CONFLICT RESOLUTION FOR FREE FLIGHT CONSIDERING DEGREE OF DANGER AND CONCESSION

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Abstract: In this study a conflict resolution technique based on danger and concession considerations is presented for free flight paradigm. A danger function which assigns a danger value for the conflict situation, and a concession function which assigns a concession value for the path followed by the aircraft are constructed. The danger and concession values are input to a fuzzy decision module. This module outputs the amount of deviation from the optimal path and the conflict is solved following these deviations. The method presented here is the third method we have been studying regarding to the conflict resolution problem. Its results are presented with a comparison to our other two studies.

1 INTRODUCTION

The air traffic load whole around the world is estimated to double in the year 2025 (Perry, 1997). The increasing demand of airspace due to the increase in air traffic forces current Air Traffic Management Systems (ATMS), which are mainly relying on human, to be replaced with safer and more efficient intelligent control systems. It is stated that "Due to the increasing traffic, the workload of human air traffic controllers will soon be too heavy to handle and the current centralized ATMS will be more and more unsafe (estimated one major accident per week by the year 2015) and also inefficient (5.5 billion dollars lost annually)", (Sekhavat and Sastry, 1998). In today's ATMS, the air-traffic controllers (ATC) take the whole load in both arranging the paths and solving the conflicts between aircraft paths. However the increase in the number of flights makes the system so complicated that it is impossible for a centralized controller to manage the control in an efficient way. More seriously, a collapse in the centralized controller would lead to the collapse of the whole system. The increasing technology, such as Center-TRACON (Terminal Radar Approach Control) Automation System for trajectory calculations and Automatic Dependent Surveillance (ADS) making use of Global Positioning System (GPS) for navigation information, lead to a new system in air traffic control, namely the 'free flight'. The idea of free flight is based on more autonomous aircraft capabilities that are only possible with the currently developed communication, navigation, guidance and intelligence technologies. One of the major problems to be solved in free flight is the conflict resolution that will avoid the crashing of aircrafts.

This paper deals with the problem of conflict resolution as a sub-problem of air traffic management based on free flight. In our previous works we had studied on the same problem with "potential field" (Erden et al., 2001) and "negotiation" (Erden et al., 2002) based conflict resolution techniques. Potential field based conflict resolution is widely studied in the literature (Bosg, 1997; Eby et al., 1999; Tomlin at al., 1998; Pappas et al., 1997; Tomlin et al., 2000). This approach is attractive because it is simple to be applied. It is based on simple calculations and it necessitates no communication between aircrafts. However, lacking of communication brings about the disadvantage of lacking of cooperation between the aircrafts. Negotiation based conflict resolution on the other hand is a technique which solves the conflict by negotiation between the aircrafts. This negotiation system necessitates quite complicated reasoning algorithms and a lot of communication between the aircrafts. These two techniques represent the trade-off between *cooperation* and *simplicity* in conflict resolution algorithms. The "danger-concession" based algorithm developed here might be considered

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as a middle range algorithm between these two. Namely, the algorithm here lets some cooperation with simpler communication between aircrafts. This technique makes use of the idea of a compromise between danger and concession. At any instant, the aircrafts determine the amount of the danger they face and the amount of the concession they have made till that time. The functions determining these amounts might be different for any aircraft. After the amount of danger and concession are determined the fuzzy rule based system determines the amount of deviation for each aircraft.

2 CONFLICT AND CONFLICT RESOLUTION

Aircrafts follow their optimised paths while flying. The optimisation is made according to the goals of each aircraft, in a global manner. The optimization criteria can be based on fuel consumption, atmosphere conditions, maneuverability of the aircraft, timing considerations, passenger comfort, etc. The structure of the plane, the pilot preferences, the task to be accomplished, or any other thing may affect the weight of cited criteria while constructing the cost function of the optimization. As a result, each aircraft has a different optimization function for path construction, and these cost criteria may change in time according to different situations. Although the aircraft paths in certain areas may be constructed by optimization, it is impossible to foresee all the air-traffic around an aircraft's flight path. Hence, there is always the possibility that any two flight-paths may cross each other at a point at same time. When this occurs aircrafts come closer than a minimum distance and a *conflict* occurs. The result of such conflict may be so tragic that they may even have a crash.

