft is climbing or descending towards the intruder (Figure 7a). When it returns to a level flight, the situation matches the following one.
- otherwise, by the projection of the acceleration (or velocity) vector onto the intersection of the tangential and horizontal planes[**] (Figure 7b).

[†] If a repulsive field is analog to an electrostatic or gravitational field (it derives from a potential), a sliding field can be seen as analog to a magnetic field (their rotational is non zero). The magnetic forces, however, are perpendicular to the velocity vector, and maintain constant the energy.

[*] In addition, very low maneuvers can be eliminated by introducing intensity thresholds, and this would probably allow to reduce the number of necessary maneuvers without compromising safety.

[**] If this projection is zero, one can use the rules of the air.



(a)

(b)

Figure 7. The two possible sliding forces.

Note: one may prefer other considerations to those presented[†]. The point, however, is just to highlight that specific avoidance strategies seem to be easily incorporated within the method.

5. CONFLICT RESOLUTION WITH A COOPERATIVE INTRUDER

A conflict resolution involving two active cooperative aircraft must provide a couple of coherent avoidance directions. These two directions can be defined as the directions of a couple of symmetrical sliding forces.

5.1. Set of Coupled Avoidance Directions

In section 4, in order to determine an avoidance action of a passive intruder, we have considered the force exerted on own aircraft by the intruder.

Let us consider now two active cooperative aircraft A_1 and A_2: A_1 has to move round A_2, and *vice versa* A_2 has to move round A_1 with the same principle.

As previously, the avoidance action of A_1 necessarily depends on the relative situation between A_1 and A_2 (e.g. relative position). In addition, since A_2 acts in order to move round A_1, the avoidance action of A_1 also depends on the avoidance action of A_2. And *vice versa*: A_2's avoidance action depends on A_1's.

To define an avoidance action for A_1, we thus have to consider the difference between the sliding force exerted on A_1 by A_2 and the sliding force exerted on A_2 by A_1. This is the *relative* sliding force for A_1. And this relative force is such that it leads A_1 to slide along its equipotential. For this purpose, the definition of the relative sliding force is identical to the definition of the sliding force introduced in section 4 (Figure 8).

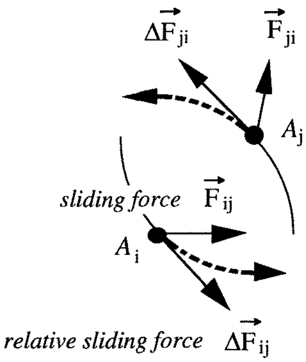


Figure 8. The two sliding forces and the corresponding relative forces (in 2D).

The relative sliding force $\overrightarrow{\Delta F}_{ij}(x_i)$ for A_i (at the position x_i) with respect to A_j (at x_j) ($i,j=1,2$; $i \neq j$) is defined by:

$$\overrightarrow{\Delta F}_{ij}(x_i) \,.\, \vec{\nabla} U_{ij}(x_j) = 0$$

with:

$$\overrightarrow{\Delta F}_{ij}(x_i) = \vec{F}_{ij}(x_i) - \vec{F}_{ji}(x_j)$$

where $U_{ij}(x_j)$ denotes the potential of A_i corresponding to A_j, and $\vec{F}_{ij}(x_i)$ the corresponding sliding force exerted on A_i by A_j.

The norm of the sliding forces, however, remains identical:

$$\| \vec{F}_{ij}(x_i) \| = U_{ij}(x_j)$$

In order to obtain its avoidance action, each aircraft has to differentiate its own sliding force from the relative sliding force. This raises two difficulties.

[†] For instance, the following consideration (suggested by X. Fron) would lead to an opposite result of the third one: since the rate of acceleration / deceleration is low comparing to those of descent / climb or heading, a longitudinal component is a wasted component. Hence, one may prefer minimize the longitudinal component of the force by considering the perpendicular projection of the acceleration (or velocity) vector.

The relative forces $\overrightarrow{\Delta F}_{12}(x_1)$ and $\overrightarrow{\Delta F}_{21}(x_2)$ of A_1 and A_2 are opposite, and must be perpendicular to both the gradient of A_1 and A_2 (i.e. they must be located within both the tangential planes of A_1 and A_2). Therefore, for each aircraft the gradient of the other must be available. This cannot be achieved since we impose independent determination of force (i.e. without any communication between aircraft).

