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CONFLICT RESOLUTION BY SPEED REGULATION

Maxime Galloux, Alexandre Gondran, Cyril Allignol and Nicolas Barnier
Laboratoire MAIAA, École Nationale de l’Aviation Civile, France
maxime.galloux@gmail.com
gondran,allignol,barnier@recherche.enac.fr

Abstract – To overcome the traffic growth predicted by current ATM research programs in Europe and the US, we propose a new model to avoid conflicts based on small speed regulations, as depicted in the ERASMUS project [2], with interval conflict constraints as in [3].

After a first conflict detection phase, a centralized solver computes new RTAs to dynamically adjust the flight plans during the flight, taking operational costs for airlines and for ATC into account. The resolution would be iteratively performed over a rolling horizon to handle the uncertainties inherent to trajectory prediction.

The described model is currently being implemented using Constraint Programming and Local Search as optimization techniques. Simulations will be carried out with Europe-wide traffic data.

Key words – Air Traffic Management, Speed Regulation, Conflict Avoidance

I. INTRODUCTION

For more than forty years, global air traffic has never ceased to increase. The current traffic control systems are reaching their structural limits, so that the traffic growth might reduce the safety level of the airspace. Thus, new methods and concepts are to be set up in order to adapt to this traffic growth by taking into account. Our model assumes that a conflict between two flights that follow intersecting trajectories with an accuracy of a few seconds. Its output is therefore a set of RTAs for each flight involved in a potential conflict within the time window of the resolution, trying to minimize the number of actual conflicts and their durations.

In this context, the trajectory of a flight i is represented by a sequence of 3D points and associated times corresponding to the waypoints of its route indicated by the flight plan:

\[ \{ \omega^k_i, \theta^k_i \mid k \in [1, n_i] \} \]

where the \( \sigma^k_{i,k} \) are the decision variables and \( n_i \) the number of waypoints of flight i. Furthermore, we note:

- \( \sigma^k_{i,k} \) the curvilinear abscissa (or oriented length along the trajectory) of each waypoint \( k \) of flight \( i \);
- \( \omega^k_i \) the speed, considered constant, between waypoints \( \omega^k_i \) and \( \omega^{k+1}_i \).

II. SEPARATION CONSTRAINTS

As in [4], this model is designed to take into account the functionalities of future Flight Management Systems (FMS) in the SESAR context, which will be able to dynamically accommodate several RTAs on the waypoints of their trajectories with an accuracy of a few seconds. Its output is therefore a set of RTAs for each flight involved in a potential conflict within the time window of the resolution, trying to minimize the number of actual conflicts and their durations.

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DISCRETIZATION OF TRAJECTORIES

Following the conflict model presented in [3], potential conflicts between two flights i and j are detected by pairwise checks on the points of a discretization of each trajectory, with a grain fine enough to ensure that even the shortest potential conflicts will be taken into account, as described in [5] for example. We note:

\[ \{ (p^{k'}_i, t^{k'}_i) \mid k' \in [1, m_i] \} \]

the discretization of the trajectory of flight i consisting of a sequence of \( m_i \) 3D points \( p^{k'}_i \) and associated times \( t^{k'}_i \), as illustrated in [5].

Similarly to the waypoints, we note \( s^{k'}_{i,k} \) the curvilinear abscissa of each point \( p^{k'}_i \). These abscissae can be easily...
computed by adding the distances between the previous points of the trajectory:

\[ s_i^k = \sum_{l=1}^{k-1} \text{dist}(p_i^l, p_i^{l+1}) \]

providing that the turning points of the trajectory, i.e. the waypoints \( \omega_i^k \), are included in the discretization points \( p_i^k \).

A similar relation would be true for the abscissae \( \sigma_i^k \) of the waypoints (as they indeed are the turning points), but only during cruise, as the waypoints are too distant from each other to approximate the vertical profile of the descent or climb phase precisely enough.

**CONFLICT DETECTION**

Two points \( p_{i'}^k \) and \( p_j^l \) of flight \( i \) and \( j \) are in potential conflict if their horizontal and vertical distances both violate the separation norm (usually 5 NM horizontally and 1000 ft vertically), as depicted in figure 1 for the horizontal plane. For two such points, there would be an actual conflict between flights \( i \) and \( j \) if they are located at these points at the same time. To avoid a conflict, it is therefore necessary that:

\[
\forall k' \in [1, m_i], \forall l' \in [1, m_j], \quad \text{dist}_H(p_{i'}^k, p_j^{l'}) < 5 \text{ NM} \quad \land \quad \text{dist}_V(p_{i'}^k, p_j^{l'}) < 1000 \text{ ft} \quad \Rightarrow \quad t_{i'}^k \neq t_j^{l'} \tag{1}
\]

where \( \text{dist}_H \) is the distance in the horizontal plane and \( \text{dist}_V \) in the vertical plane.

For intersecting trajectories, we assume, as in [4], that successive potentially conflicting points are all located in the vicinity of the same waypoint. As the speed is considered constant between two consecutive waypoints, it is possible to translate these conflict inequations [1] to their closest waypoint, such that the conflict constraints can be expressed as a temporal separation at this waypoint.

The resolution will therefore consist in regulating the speed of these flights (through the issuing of RTAs at the waypoints only) so as to avoid conflicts, i.e. ensure that the corresponding inequation \( \theta_i^k \neq \theta_j^l \) holds for all the neighbouring pairs of potentially conflicting points \( p_{i'}^k \) and \( p_j^{l'} \).