The accepted formal definition of the conflict is given in terms of the accepted minimum separation criteria between aircrafts. This criterion is 1000 feet vertically and 3 miles horizontally around airport, 5 miles horizontally elsewhere in the en route environment. Since the conflicts are mostly in the en route the concern for the free flight conflict resolution techniques is the 5 miles limit. In fact, this 5 miles standard comes from the technical limits of the radar, which completes a scan every 12 seconds (Perry, 1997). When the satellite-based ADS technology is implemented on a large scale, this 5-miles separation standard can be significantly reduced, and hopefully the free flight system will have much less separation standards. Currently this standard is in order and the applications here will be based on this 5-miles separation. In (Tomlin at al., 1998), the detection zone defined by the radius of aircraft's sensing capability is suggested to be 100 miles. This range could be of concern for the conflict resolution algorithms to operate in general applications.

As mentioned before, general conflict situation formalizations and resolution techniques are mainly concerned with the en route flight. The en route flights of aircrafts are generally constant speed, linear, constant level cruise flights. The preferable solutions for conflicts are maneuvers that change the direction of the flight, in the same level, with constant speed. This is what pilots prefer for flight quality and passenger comfort. The conflict formulation and the proposed resolution technique in this research are in accord with this preference: the conflict resolution technique here is based on constant speed, constant level maneuvers.

In current air-traffic control systems, conflict resolution is performed centrally by ATC. The technique is totally centralized, and air traffic controllers have the highly stressful task of manually guiding and sequencing many aircrafts through their sectors of airspace. In order to simplify the system, ATC avoids the problem of multi aircraft conflict by placing the aircrafts in holding patterns (Tomlin et al., 1998). This simplification of the system results in inefficient solutions. Furthermore, the current system is unreliable since any failure in the central ATC will affect all the aircrafts relying on that center.

In free flight control scheme aircrafts will be capable of solving conflicts between themselves. The stressful task of ATC will be distributed among the aircrafts; they will take action according to real time situations, rather than predefined routes or plans. Although the decentralization of the conflict resolution will be achieved relying on the intelligent systems, it still seems to be too early to leave out the ATC. Even in a completely free flight system ATC will exist to foresee some of the conflicts and inform aircrafts about these when they are far away from their detection zone. This will probably be more safe and efficient since it will be possible to take effect in advance. In this research such a contribution of ATC to conflict resolution is not of concern. Only autonomous conflict resolution applicable to the conflicts in detection zone is studied.

When two conflicting aircrafts are taken into account, they both have their pre-planned, probably linearly directed, routes that cross each other at the same time. In order to solve the conflict, at least one of them should change its route in near region of the conflict. But it will be fairer if both of them deviate from their routes. Of course, each one will want to deviate less from its path. (Then the conflict resolution problem can be considered and modelled as a zero-sum game (Mestertob-Gibbson, 1992), being competed on the amount of deviation.) The conflict resolution should avoid the conflict with minimum deviation from the optimised paths. From point of view of an aircraft there is a trade-off between eliminating the danger and following the optimal path. In the technique here the trade-off between the danger and concession of an aircraft is considered to represent the trade-off between the sacrifices of the two aircrafts. It is assumed here that when the two aircrafts determine their deviations depending on the amount of danger of the conflict and the concession each has made, the resultant solution between the two aircrafts will be a fair one.

