Advanced Work on the HIPS

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Contents

Chapter 1

Introduction

Keywords: conflict, no-go zone, trajectory, conflict resolution, separation, conflict prediction, trial and error, manoeuvering surface, automatic resolution.

1.1 Short Summary of the Work conducted

This report describes advanced work conducted on the HIPS (Highly Interactive Problem Solver, [1], [2]), a decision support tool for enroute ATC (Air Traffic Control). The HIPS uses the concept of no-go zones, i.e. zones for one selected subject aircraft are calculated and displayed on three different displays (horizontal, vertical, lateral), which indicate in which areas there will probably be a conflict with environmental aircraft, if the aircrafts trajectory passes through them. The first part of the project deals with the reconstruction and analysis of unexpected and confusing no-go zone shapes, which occurred during flight tests conducted within the framework of the FREER (Free Route Experimental Encounter Resolution see B.5) programme. The problem is identified and a solution proposed. In the second part adaptability of HIPS to TMA (Terminal Manoeuvering Area) operations and departure control in particular is analyzed. As a result of the difficulties arising, the DECORS (DEparture COnflict Resolution System) was designed and integrated into HIPS.

1.2 Enroute Air Traffic Control

Enroute ATC covers a portion of the climb to the desired cruising level, the cruise, as well as the initial descent of a flight to the destination airport. The enroute portion of a flight is characterized by small heading, speed and altitude changes.

1.3 The Enroute Controller

Today an important part of the enroute controller's work consists of detecting and resolving conflicts between aircraft. Two aircraft $A1, A2$ are in conflict, if at a given time they do not respect the separation minima, e.g. vertical separation S_v of 1000 ft (2000 ft above FL 290, see B.1) and horizontal separation S_h of 5 nautical miles (approx. 9km). A more mathematical formulation:

$$\text{A1 conflicts with A2} \Leftrightarrow \exists t : d_h(A1, A2, t) < S_h \wedge d_v(A1, A2, t) < S_v$$

with $T_0 \leq t \leq T_1$ where $[T_0, T_1]$ is the interval where both involved aircraft are simultaneously within the sector. This safety buffer around an aircraft is called separation tube. The controller has several options to resolve a conflict once he has detected it. He may choose a vertical manoeuvre, i.e. climb or descend one of the aircraft, a lateral manoeuvre, i.e. increase or decrease the speed of one of the aircraft, a horizontal manoeuvre, i.e. turn one of the aircraft to the left or right of its track. He might also choose to manoeuvre both aircraft, or to use a combination of the three basic manoeuvres, in order to avoid the conflict. There may also be more than two aircraft involved in a conflict.

1.4 Medium Term Conflict Detection

The task of detecting conflicts may be done automatically, if 4D trajectory data is available, consisting of the x,y coordinates, the altitude and the crossing time at each waypoint, for a 10 to 20 minutes period into the future. The conflicts are calculated for each pair of aircraft by intersecting their separation tubes (for more details see [3]), defined by their 4D trajectories. Uncertainties concerning the future aircraft position, especially concerning the prediction of waypoint overfly-times, have to be taken into account [4].

1.5 The HIPS

As mentioned above the HIPS is a decision support tool, which aims to assist the controller in solving conflicts by modifying an aircrafts trajectory in the lateral, horizontal and/or vertical plane. HIPS uses a medium-term conflict prediction algorithm in order to calculate conflict lines. A conflict line is the temporal section on an aircrafts trajectory during which it does not respect the separation minima with one or more environmental aircraft. If a conflict between two aircraft is detected, the controller may select one aircraft to manoeuvre in order to avoid the conflict, which is called subject aircraft. For each basic manoeuvre the no-go zones for the subject aircraft are displayed in a separate window. The controller can modify the trajectory avoiding the no-go zones in order to resolve the conflict. The HIPS was originally developed for *enroute* ATC and the algorithms used to calculate the zones are based on certain important assumptions concerning enroute flight operations (few and small heading, altitude and speed changes). Furthermore these zones evolve dynamically with the modification of the trajectory. Attention must be drawn to the point that the horizontal zones are an *abstraction* based on assumptions about *potential* future manoeuvres.

Chapter 2

HIPS Horizontal no-go Zone Algorithm Problems

2.1 Reconstruction and Analysis of the problem

This part of the project deals with the reconstruction and analysis of a problem with the horizontal no-go zone algorithm, which occurred during flight tests within the framework of the FREER project (see B.5).
A horizontal resolution manoeuvre is normally first evaluated by the controller, in order to allow the aircraft to maintain its present speed/altitude, and thus the most important. Problems occurred when a relatively slow aircraft was crossing the trajectory of a fast aircraft at an angle of 45 to 90 degrees. It led to confusing extremely long and narrow no-go zone shapes along the trajectory of the fast aircraft, which contained a large area actually *not* creating a conflict and therefore not very helpful to the controller (see fig 2.1). The first step consisted of trying to recreate the problematic situation by using a similar traffic sample.

In order to analyze the problem a tool (see fig 2.5) was developed and integrated into HIPS, in order to display and analyze the way the horizontal no-go zones are calculated.

2.1.1 Abstract Description of the HIPS Horizontal no-go Zone Algorithm

The technical details of the computation will be left out (for more details see [3]) and only the abstract concept shall be described. If the trajectories of two aircraft overlap in time those portions of their trajectories are considered, which have the same start and end time. An initial test is conducted, in order to decide if those sections are sufficiently close, to justify a no-go zone calculation. If this is the case, the horizontal no-go zone algorithm is applied to the specific portion of the trajectory. The basic idea of the algorithm is to use an infinite set of parallel trajectories, and to calculate the conflict lines for each parallel

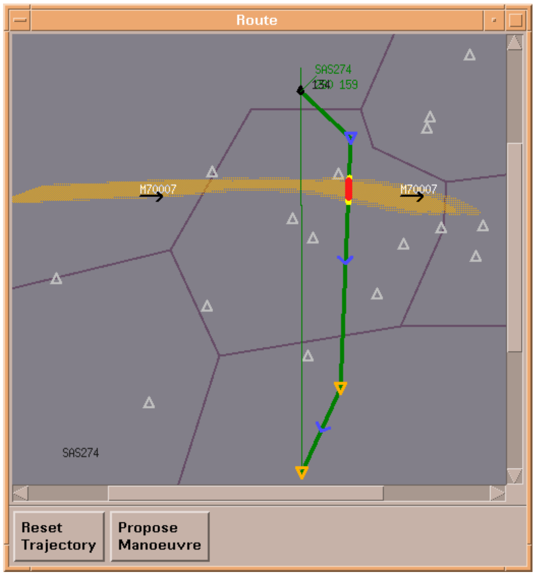

Figure 2.1: An example for a confusing long and narrow no-go zone

trajectory in order to build up the no-go zone. A concrete set of conflict lines is used to construct the sample points for the zones (see fig 2.2). It is essential to know how these parallel trajectories are constructed, since their construction seems to be the main problem of the algorithm. The parallel waypoints are defined by projections along normals bisecting the angle between two straight route segments. The crossing times for these points remain constant, i.e. the speed is scaled according to the distance between two waypoints of an offset parallel track and the corresponding initial track, furthermore the transition to the offset track is considered to be instantaneous (see fig. 2.3). Attention must be drawn to the point, that speed is scaled, rather than time, that the transition to an offset track takes place instantaneously and that the transition itself is not modeled in any way. Another problem is the influence of small portions of trajectory on the normals bisecting the angles between two straight sections, which dramatically change the geometry of the parallel trajectories used to calculate the sample points for the zones (see fig. 2.4).
Attention has however to be drawn to the point, that the algorithm used to determine if the common sections of two trajectories (common in terms of equal start and end times) are subject to a no-go zone calculation might also need to be reviewed, because if it was more strict it might filter out those sections causing the problematic shapes. An initial examination showed however that a refinement of this algorithm had no major impact on the no-go zones.