The solution is to force the gradient vectors in the same direction (i.e. the tangential planes are parallel). To be precise, $\exists\ k \in R$ such that:

$$\vec{\nabla} U_{ij}(x_i) = k\, \vec{\nabla} U_{ji}(x_j)$$

And therefore A_1's and A_2's potentials have to be such as:

$$U_{ij}(x_i) = k\, U_{ji}(x_j) + U_0$$

Under this condition that restricts the potential of all cooperative aircraft, the determination of the sliding force does not require any information about the others' potential. The two sliding forces are thus *coupled* by a relation shared equally by the couple of aircraft.

Second difficulty: since the previous relation does not define a unique couple, how can each aircraft select the same couple of forces independently ? The underlying idea is to add other relation(s) which are shared equally by the aircraft. In the next section, the avoidance strategies introduced previously will provide such relations.

One can note that if the potentials are equal (i.e. $k = \pm 1$ and $U_0 = 0$), the norms of the two forces are equal, hence the two forces are *symmetrical* with respect to the gradient axis (Figure 9).

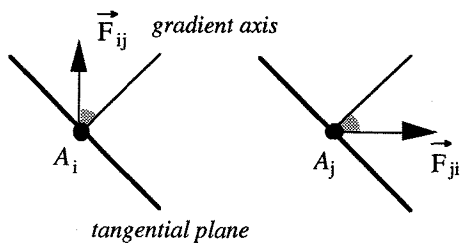


Figure 9. The symmetrical forces. The tangential planes are parallel and the norm of the forces are equal.

5.2. Specific Coupled Avoidance Directions

The definition of the two coupled sliding forces leaves the avoidance directions incompletely defined. In addition, since the condition of coordination relies on the relative sliding forces, we have added an new "degree of freedom" for the sliding forces: they can be located within the tangential plane or anywhere else.

To obtain a unique couple of forces, we will provide each aircraft with the four considerations introduced in section 4.2. And in order to deal with the new degree of indetermination which may arise, a new criterion must be introduced. However, we must be aware that these strategies must be shared equally by the two aircraft (like the definition of sliding forces) so that they will be able to act independently.

One can note that the norm of the relative force depends on the orientation of the two sliding forces. If the force orientations are close to the gradient axis, the norm of the relative force is low, and therefore the avoidance will require more time to be achieved (and in particular, if the forces are located within the axis, the norm is zero and the aircraft will remain at the same relative positions). Therefore, the last criterion is to determine a fast avoidance. For this purpose, we force the relative force to be as intensive as possible. This implies that the sliding forces must be opposite, hence they must be located within the tangential plane.

The sliding forces can thus be defined.

- If A_i is climbing or descending towards A_j, it should return to a level flight, while A_j should hold on its current maneuver. For this purpose, $\vec{F}_{ji}$ has the same direction to A_j's acceleration (or velocity) vector, and then $\vec{F}_{ij}$ is the symmetrical of $\vec{F}_{ji}$.
- If the two aircraft are climbing or descending towards each other, they should return to a level flight. The two forces are defined (as previously) as the negated projection of the vertical relative acceleration (or velocity) vector onto the tangential plane (and until one aircraft returns to a level flight).
- Otherwise, the sliding forces are defined by the projection of the relative acceleration (or velocity) vector onto the intersection of the tangential and horizontal planes.

6. SIMULATIONS AND EXPERIMENTS

6.1. Simulations

The following simulations (Figure 10) show four typical encounters. For a better understanding the encounters take place within the horizontal plane. The aircraft are cooperative and follow their flight plan (straight line).

One can note (Figure 10a) that the symmetrical sliding forces (plotted at each point of the trajectories) eliminate the dynamic minima which appears with repulsive force (Figure 2); the two encounters are identical. Aircraft coordinate their avoidance actions by departing symmetrically from their flight plan when the threat increases. In the next simulation (Figure 10b), an aircraft has been "inserted" between the two external ones. The following encounter (Figure 10c) involves four aircraft converging towards the intersection point. In the last encounter (Figure 10d), the initial conditions of position and velocity vectors would lead the aircraft to reach the intersection at practically the same time. The aircraft avoid each other as if there were a one-way round about.