3 CONFLICT RESOLUTION CONSIDERING DEGREE OF DANGER AND CONCESSION WITH A FUZZY RULE BASED REASONING

Structure of the Model

In this conflict resolution model the degree of danger and concessions made by the aircrafts are taken into account. A fuzzy-rule based reasoning is used to relate danger and concession values to the deviation of aircraft from its optimum path. The deviations are performed by turning in the clockwise direction from the optimum paths. Clockwise direction is considered here as the "'rule of the road' which specifies the direction of the avoidance for conflict maneuvers" (Pappas, 1997). There is no negotiation in this scheme, but some cooperation in the sense to transmit the position, velocity, and destination information. Considering the communication between aircrafts, this technique is not as complicated as the negotiation model (Erden et al., 2002), but a little more complicated than the potential field model (Erden et al., 2001). The danger and concession values are determined by the danger and concession functions of the aircrafts. It is necessary to make appropriate danger and concession definitions according to the structure of the plane and formulate it to give a value in the range [0,1]. These functions would be expected to be different for each aircraft due to different considerations in conflict resolution, but they are taken as the same in the simulations here. From the view of a plane the data it needs related to the other plane is the other plane's instant position, velocity and destination. The solution generated by this method will be a fair one according to the danger and concession definitions. In the simulations in this research, similar aircraft and similar pilot considerations (minimum deviation) are assumed; hence the results obtained are expected to be fair in the sense of equal deviation from the paths. The block diagram of this model is given in Fig. 1.

After the degree of deviation is determined (Fig.1), it is multiplied by π/2, and this gives the deviation angle of the plane. The deviation is $(u\times \pi/2)$ degrees clock-wise turning according to the direction pointing to the destination from the instant position of the aircraft. Determination of this deviation has nothing to do with the heading of the aircraft; hence the aircraft may turn in counter clockwise direction, if its direction of heading is more than the required clockwise turning.

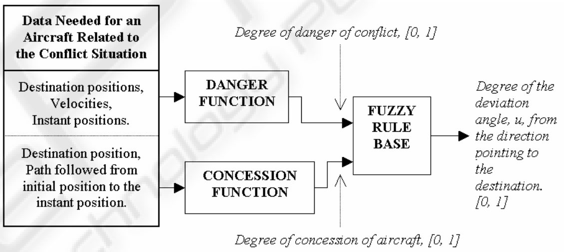


Figure 1: Block diagram for the reasoning of degree of deviation.

Concession Function

Concession function assigns a degree of concession value to the aircraft according to the conflict situation. This calculation considers the path followed by the plane up to that instant, and the path it would have followed if no conflict had occurred. Consider the situation in Fig. 2. In this figure the conflict resolution process starts when the plane is at point **A**, and **B** is the point that the plane wants to reach after solving the conflict. *S* denotes the optimum (in general shortest) path from **A** to **B** that the aircraft would have followed if there had been no conflict. **P** shows the instantaneous position of the aircraft. The aircraft has followed the path designated by L_1 up to that instant from the beginning of conflict resolution, and at best it can go through L_2 from that point on. The concession the aircraft has made till now is a matter of the difference between the optimum path without conflict and the best path it can have followed from that time on. Let's define L as the sum of L_1 and L_2,

$$L = L_1 + L_2 \qquad (1)$$

Then a normalized concession can be defined as follows,

$$Concession = (L - S)/L \quad , \quad [0, 1] \qquad (2)$$

When L is too large, it means that very much deviation from the optimum path has occurred, and concession approaches to 1. Concession is zero if L and *S* are the same, namely if there is no difference between the optimum path and the best path that has being followed till that instant.

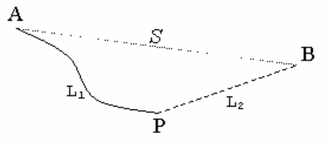


Figure 2: Variables used in calculation of concession.

Danger Function

Danger function assigns a danger value to the conflict situation according to the degree of danger. Each aircraft is assigned the same value of danger because they are both subject to the same conflict. The function considers the minimum distance that would occur between the aircrafts if they flew on the direct paths from their instant positions to their destinations. This distance is compared with the minimum safe distance allowed between the aircrafts.

Consider the conflict situation in Fig. 3. Aircraft 1 is initially at (x_1,y_1) at $t=0$, with velocity v_1, its destination being (x_2,y_2). Aircraft 2 is at (u_1,z_1), with velocity v_2, and its destination is at (u_2,z_2).The distance between is d_a at that instant. Their distances to the intersection of their direct paths (x_i,y_i), are l_1 and l_2 respectively. Minimum distance is assumed to occur when the aircrafts are at the square points at time t_c. This assumption is valid for all situations of minimum distance occurrence; even in the case one plane has passed the intersection point. A careful inspection will reveal that in different cases the signs of parameters will change but the results found will be the same. Hence, it is valid to perform the calculation for this particular case and apply it to any conflict situation.