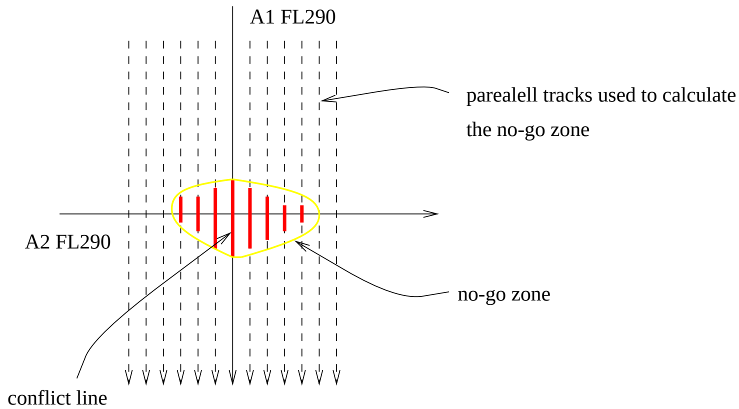

Figure 2.2: Conflict lines and no-go zone calculation

2.1.2 Reasons for confusing Zone-Shapes

As mentioned above, there are three major factors restricting the realism of the model used:

1. The assumption that transitions to offset parallel tracks take place instantaneously

2. The scaling of speed instead of time on parallel sections which may be much shorter/longer than the original one (assumed speed for these sections might even be outside the aircraft envelope, see B.3)

3. The effect of small route segments, joining the next segment at a great angle, on normal direction, e.g. when leaving a holding pattern to join an airway. In this case the assumptions made, concerning enroute trajectories, do not hold any more

The assumption that transitions onto distant offset tracks take place in zero time, proved to be one of the main influencing factors for the observed confusing shapes. A modification of the visualization tool (see fig. 2.6), which displayed portions of the no-go zone in different colours, corresponding to the distance of the offset track responsible for that portion of the zone, showed clearly that the parts of the no-go zone which actually were conflict-free, were created by very distant parallel trajectories, and the transition time could not be neglected.

2.2 Solutions

2.2.1 First Solution

A first solution might be to extend the mechanism used by the debugging tool, in order to display the zones in a differentiated manner, i.e. to associate a colour

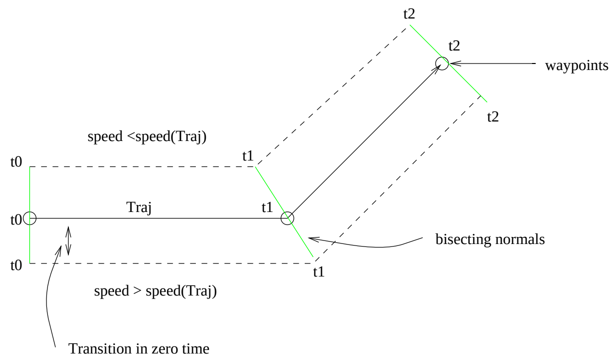

Figure 2.3: Construction of parallel trajectories for the no-go zone calculation

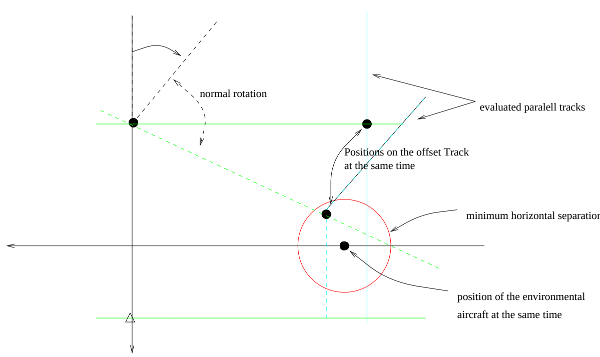

Figure 2.4: An example for the impact of normal rotation on the construction of the evaluated parallel trajectories, and its impact on the shape of the no-go zones

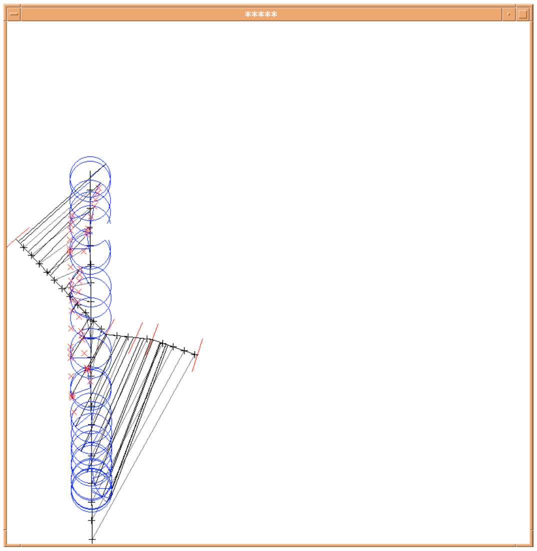

Figure 2.5: The analysis tool displaying the aircrafts trajectories with time ticks, connecting points of same time by gray lines, and indicating the horizontal separation tubes at a fixed time by blue circles

to the distance of the offset conflict line, and thereby associating a conflict-probability to each portion of the zone (see fig. 2.6). If the zone is very large and it appears that it can not be avoided by a trajectory modification, one might try to modify the trajectory in the direction of a for example less illuminated zone. Furthermore the analysis tool showed, that the HIPS zones with normal shapes were pretty homogeneous concerning their colour, i.e. created by parallel tracks, which were relatively close to the original track and for which an instantaneous transition is a reasonable assumption. The differentiated zones were displayed in the window of the analysis tool.

2.2.2 Second Solution

The second solution consists of the elimination of the two assumptions, i.e. instantaneous transition and speed scaling, and by considering a set of concrete parallel trajectories in order to limit the manoeuvering surface to a reasonable dimension. The function `RouteZones()` was completely rewritten containing some 250 lines of code.