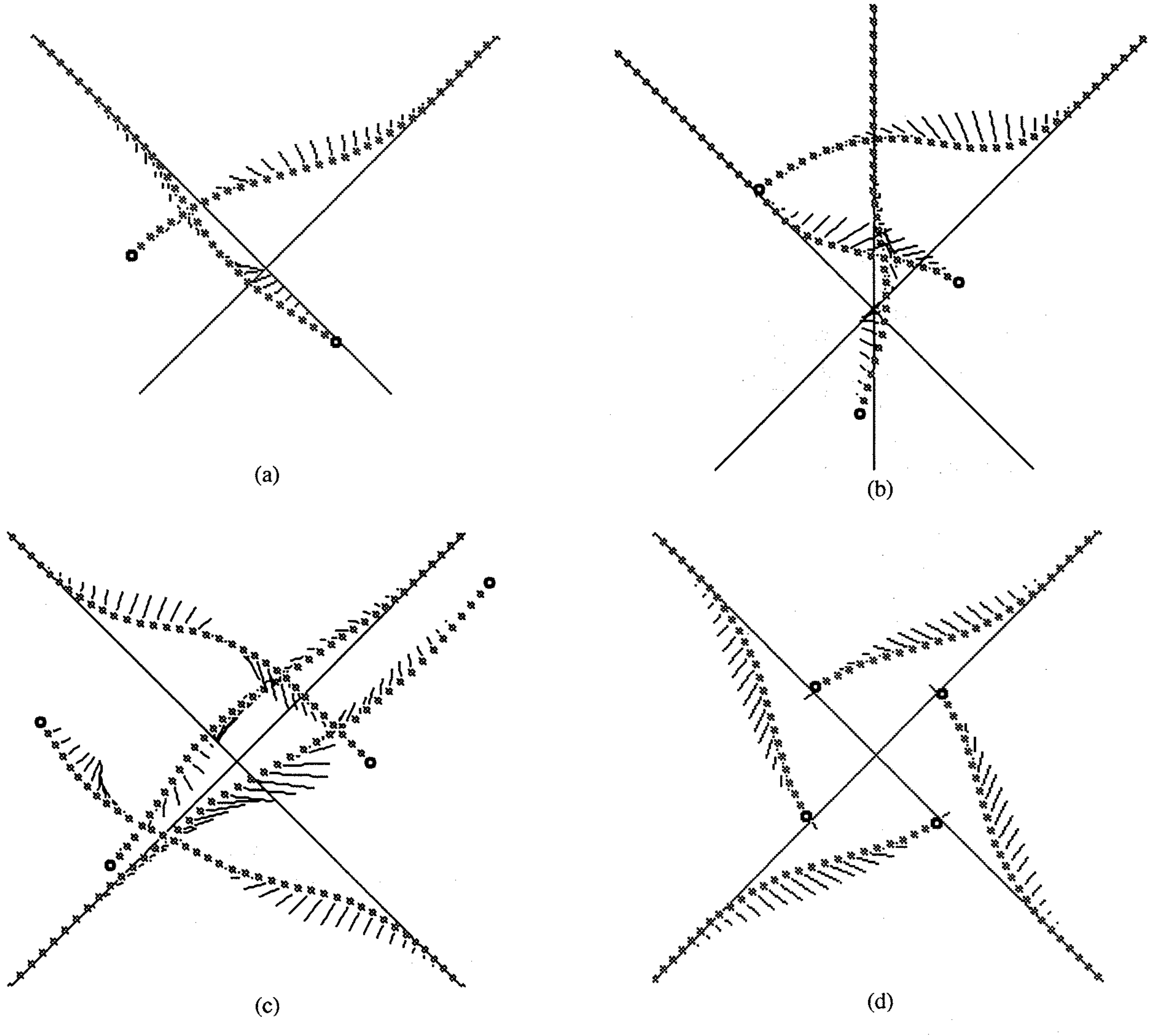


Figure 10. Simulation of 2D encounters.

6.2. Experiments

In order to test the coordination mechanism in adverse conditions, we generated encounters with cooperative aircraft converging (in 3D) towards one point and practically at the same time.

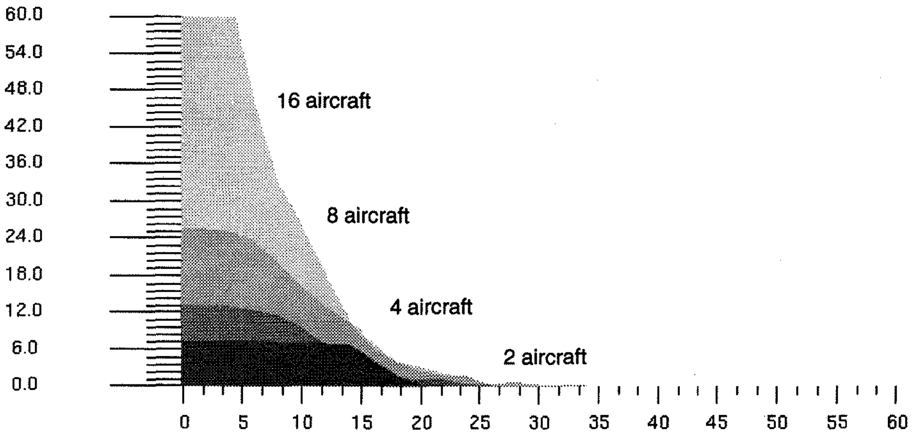
A encounter involving *n* aircraft is defined as follows:

- the aircraft are located at the vertices of a regular polygon with *n* sides whose inscribed circle presents a radius of 90 NM; the initial altitude is randomly 26000 ft or 34000 ft.
- the flight plan consists in reaching the centre of the polygon at altitude of 30000 ft, then reaching the opposite side to the start point (the plan length is 180 NM).
- the vertical speed is determined randomly (the horizontal speed is in the order of 7 NM / min).

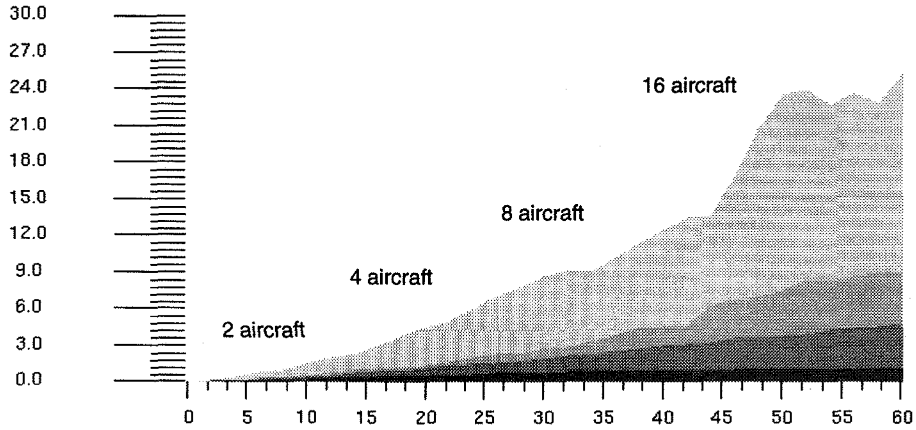
The simulated cycle duration for each aircraft is 10 seconds[†]. Safety separations are:

$\tau_0 = 1$ min, $s_0 = 1$ min,
$h_0 = 4$ NM and $v_0 = 1000$ ft.

The following curves (Figure 11) illustrate the evolution in the average number of conflicts and the deviation (related to the flight plan) with an increasing intruder density. Results match scenarios with 2, 4, 8 and 16 aircraft, obtained by varying the range (hence the distance threshold h_1) from 0 to 60 NM, by 2 NM increments.



Average number of conflicts per aircraft (and per cycle) as a function of the range (NM)



Deviation (in %) as a function of the range (NM)

Figure 11. Experiment results by using convergence scenarios.

The important result is that the coordination mechanism defines a consistent avoidance behavior of all the aircraft, whatever their number. Indeed, the minimum separations are kept despite a density of 16 aircraft (we even have experimented with 100 aircraft and the method works!). For a short range, the number of conflicts increases in line with the number of intruders. On the other hand, the range permitting the avoidance of any conflicts (hence of any collisions) does not depend on the number of intruders: it remains unchanged at about 35 NM. The deviation (which increases with the number of intruders) is then in the order of 10% with 15 intruders.

[†] Although this duration is excessive for a real implementation, it allows to experiment within a reasonable time. The actual duration is less than 0.05 second on a Sparc station 2.

7. CONCLUSION

We have presented a method of action coordination in the domain of air traffic, based on the general principle of symmetrical force fields. This method enables us to define a fully distributed and real-time conflict resolution mechanism, without requiring any form of communication or negotiation between the aircraft.

Although this approach seems promising because of its simplicity, reactivity and robustness, the ultimate question has not been addressed yet: can this mechanism be made compatible with the constraints of air traffic and ATC operating environment ? This raises the problem of the aircraft's intention which should be taken into consideration, and the stability of the avoidance maneuvers. It raises also the problem of incorporating a model of delay and uncertainty of information within the method.

If we could make it possible for the method to deal with these problems, it would provide the basis of an ACAS logic ensuring the coordination with other identical ACAS. Furthermore, it would allow to define the principle of a distributed air traffic control system. This question will constitute our future work.

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