Using simple geometry, coordinates of the intersection point of direct paths are found as in Eq.3 and Eq.4.

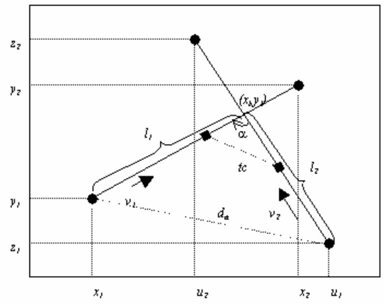


Figure 3: Calculation of the minimum distance in a conflict situation.

$$x_i = \frac{z_1 - y_1 - u_1 \cdot \dfrac{z_2 - z_1}{u_2 - u_1} + x_1 \cdot \dfrac{y_2 - y_1}{x_2 - x_1}}{\dfrac{y_2 - y_1}{x_2 - x_1} - \dfrac{v_2 - v_1}{u_2 - u_1}} \qquad (3)$$

$$y_i = y_1 + (x_i - x_1) \cdot \frac{y_2 - y_1}{x_2 - x_1} \qquad (4)$$

Then the remaining calculation is to find the distance between the aircrafts at any time, and minimizing it with respect to time. The distance between the aircrafts at time t is given by Eq.5 (by the cosine theorem).

$$d(t) = \sqrt{(l_1 - v_1 t)^2 + (l_2 - v_2 t)^2 - 2(l_1 - v_1 t)(l_2 - v_2 t)\cos\alpha} \qquad (5)$$

When we take the derivative of *d(t)* and equate it to zero, we find the minimum distance time as,

$$t_c = \frac{v_1 l_1 + v_2 l_2 - \cos\alpha \cdot (v_1 l_2 + v_2 l_1)}{v_1^2 + v_2^2 - 2 \cdot \cos(\alpha) \cdot v_1 v_2} \qquad (6)$$

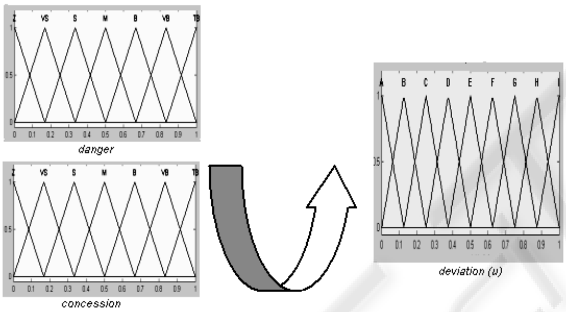
The minimum distance (d_{min}) occurs at time t_c. The danger function is defined as in Eq.7.

$$danger = \begin{cases} \dfrac{r_{min}}{d_a} \cdot \dfrac{r_{min} - d_{min}}{r_{min}}, & if \quad d_{min} \langle r_{min} \\ 0 \quad , & if \quad d_{min} \geq r_{min} \end{cases} \qquad (7)$$

Danger is calculated when the minimum distance is less than the danger distance, r_{min}, namely if a conflict situation exists. Considering the first line of the equation, the right part stands for the degree of danger; it is *0* if d_{min} is equal to r_{min} (no conflict), and *1* if d_{min} is equal to zero (the aircrafts will crush if the conflict is not solved). The left part, r_{min}/d_a, makes the distance between the aircrafts effective in determining the degree of danger. If they are far away from each other there is not much to worry since they will have time to make maneuvers; then this ratio is almost zero. On the other hand it approaches to *1* if the aircrafts get close to each other. With this function a value in the range [0, 1] is assigned to the situation, as the degree of danger.