Transitions to Offset Parallel Tracks

The following assumption is made: The transition has taken place before the actual time, i.e. the aircraft is already considered to be on the parallel track at the time the computation starts. Some modifications are made concerning the

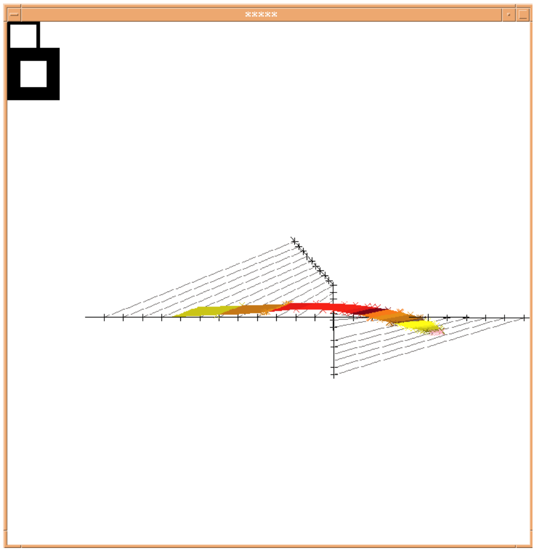

Figure 2.6: A differentiated zone as displayed by the analysis tool, only the red areas corresponding to the closest parallel trajectories will actually create a conflict if the trajectory passes through them

crossing times of the waypoints on the parallel routes. A time delay, depending on a standard transition angle α and the distance of the offset track, is subtracted from the first waypoints time on the offset track. The transition angle α might vary between 15 and 35 degrees, which is a reasonable assumption for a transition to an offset parallel track during enroute flight (see fig 2.9). Angles between 20 and 30 degrees were used for testing. The time of a successive waypoint on an offset track is calculated in function of the time of the preceding waypoint, the distance between the two waypoints and the speed on the corresponding section of the original trajectory. In this way time is scaled to the new trajectory, instead of speed and the transition delay (time lost to acquire the offset distance of the parallel track) is respected. These offset tracks are computed iteratively spaced by 3 NM and with a maximum offset of 120 NM to the left and to the right of the initial trajectory, which defines a sufficiently large manoeuvering surface, since one might choose a *different* type of basic manoeuvre when the first conflict-free offset track is more than 10 to 15 NM away from the original track.

Results obtained using the modified algorithm

The results obtained from the tests are very promising, since the desired effect, the elimination of the long narrow shapes was achieved. Adding the transition delay, depending on the offset distance seems to bend out the zone of the environmental trajectory and therefore eliminates a great unnecessary confusing

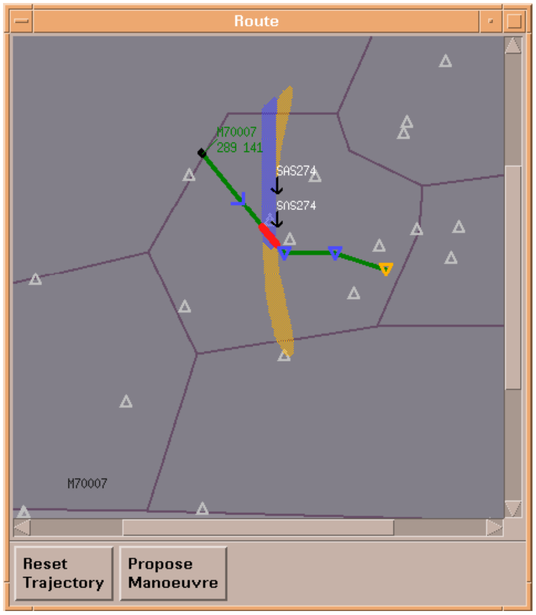

Figure 2.7: An example for a confusing no-go zone (brown), and the zone calculated by the modified algorithm (blue)

portion of it (see fig 2.7). The zones were in general much smaller, less confusing and thus gave better hints to the controller, in which direction to modify the trajectory. More intensive testing of the proposed algorithm and its integration into the FREER platform showed an overall better performance (subjective criteria) in the problem cases and a similar, or slightly worse performance in normal cases.

2.2.3 Third Solution

The third solution is of more experimental nature, since it represents the transition from a decision-support tool towards full-automatic conflict resolution, by displaying the minimum cost conflict resolving parallel route (in terms of flight time, to the last point of the known original trajectory) on the horizontal no-go zone display (see fig. 2.8). Furthermore it uses the proposed modified algorithm to calculate the horizontal no-go zones. The displayed minimum cost conflict resolving parallel routes are considered as additional indication to the controller, for the direction of the trajectory modification, i.e. to the left or the right of the present trajectory in order to achieve the most economic solution. The optimal parallel route is calculated together with the parallel offset trajectories iteratively, i.e. for each offset distance an alternative trajectory is constructed with an 30 degree transition from and back to the original trajectory. If this

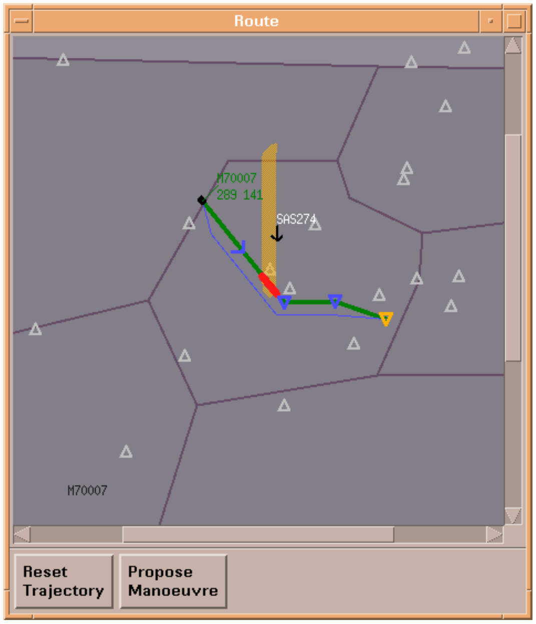

Figure 2.8: An example for an optimal (in terms of track length) conflict resolving parallel trajectory displayed in blue colour

trajectory is conflict free it is stored. At the end of the zone computation, there exists a potentially empty set of alternative conflict free tracks. One simply has to determine the minimum of this set, depending on the chosen optimization criteria and then display the optimal conflict-free parallel track.

The computation and evaluation of these alternative tracks was added to the function `RouteZones()`.

The alternative parallel trajectories (including transitions) could also be used in order to calculate even more realistic sample points, but the conflict lines proved to be too irregular, due to the more complicated geometry of these trajectories (see fig 2.9).

2.3 Final Remarks

The main problem of the HIPS route-zone algorithm seems to be the construction of a set of uniform reasonable alternative tracks, in order to calculate the sample points for the zones. This means that the manoeuvering space available has to be limited in a way that only zones created by reasonable, flyable and economic (in terms of fuel consumption) potential resolution manoeuvres are displayed. The main difficulty consists of defining what a reasonable manoeuvre is and to determine what the aircrafts behavior should be after the resolution of the conflict, concerning the re-transition to its original track.