Fuzzy Reasoning

The fuzzy reasoning block assigns a degree of deviation angle to each danger-concession pair. The logic is simple, that the deviation should be increased with increasing danger, and be decreased with increasing concession. Since avoiding danger is more important than making less concession the predominance is given to the danger consideration. (This can be observed on the last columns of the rule table. If there is a big danger, the deviation is determined to be very big – as F, G, I – even if the concession is zero.) The input and output membership functions and the rule table are shown in Fig. 4. Input and output variables are in the range [0, 1] as mentioned before.



Dang. Conces.	Z	VS	S	M	B	VB	TB
Z	B	C	D	E	F	G	I
VS	B	C	D	E	F	G	H
S	B	B	D	E	F	G	H
M	A	B	C	E	F	G	H
B	A	B	C	D	F	G	H
VB	A	A	C	D	E	G	H
TB	A	A	C	D	E	F	H

Figure 4: Membership functions and the rule table of fuzzy reasoning using the degree of danger and concession.

Simulation Results

Fig. 5 shows four simulation results for different conflict situations. The parameters and velocities of the aircrafts are depicted on the figures. In these simulation results there are two noteworthy things. One of them is the smoothness of the paths. The other is that the maneuvers have been made immediately after the planes go in the alert zone, far before they get too close to each other. For the figure at the right-bottom, the alert zone is doubled (40nm) compared to other figures, to see the early effect of resolution. The planes have put themselves in non-conflicting routes at about 20 nm away from each other. The right-up figure is also important to see the early effect and smooth path features of this technique. (A comparison of this figure with the similar ones in the negotiation case (Erden et al., 2001) would reveal that, in this technique the paths are smoother and the planes approach each other only once as near as the minimum distance.)

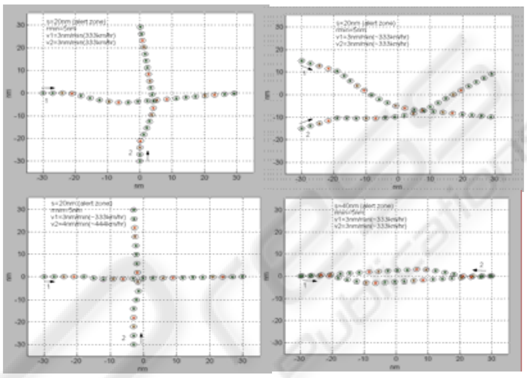


Figure 5: Simulation results for danger-concession-fuzzy resolution model.

Danger-Concession-Fuzzy Reasoning Based Conflict Resolution for More Than Two Aircraft Conflicts

Being suitable to be generalized for more than two aircraft conflicts is another important feature of conflict resolution algorithms. (Potential field technique is very easy to be generalized for more than two aircrafts (Erden et al., 2001), but negotiation based conflict resolution is not. In our study negotiation was generalized only to three aircraft conflicts. (Erden et al., 2002). The technique here is similar to potential field technique in the sense of easiness to be generalized to more than two aircrafts.

In danger-concession-fuzzy reasoning based algorithm above each aircraft is assigned a degree of danger value according to the conflict situation with the other aircraft, and a concession value considering how much deviation the aircraft has made from its optimal path. These danger and concession values are used in a fuzzy reasoning module to determine the degree of deviation from the direct path pointing to the destination. With this degree of deviation the vector to be commanded to the aircraft is determined. In order to generalize this method to more than two aircraft conflicts, the same algorithm is used for each aircraft in the conflict. Each aircraft in the conflict is assigned a direction to be followed by every other aircraft in the conflict. The vectors pointing in these directions are summed, and this gives the resultant direction to be followed by the aircraft. In this way an average of the deviations commanded by all aircrafts is obtained as the resultant deviation. In Fig. 6, the results obtained for three, four, and five aircraft conflicts are depicted. The parameters used are indicated on the figures.

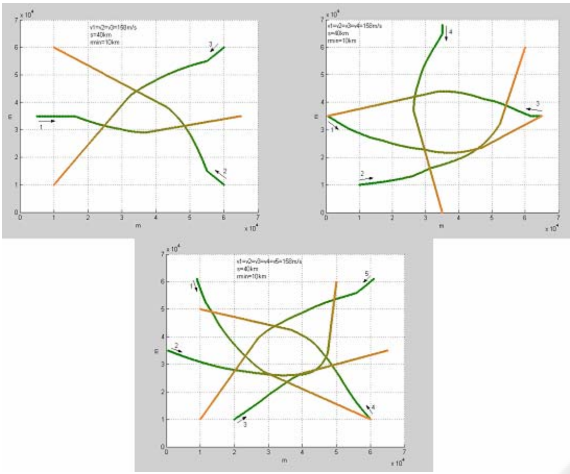


Figure 6. Danger-Concession-Fuzzy Reasoning based conflict resolution for more than two aircrafts.

In these figures one can observe two positive features of the algorithm. First one is that aircrafts make maneuvers in advance before approaching to each other. In this way the conflict is solved much before they come close. (This problem was faced with the negotiation based conflict resolution (Erden et al., 2002).) Second, the maneuver is distributed to a wide range of route, hence sharp turns are avoided. (This is a general problem of potential field based conflict resolution, where unflyable paths occur (Erden et al., 2001)). The alert zone in these simulations is taken to be 40 km. Some of the aircrafts are already in the alert zone of others when the simulation starts.

A drawback of this method is that: the aircrafts are directed according to the determined directions, but the safety of these directions is not tested at each iteration. (That was the case in negotiation based conflict resolution). In the case of the method described here, there may be situations that two aircrafts approach too much to each other when the traffic is too crowded. This is the case in Fig. 7. In this figure the parameters related to danger and alert zones are different from the above figures. The situation is a five aircraft conflict. Aircrafts 4 and 5 come too close to each other at the point indicated by the arrow. At these points the distance between them is less than the minimum separation distance depicted on the figure. This kind of a problem is probable to occur with any kind of conflict resolution technique when the number of aircrafts in the conflict situation is heavily increased. This result points to the fact that heavier air traffic conditions necessitate more safe-guaranteed conflict resolution techniques. It should be necessary to equip the conflict resolution algorithms with testing modules and modify the generated paths if the requirements are not met. It would also be possible to avoid such problems by tuning the parameters of the algorithm. For example increasing the coefficient in danger calculation might result in paths more far from each other. However, such an approach would provide a partial solution rather than a general one. This is because there would occur again such problems if the conflict situation is changed and more and more aircrafts are included.

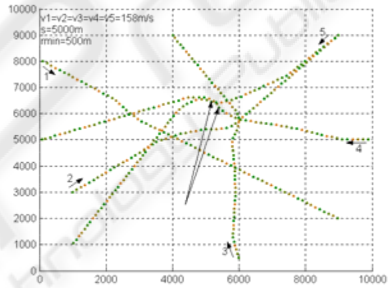


Figure 7: A five aircraft conflict resolution in which aircrafts 4 and 5 come too close to each other.

4 CONCLUSION

The increase in air traffic, force the air traffic management systems to be evolved towards more decentralized control systems. With the improved technologies in the fields of radio wave communication, navigation, and intelligence, it seems the current air traffic management systems will soon be replaced with multi agent based decentralized management systems compatible with ‘free flight’. Free flight is a recently developed air traffic control structure in which much of the workload of the central controller is distributed among the aircraft agents and aircrafts are capable of planning their paths and solving much of the conflicts cooperating with each other. One of the major problems to be solved in a free flight system is “conflict resolution”. The paths of two aircrafts are said to be conflicting if the aircrafts come closer than a predefined distance at some point of these paths. Conflict resolution algorithms are to solve these conflicts by modifying the pre-planned paths of aircrafts in a proper manner. The matter here is that conflict resolution algorithms should be compatible with the free flight understanding, in the sense that they should be feasible to be applied to different optimisation strategies of aircrafts. It is not supposed to force the aircrafts in predefined structured paths, rather to consider different criteria such as size, maneuverability, pilot considerations, passenger comfort, etc and command an appropriate maneuver in real time. The paths generated should be near optimal with respect to these aircraft specific criteria. Therefore the matter is to develop conflict resolution algorithms capable of handling different optimization strategies.