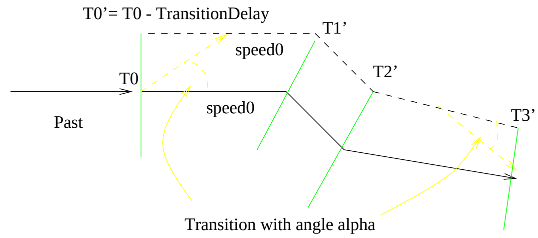

Figure 2.9: An example for the proposed modified parallel trajectory with and without the actual transition portions (yellow)

One solution was presented using a periodic transition to a parallel track. But what happens when the parallel track creates a second conflict after the initial conflict has been resolved? One could think of a recursive application of this method to the new conflict.
Another solution would be to use the GEARS [7] horizontal-manoeuvre algorithm, which uses an incremental method to solve a basic conflict, i.e. a conflict between a pair of two aircraft, by evaluating heading changes within a certain reasonable scope (e.g. +/- 30 degrees) and applying this method recursively to each previously successful heading change and succeeding conflict. This would have the advantage that the zones would be based on a realistic set of resolution trajectories. If no horizontal resolution trajectories exist the present algorithm can be used. This solution was implemented and tested after the initial report and a short description might be found in the Appendix (C).

Chapter 3

Adaptability of HIPS to TMA Operations

3.1 Introduction to TMA Operations and Departure Control in particular

TMA (Terminal Manoeuvering Area, see B.2). Departure Control is restricted in many ways compared to enroute ATC. The presence of big heading changes, the continuous acceleration and a high climb rate are characteristic for departing traffic. Furthermore the manoeuvering airspace is much more restricted, since departing aircraft have to strictly adhere to the initial portion of their SID (Standard Instrument Departure, see B.4), for noise abatement or avoidance of high terrain in the vicinity of an airport. Furthermore it might be restricted by a complex system of closely spaced departure and arrival routes, as it is the case in the Paris area for example. Therefore the airspace available for conflict resolution manoeuvres is extremely restricted. The performance of an aircraft is another restricting factor. Heading changes of 180 degrees or more are characteristic of SIDs. Furthermore the traffic is quite mixed at low altitudes i.e. aircraft with significantly different performances are using the same airspace, which imposes restrictions on the departure frequency, if for example a fast aircraft takes off behind a slow one, which also has a low climb rate.

3.2 Adapting HIPS to Departure Control?

The main problem consists of limiting the manoeuvre surface to a reasonable size and of modeling turns, which have a much more significant effect in TMA operations. The main difficulty of calculating reasonable zones was the phenomenon of normal intersection (see fig. 3.1). The straight lines defined by the normals bisecting the angle between two straight portions of the aircrafts trajectory, may in the case of two close turns into the same direction, intersect very close to the original trajectory and therefore if parallel trajectories were to be used for zone calculation, the parallel trajectory would be inverted in case of an offset-distance beyond the distance of the normal intersection point. Furthermore it has to be pointed out, that a better model for turns, i.e. in the form of small straight sections, would have no impact on the computation of the no-go zones, because turns are also restricted by a minimum turn radius, which is a problem similar to normal intersection. That means that the maximum offset distance of a considered parallel track to the interior of a turn is limited either by the minimum turn radius or by the distance of the normal intersection point. It has also to be mentioned, that a phenomenon called complex normal intersection was observed, in the case of successive big heading changes into the same direction, i.e. in the case of successive left-turns or successive right-turns not only neighboring normals would intersect near the original trajectory. Since the no-go zones are a very abstract concept, it was not considered necessary to refine the modeling of the trajectories (e.g. modeling turns) used for the calculation of the no-go zones in TMA operations.

Assumptions:

- 4D trajectory data and negotiation is available
- Minimum separation of 90 secs is applied between aircraft, irrespective of their performance and wake-turbulence category

Definitions:

- A simple normal intersection is the intersection of the straight lines defined by the normals of two neighboring points of the trajectory.
- A complex intersection is the intersection of the straight lines defined by the normals of two non-neighboring waypoints.
- The intersection distance $I_d(j)$ for a section $(j, j+1)$ is defined as $min(d(I,j), d(I,j+1))$, with I the intersection point of the straight lines defined by the normals at j and $j+1$, d the Euclidean distance between two points and $0 \leq j \leq n-2$ where n is the number of points of an aircrafts trajectory.
- The global minimum intersection distance for the right hand side of a trajectory is defined as $\min_j(I_d(j))$ with $0 \leq j \leq n-2$ and $I_d(j) = \infty$, if I is on the left hand side of the trajectory or if the normals are parallel. The left-hand side minimum is calculated in the same way.
- The initial section of an SID, is the section were no modifications of the horizontal and/or vertical trajectory of an aircraft are allowed.

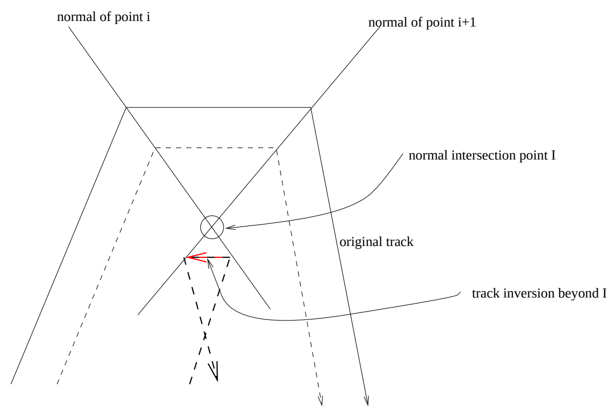

Figure 3.1: An example for track inversion due to a close normal intersection

3.3 A Proposal for calculating no-go zones

The main problem was how to limit the manoeuvering surface to a reasonable size. The initial idea was to reduce the maximum offset distance of a parallel track in relation to the enroute algorithm and to also reduce the spacing between the parallel tracks considered. Therefore the spacing was limited to 0.3 NM and the maximum offset distance to 20 NM for each side of the trajectory. This restriction of the manoeuvering surface is justified by the presence of neighboring STARs and restrictions concerning the exit point and the hand-over to enroute ATC. As mentioned above there is another limiting factor, the normal intersections which becomes very restrictive in the presence of extreme heading changes. Two solutions seem to exists for this problem:

1. To omit the initial section of the SID considered, which usually contains the most abrupt manoeuvres and to define a start of no-go zone computation point, this has to be done for each SID/trajectory separately and can easily be automated. It seems to be a good approach to the problem, since due to the various restrictions on the manoeuvering surface, imposed by noise abatement procedures and manoeuvres for avoiding high terrain on the initial portion of a SID, the manoeuvering area is very limited. The start-point may be calculated, by successively calculating the distance of the simple normal intersections for each section of the trajectory and take a point as start point after which the intersection distance is constantly greater than a predefined threshold, e.g. 10 NM. The case of complex normal intersection is only important in the case, where the intersection distance of two non-neighboring sections is inferior to the minimum intersection distance of all intermediate points.