The conflict resolution algorithm developed here is based on considering the degree of danger in the conflict, and the degree of concession the aircraft has made by deviating from its optimal path till that instant. Degree of danger and degree of concession are fed to a rule based fuzzy reasoning module to determine the degree of deviation. In determining the degree of danger the minimum distance that would occur from the optimal path is utilized. For this the information of actual position, destination, and velocity of the other aircraft is needed. (Therefore a communication channel, less complicated than in the case of negotiation is needed for transmission of some data. (Erden et al., 2002)) This scheme is also suitable for the consideration of different criteria for aircrafts. The definitions of danger and concession may change with respect to different criteria. (It seems that this technique lies between the potential field (Erden et al., 2001) and negotiation (Erden et al., 2002) approaches considering the simplicity in the sense of algorithmic and technological applicability. The algorithm is simpler than negotiation but not as simple as potential fields, and it needs some communication but not as much as in the case of negotiation.)

The technique presented here can be compared with the ones we had studied before also on the basis of the paths generated. In potential field case, although the technique is simple to apply and easy to manipulate, the paths generated tend to be stuck in some situations and sometimes result in unflyable paths. This is a result of the fact that the forces defined may cancel out the effects of each other in a way the aircraft cannot jump out of the situation it is stuck in. And in some instants the effect of one of the forces immediately becomes so significant that a very sharp, unflyable path occurs. These two problems are faced with in many different applications of potential fields with different force definitions during the studies. The negotiation technique overcomes this problem, since the maneuvers are determined by negotiation rather than the guidance of forces. However, this technique still suffers from the sharp turnings although they are flyable. Since the negotiation cannot take place in far distances, the maneuvers can only be made when the aircrafts come close enough to be able to negotiate. Starting the maneuvers in close regions results in sharp turnings. The danger-concession technique does not need a complicated communication like negotiation. It is possible that the position and velocity information of aircrafts can be transferred to considerably far distances. Therefore, danger-concession technique enables the aircrafts to make maneuvers in advance before coming close to each other. Consequently the resulting paths are smooth and almost equally distributed to all flight paths. However, it should be noted that the paths generated by the danger-concession technique are not tested in each maneuver, as it is case in the negotiation technique. A way of equipping the danger-concession technique with a testing mechanism might be to incorporate it with negotiation. This incorporation might be in a way that aircrafts follow the paths generated by the danger-concession technique, and start negotiation in the case they are close to each other.

Another comparison of the three conflict resolution techniques may be based on how much cooperation of the other parties in conflict is needed for the techniques to work properly. This point is important especially when a breakdown in the system of any aircraft is considered. The most robust technique considering a breakdown is the potential field based conflict resolution, since the only thing necessary is the position information of the other aircrafts, which can easily be gathered with onboard radars. Hence, it does not need any communication between aircrafts. The danger-concession based technique, presented here, necessitates the final position and velocity information of the other aircraft. Therefore it needs some communication. However, velocity and final position information can be estimated with some simple onboard algorithms. In case of any communication breakdown these estimation algorithms may take effect and in this way the algorithm may not necessitate any communication between aircrafts. In the negotiation case communication between the aircrafts is a must. Therefore negotiation based conflict resolution could not be used if any of the aircrafts is unable to negotiate.

It should be noted that the ‘free flight’ based air traffic management is yet in the level of an idea to be applied in future. Therefore the flight and conflict resolution specifications of this kind of a flight system are not yet well defined. Besides, there is not a widespread established technology compatible with this scheme. This research should be considered as a study that may give ideas for constructing future conflict resolution schemes for free flight. The technology used, the design structure, and the capability of high-tech aircrafts will determine the concrete specifications of the conflict resolution algorithms to be used in free flight. One more thing to be noted is that this research is a simulation based study; hence the algorithms developed here lack mathematical verifications. Therefore in any application of these kinds of conflict resolution techniques, some assurance mechanisms may be necessary to test the resulting paths (such an assurance exists in negotiation based conflict resolution (Erden et al., 2001)).

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