2. To calculate the global minimum of all simple intersection distances to the right and to the left of the track, and to use it as a limiting factor

for the maximum distance of the considered offset tracks. The global minimum distance evolves with time, since only the remaining part of the trajectory is considered for the minimum (re-) calculation, i.e the width of the manoeuvering surface considered may grow with time. Since for the initial portion of an SID horizontal manoeuvres are very restricted due to the reasons mentioned above, the controller may choose to regulate the climb rate of the aircraft implicated in the conflict, i.e. modify the vertical profile and afterwards choose a horizontal manoeuvre when the workload in the cockpit is lower, and more complicated instructions can be issued and the no-go zone information becomes less confusing. It was decided to implement the second method.

3.4 Implementing the second Solution

For the calculation of the no-go zones the modified algorithm, respecting transition delays was used, and a function calculating the normal intersection distance for each segment, as well as the global minimum intersection distance was added. In order to be able to quickly evaluate the impact of normal intersection the display was modified in such a manner, that the conflict lines created by the concrete parallel trajectories were displayed directly, i.e. no zones were constructed. This required however a number of changes to the HIPS source code.

3.5 Testing

The traffic samples used are pretty unfavorable, i.e. all aircraft are assumed at a minimum interval of 90 secs, and succeeding aircraft are faster and climbing at a higher rate than preceding ones on the same SID, thus creating a large number of conflicts. The tests showed that even in this unrealistic and unfavorable situation a combined solution may be found quickly by modifying the vertical profile for the initial portion and the horizontal afterwards. It is however not possible to modify the initial climb profile when departing aircraft have to adhere to a certain climb profile due to high terrain or noise abatement procedures. The Athens and Frankfurt TMAs and SIDs were used for testing [5], [6], since Frankfurt represents a typical busy European airport with some initial restrictions on its SIDs for noise abatement. The Athens SIDs comprise numerous restrictions and extreme turns due to noise abatement procedures and high terrain around the airport, therefore the manoeuvering surface is extremely restricted. The tests showed however that the no-go zones can become quite confusing and resolving a conflict on the horizontal plane may become quite difficult, especially under time-pressure. Furthermore it is difficult to conceive and negotiate a complicated 4D trajectory in a phase where the cockpit crew is very busy and reaction time for the controller is less than for enroute ATC. Due to the uncertainty concerning the exact take-off time of an aircraft, it is very difficult to predict a conflict between an aircraft which is already airborne, and an aircraft entering the runway, and to take preventive action by manoeuvering the aircraft which is already airborne. In order to solve this problem, one might suppose that the succeeding aircraft is assumed by the controller at the minimum spacing interval, and therefore make a worst case analysis and take action, which might finally be unnecessary if the succeeding aircraft is delayed. The HIPS display was modified for DECORS in such a way, as to highlight conflict lines caused by a non-assumed succeeding aircraft in a different colour.

Chapter 4

DECORS

Assumptions:

- The aircraft are assumed by departure control at a predefined fixed point and altitude with a minimum time separation of 90 secs.
- The 4D trajectory of each aircraft is known in advance, as well as the take-off sequence

Definitions:

- Enroute Horizontal Separation: 5 NM
- TMA Horizontal Separation: 3 NM
- Vertical Separation (Enroute and TMA): 1000 ft
- The assumed aircraft is the aircraft which appeared last on the radar screen at the predefined assumption point
- Exit Level: The FL (see B.1 at which an aircraft exits the TMA and leaves the Control of DECORS
- Vectoring Start Point: For each SID a vectoring start point is defined in order to indicate the position at which a horizontal manoeuvre can be started, since the initial portion of an SID is always restricted for horizontal manoeuvres
- Vectoring Side: For each SID a variable is set indicating to which side (left or right) of the trajectory, starting at the Vectoring Start Point, an aircraft may be vectored, in order to avoid other SIDs and STARs

4.1 Remarks about Automatic Conflict Resolution

- A solution can not be guaranteed by a resolution algorithm.
- If more than two aircraft are involved in a conflict, a pairwise solution sequence has to be determined by the resolution algorithm [7].
- This problem is solved in the case of DECORS by using the departure sequence, since if a departure conflict occurs, the succeeding aircraft will have a higher speed and/or climb-rate and has to manoeuvre according to the *classical* rules of the air in order to avoid the conflict.
- Situational awareness as well as controller acceptance are the major issues involving the human being in the control loop.
- Another solution which has to be considered for departure control is the delegation of separation responsibility to the aircraft, i.e. instructions to follow a preceding aircraft at a distance of 3 NM or 1000 ft.

4.2 Controller Actions for departure Control

When two departing aircraft are in conflict the departure controller has various options for resolving the conflict:

- Vectoring one or both aircraft, in order to establish sufficient horizontal separation for an unrestricted climb (in terms of climb-rate or speed restrictions)
- Adjust the climb-rate of one or both aircraft involved in the conflict, so as to constantly maintain a sufficient vertical separation
- Turn one or both aircraft directly to a point on their trajectory instead of vectoring
- Delegate responsibility for separation to the pilots in VMC (Visual Meteorological Conditions)
- In case of an enroute separation conflict, change the exit altitude of an involved aircraft, or vector one aircraft to a different exit point
- Use a combination of the previous manoeuvres

The goal of DECORS was to imitate this behavior, in order to calculate and display conflict resolution suggestions at the assumption of an aircraft, as well as to display worst-case conflict lines for non-assumed aircraft, and to use the no-go zones and conflict lines as they have previously been adapted to TMA operations. The main changes in the HIPS source code concern the file `FlightPool.C`, to which some additional 2000 lines of code have been added.

The above set of rules had to be implemented, and a evaluation-sequence for the different resolution possibilities, in the trial and error process had to be established. It has to be pointed out that no guarantee exists, that a solution will be provided by DECORS, a statistical evaluation with several realistic traffic samples should be conducted, in order to determine the resolution rate. Some failures were observed in difficult cases where 4 successive departures were using the same SID with minimum separation and increasing speed and vertical speed, i.e. the less performing aircraft took off first, succeeded by the second less performing etc. Another basic problem of this kind of approach is the impact on the situational awareness, when automatic solutions are accepted which might include both, altitude and heading changes. Furthermore the information concerning these trajectory modifications has to be collected from two different displays (horizontal and vertical), a process which might take some time.

4.3 Resolution Strategy Components

- Conflict Classification
- Solution Validation
- Preventive Action
- Balanced Solution
- Restricted Solution
- Exit Level Changes
- Vectoring Around
- Vectoring Parallel
- Enroute Separation Conflicts

4.3.1 Conflict Classification

When an aircraft is assumed the conflicts with all preceding aircraft are calculated and stored in a list. In case of conflict with only one preceding aircraft, it is classified as simple conflict. Furthermore it is analyzed if the conflicting aircraft use the same or a different SID. Otherwise the conflict is classified as complex.

4.3.2 Solution Validation

It is the responsibility of the aircraft assumed, to manoeuvre in order to resolve the conflicts with all preceding aircraft. The resolution of conflicts with succeeding traffic is not taken into account, due to the uncertainty about their take-off

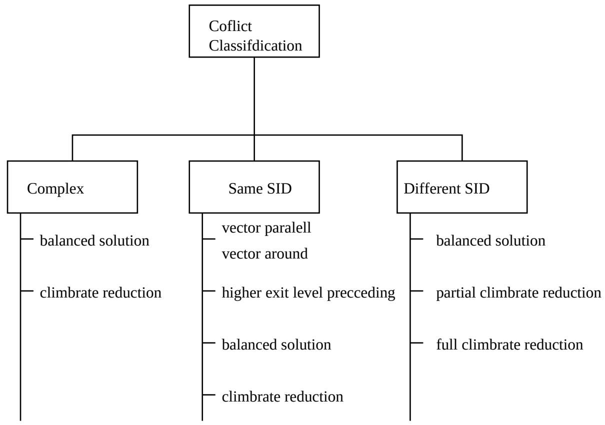

Figure 4.1: Conflict classification and corresponding trial and error solution evaluation sequence

time. At the assumption of an aircraft a trajectory-modification is proposed by the system, which might solve these conflicts. Its validity has to be checked by applying the medium term conflict detection algorithm to the new environment with the modified trajectory (trajectories, in the case of a balanced solution). If the proposed solution does not solve the conflict or creates a conflict with another preceding traffic, the solution is rejected. If all proposed solutions for the specific case are rejected no solution could be found by the system, and a respective message is displayed in a text window. Another important aspect of solution validation is the check for aircraft envelope adherence, i.e. if the proposed trajectory can be flown by the aircraft, e.g. when an augmentation of the climb-rate is proposed as solution.

4.3.3 Preventive Action

There are two types of preventive action:

1. Preventive action taken by the system, in order to shift potential conflicts with succeeding aircraft away from the initial portion of a SID, where the manoeuvering surface as mentioned earlier is extremely restricted, in order to facilitate the resolution and to increase the temporal distance to the conflict. This also leads to less confusing no-go zones, since the conflict lies on the later part of the SID, which is normally less problematic for no-go zone calculation.

2. Preventive action taken by the controller. The controller may modify the trajectory of an aircraft, such as to avoid no-go zones caused by succeeding traffic, and based on the worst case assumption that they will be assumed

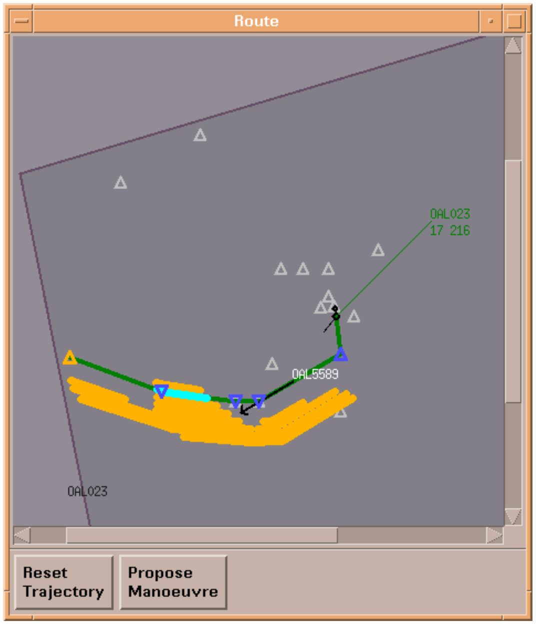

Figure 4.2: Conflict caused by succeeding aircraft OAL5589 (not airborne) and corresponding worst-case no-go zone

at the minimum time interval. The conflicts caused by succeeding traffic are shown in a different colour (see fig. 4.2).

DECORS tries to take preventive action by iteratively evaluating trajectories with a higher climb-rate than the actual trajectory, in order to quickly vacate the initial portion of the SID, if the assumed aircraft is not in conflict with the preceding aircraft.

4.3.4 Balanced Solution

A balanced solution is evaluated in the case of a simple conflict, and consists in increasing the climb-rate of the preceding aircraft, if it has not been subject to trajectory modification due to a previous conflict, and decreasing the climb-rate of the assumed aircraft. In this case both trajectories have to be checked for validity with all other aircraft controlled by DECORS.

4.3.5 Restricted Solution

A restricted solution consists of reducing the climb-rate of the assumed aircraft, for a portion, or for the entire SID (see fig 4.3).

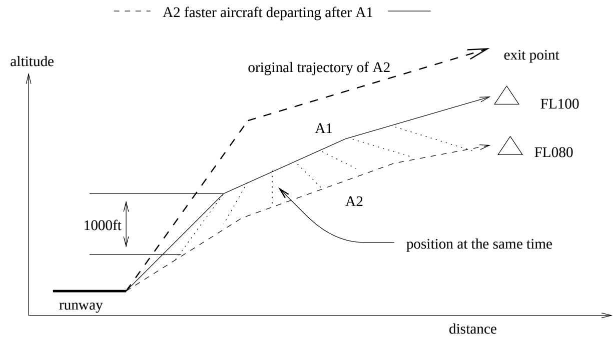

Figure 4.3: Imposing a climb-rate restriction by modifying the vertical trajectory of a succeeding faster aircraft

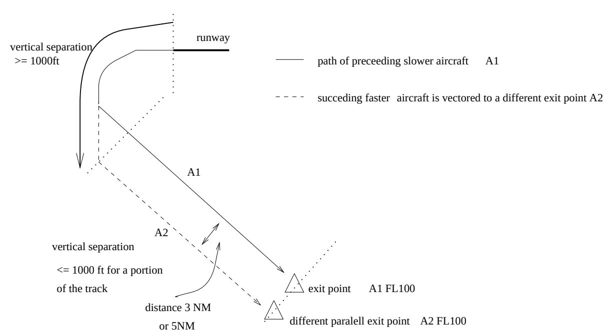

Figure 4.4: Construction of a parallel trajectory to a different exit point

4.3.6 Vectoring Parallel

If two aircraft are on the same SID and have the same exit level, the assumed aircraft may be vectored onto a parallel track, towards a parallel exit point, in order to resolve the conflict (see fig 4.4 and 4.5).

4.3.7 Vectoring Around

If two aircraft are on the same SID and the assumed aircrafts exit level is higher than the preceding one's, the assumed aircraft may be vectored to a parallel track, at an offset distance $\geq$ the minimum TMA horizontal separation, in order to climb past the other aircraft, and once it has passed it vertically turn back to the exit point (see fig 4.6).

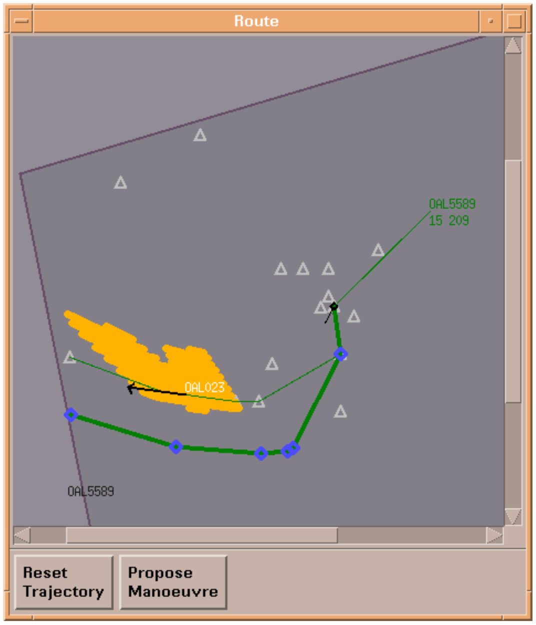

Figure 4.5: Vectoring succeeding aircraft OAL5589 (now airborne) to a different exit point

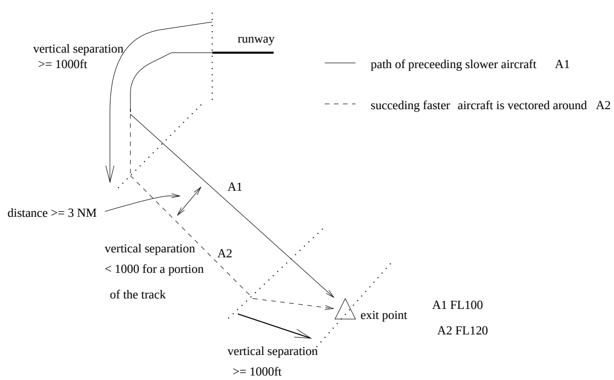

Figure 4.6: Vectoring around and climbing through the level of a preceding slower aircraft

4.3.8 Enroute Separation Conflicts

Two aircraft on the same SID and with the same exit level are checked additionally for horizontal enroute separation which is normally greater than the horizontal separation in the TMA. In this case two alternatives are evaluated, either vectoring the assumed aircraft onto a parallel track, at an offset distance $\geq$ the minimum *enroute* horizontal separation, towards a parallel exit point. The second option consists of changing the exit level of one of the two aircraft.

4.3.9 Evaluation sequence

The set of possible solutions has to be evaluated in a certain order, depending on the conflict classification as well as of a set of rules of preferential solutions. The following rules are established:

1. Changes of exit levels are to be evaluated last in order to avoid re-coordination with enroute ATC.

2. Therefore in case of a same SID simple conflict, a vectoring solution is evaluated first.

3. Climb rates shall be kept as high as possible, in order to avoid congestion of the initial portion of the SID which normally coincides with or is in the proximity of the initial portions of other SIDs.

4. If an exit level is changed DECORS tries to assign a higher level to the aircraft requesting the higher cruising level, if the exit levels are equal, the preceding traffic gets the higher exit level.

5. In a complex conflict or a different SID simple conflict, solutions involving vectoring are not considered.

4.4 Using DECORS

Each time a new departing aircraft is assumed a computation is started, in order to solve potential conflicts with preceding aircraft or to take preventive action. The modified trajectory is displayed on the three HIPS displays and a message appears in a text window ,indicating which type of manoeuvre is proposed by the system, the controller may choose to further modify the trajectory, to accept or to reject the proposed solution.

Appendix A

Abbreviations

ACC	Area Control Centre
ASAS	Airborne Separation ASsurance
ATC	Air Traffic Control
ATM	Air Traffic Management
DECORS	DEparture COnflict Resolution System
EEC	Eurocontrol Experimental Centre
FL	Flight Level
FREER	Free Route Experimental Encounter Resolution
ft	feet 1 $foot = 0.3048\ m$
GEARS	Generic Enroute Algorithmic Resolution Service
HIPS	Highly Interactive Problem Solver
NM	Nautical Mile 1 $NM = 1.852\ km$
PATs	PHARE Advanced Tools
PHARE	Programme for Harmonized ATM Research in Eurocontrol
SID	Standard Instrument Departure
STAR	STandard Arrival Route
TMA	Terminal Manoeuvering Area
VMC	Visual Meteorological Conditions

Appendix B

ATC-specific explanations

B.1 The Flight Level System and Exit Levels

Altitudes in Aviation are measured in feet, Flight Level 190 corresponds to a barometric altitude of 19000 ft, i.e. a FL corresponds to a pressure level. Flight Levels available are spaced by 1000 ft below FL290 and by 2000 ft above. Furthermore they are split into even and odd levels depending on the heading of the aircraft, i.e. 0 degrees through 179 degrees odd and 180 through 359 even. Even FLs are e.g. 020, 040, ..., 280 and 310, 350, ..., odd FLs are 010, 030, ..., 290 and 330, 370, ...
The airspace controlled by one ACC or Approach control centre is split up into different sectors. When an aircraft crosses the horizontal or vertical boundary between two sectors, it crosses a sector entry/exit point. The FL which has previously been coordinated for the specific aircraft and point is called the exit flight level, for the sector the aircraft is leaving.

B.2 TMA

A TMA is an airspace normally extending from 20 up to 40 NM around a major airport, in which arriving traffic is lined up and sequenced for final approach and departing traffic is handled until its hand-over to enroute ATC.

B.3 Aircraft Envelope

The aircraft Envelope consists of a set of maximum and minimum values for critical flight parameters such as speed, angle of attack, climb rate etc. depending on the aircrafts configuration, e.g. with flaps extended or retracted.

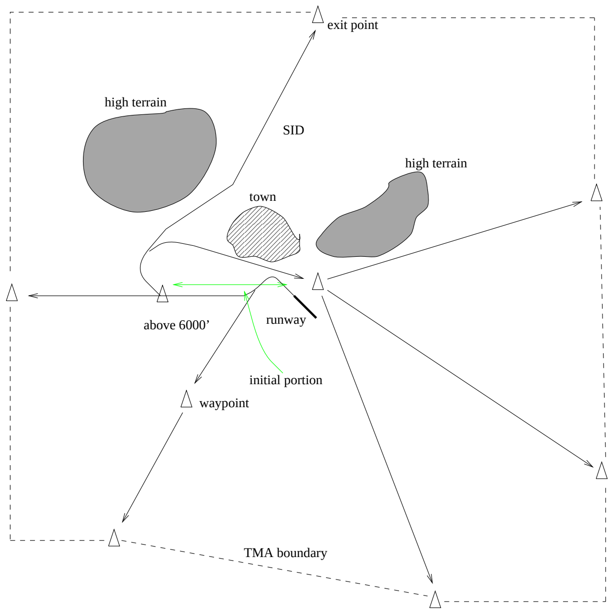

Figure B.1: typical SID layout

B.4 SIDs

A Standard Instrument Departure connects an airport to the airway system via the TMA exit points. These routes are published for each airport and each runway and runway direction. They are designed in such a manner as to avoid high terrain and built-up areas (noise abatement) surrounding the airport (see fig B.1).

B.5 FREER

FREER is a new concept for ATM, which is based on ASAS (Airborne Separation ASsurance), where each flight may file its individual flight-plan and does *not* have to follow the airways. Airspaces where free routing will be allowed are called free-route airspaces. FREER deals with conflict detection and resolution in this kind of airspace where conflicts are difficult to detect by a human being, because the traffic flows are not canalized any more. For low density airspaces the responsibility of conflict resolution shall be delegated to the aircraft, and the no-go zones calculated by HIPS are used to display the conflict to the pilot and assist him in resolving the conflict, when the system is switched to the manual resolution mode.

Appendix C

Calculating no-go zones based on the GEARS Algorithm

As mentioned in section 2.3, page 13, a completely different approach to calculating no-go zones would consist of basing it on the conflict-free trajectories as calculated by the GEARS [7] algorithm. A short description of the adaptation to HIPS will be given.

C.1 Construction of conflict-free alternative Trajectories based on heading changes

The following pseudo-code shows how the recursive algorithm for finding conflict-resolutions based on heading changes was implemented for HIPS. At the beginning, the closest conflict in terms of flight time is calculated. Then heading changes to the right and to the left of the actual track are evaluated iteratively up to an angle of +/- 40 degrees, spaced by 1 degree. The smallest conflict-resolving heading change for the left and the right side respectively, is used to construct the modified trajectory (see C.2). If no solution was found the corresponding branch of the recursion is a dead-end. If the rest of the modified trajectory is conflict-free it is stored in a list, otherwise there is a recursive call to the function with the modified trajectory and the next conflict as parameters. For a scenario with n aircraft the worst-case complexity is $O(2^n)$.

```
void Recursive(FirstConflict, Trajectory)
{
  if(LeftSolution(FirstConflict, ModifiedTrajectory))
    {
      if(ConflictFree(ModifiedTrajectory))
```

```
        {
          AddToSolutionList(ModifiedTrajectory);
          return;
        }
      else
        {
          GetNextConflict(NextConflict);
          Recursive(NextConflict, ModifiedTrajectory);
        }
    }

  if(RightSolution(FirstConflict, ModifiedTrajectory))
    {
      if(ConflictFree(ModifiedTrajectory))
        {
          AddToSolutionList(ModifiedTrajectory);
          return;
        }
      else
        {
          GetNextConflict(NextConflict);
          Recursive(NextConflict, ModifiedTrajectory);
        }
    }

  return;
}
```

C.2 Construction of a modified Trajectory

Constructing alternative, conflict-resolving trajectories exclusively using heading changes induces the following problems:

1. The problem of where to define the start of the turn, i.e. at which distance to the start of the conflict.

2. At which point to start the re-transition to the original trajectory (re-transition-point).

3. How to construct the re-transition to the original trajectory.

The following resolution of the above problems is proposed:

1. The start point of a turn onto a new heading, can either be defined as the re-transition-point added by the previous heading change (or the sector-entry point/present position, whichever is closer, if it is the first turn) or by a fixed time interval before the conflict e.g. 5 minutes before the conflicts

start time, if it is closer to the conflict than the re-transition-point. The first solution was implemented.

2. The re-transition-point is defined as the intersection between the straight line defined by the start point and the heading vector, and the straight line defined by the environmental aircrafts conflict line.

3. The re-transition to the original trajectory from the re-transition-point consists simply of a direct routing towards the sector-exit point (implemented solution). Another solution would be to join the original trajectory at the same angle.

C.3 Construction of the Zones

The zones are constructed by displaying the conflict lines (in blue colour) calculated by each unsuccesfull iteration of a call to `LeftSolution()/RightSolution()`. If an aircraft is in conflict with a sequence of $a_1, ..., a_n$ of n aircraft sorted by their conflict start time the zone calculated for a_2 is based on conflict resolving trajectories for the conflict with a_1. The zone for a_3 is based on the trajectories resolving the conflicts with a_1, a_2 and for a_n the resolution trajectories for $a_1, ..., a_{n-1}$. It may well be that the conflict line caused by an aircraft a_i with $i \geq 2$ is not contained in the zone, since the suceeding zones are calculated using the modified trajectory resolving the conflict with a_1. In order to properly use the modified zones, the controller should solve the conflicts respecting the sequence $a_1, ..., a_n$. In order to further facilitate the controller in resolving the conflict and understanding the way the no-go zones are calculated the conflict resolving trajectories are displayed as thin yellow lines.

C.4 Results

It is very difficult to judge the results obtained, since the quality of the zone shapes can only be judge using subjective criteria and may depend heavily on the users preferences. The key problem of all presented algorithms for no-go zone calculation, is that the controller has to acquire a good knowledge of how these algorithms work in order to use and interpret the information provided by the zones correctly. The presence of more stable zones which are practically not evolving dynamically as the trajectory is modified and the additional information provided by the conflict-resolving trajectories seem to be particularly helpful. Some basic problems concerning the start-of-manoeuvre point as well as the way the re-transition onto the original trajectory should take place remain unresolved. It seems however that displaying a set of automatiaclly calculated conflict-resolving trajectories and additionally displaying no-go zones to improve situational awareness would be the best way to resolve conflicts in the horizontal plane.

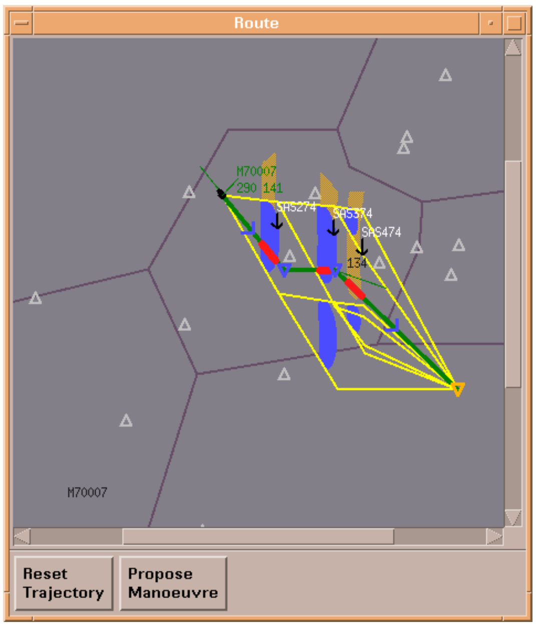

Figure C.1: An example for several conflicts with three environmental aircraft, conflict-resolving trajectories are displayed in yellow, the zones calculated by the new algorithm are shown in blue and those calculated by the transition-delay algorithm in beige

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