However, catch-up conflicts along the same route portion (or if the angle of intersecting trajectories is very low) cannot be considered local to a single waypoint. Thus, all potentially conflicting points located between waypoints \( \omega_i^{k-1} \) and \( \omega_j^{k+1} \) are reported to a potential conflict associated with \( \omega_i^{k} \). Several such conflicts will then be defined at each successive waypoints as long as the flights follow the same route.

We can now define a generalized (intersecting or catching-up) potential conflict between two flights \( i \) and \( j \) as the set of conflicting pairs of trajectory points around a single waypoint:

\[
C_{ij}^{kl} = \{ (k', l') \in [1, m_i] \times [1, m_j], \quad \text{s.t.} \quad p_{i'}^k \quad \text{and} \quad p_j^{l'} \quad \text{are in potential conflict near} \quad \omega_i^k = \omega_j^l \}
\]

\[
\text{and} \quad \sigma_i^{k-1} < s_i^{k'} < \sigma_i^{k+1}, \quad \sigma_j^{l-1} < s_j^{l'} < \sigma_j^{l+1}\}
\]

To compute the resulting constraint between \( \theta_i^k \) and \( \theta_j^l \), we first need to express \( t_{i'}^k \) as a function of \( \theta_i^k \) and the speed of the aircraft, which is \( v_i^{k-1} \) before waypoint \( \omega_i^k \) and \( v_i^k \) afterwards. Therefore:

\[
\forall k' \in [1, m_i], \quad \exists l' \in [1, m_j],
\]

\[
t_{i'}^k = \left\{ \begin{array}{ll}
\theta_i^k + \frac{s_i^{k'} - \sigma_i^k}{v_i^k} & \text{si} \quad s_i^{k'} \geq \sigma_i^k \\
\theta_i^k + \frac{s_i^{k'} - \sigma_i^k}{v_i^k} & \text{si} \quad s_i^{k'} < \sigma_i^k
\end{array} \right. \quad \tag{2}
\]

Inequation [1] and equation [2] can then be combined, with four different cases depending on the locations of points \( p_{i'}^k \) and \( p_j^{l'} \) with respect to waypoint \( \omega_i^k = \omega_j^l \). Note that if flights \( i \) and \( j \) have several distinct (non continuous) potential conflicts, there will be as many (non empty) sets \( C_{ij}^{kl} \) of conflicting points:

\[
\forall (k, l) \in [1, m_i] \times [1, m_j] \quad \text{s.t.} \quad C_{ij}^{kl} \neq \emptyset, \forall (k', l') \in C_{ij}^{kl}, \quad t_{i'}^k \neq t_j^{l'} \quad \text{implies}
\]

\[
\theta_i^k - \theta_j^l \neq 
\left\{ \begin{array}{ll}
\frac{s_i^{k'} - \sigma_i^k}{v_i^k} - \frac{s_j^{l'} - \sigma_j^l}{v_j^l} & \text{si} \quad s_j^{l'} \geq \sigma_j^l \text{ and } s_i^{k'} \geq \sigma_i^k \\
\frac{s_i^{k'} - \sigma_i^k}{v_i^k} - \frac{s_j^{l'} - \sigma_j^l}{v_j^l} & \text{si} \quad s_j^{l'} \geq \sigma_j^l \text{ and } s_i^{k'} < \sigma_i^k \\
\frac{s_i^{k'} - \sigma_i^k}{v_i^k} - \frac{s_j^{l'} - \sigma_j^l}{v_j^l} & \text{si} \quad s_j^{l'} < \sigma_j^l \text{ and } s_i^{k'} \geq \sigma_i^k \\
\frac{s_i^{k'} - \sigma_i^k}{v_i^k} - \frac{s_j^{l'} - \sigma_j^l}{v_j^l} & \text{si} \quad s_j^{l'} < \sigma_j^l \text{ and } s_i^{k'} < \sigma_i^k
\end{array} \right. \tag{3}
\]

However, these expressions depend on the (unknown) variable speeds of aircraft, whereas the conflict model presented in [2] uses static bounds for the time difference between flights \( i \) and \( j \) at waypoint \( \omega_i^k = \omega_j^l \). In the next section, we explain how the speed variations are tightly bounded in our operational context, which allows us to approximate the values of equation [3] by small intervals.
III. SMALL SPEED ADJUSTMENT AND
CONFLICT APPROXIMATION

Following [4], we consider the same kind of small speed
variation as in the ERASUS project [5]. Two ratio par-
teters \( \alpha \leq 1 \) and \( \pi \geq 1 \) are introduced to bound the possi-
ble speed adjustment, such that if we note \( \nu_0^i \) the reference
speed of flight \( i \), all other speed variables are restricted to take
values in a small interval \( [\alpha \nu_0^i, \pi \nu_0^i] \):

\[
\forall i \in [1, n], \forall k \in [1, n_i - 1], \nu_k^i \in [\alpha \nu_0^i, \pi \nu_0^i]
\]

where \( n \) is the number of flights in the instance.

These ratio parameters are typically chosen in the range
\( \alpha = 0.97 \) and \( \pi = 1.06 \) to limit the cost of regulation on the
fuel consumption of aircraft and to have the smallest impact
possible on standard Air Traffic Control (ATC) practices.

As the speed variations considered are small and bounded,
we can bound the values of \( \theta_k^i - \theta_j^i \) described in equation \( 3 \)
by constants \( r_k^{ij} \) (lower bound) and \( r_k^{ij} \) (upper bound) de-
defined as follows:

\[
\forall (k, l) \in [1, n_i] \times [1, n_j] \text{ s.t. } C_{ij}^k \neq \emptyset, \forall (k', l') \in C_{ij}^k
\]

\[
r_k^{ij} = \min_{(k', l') \in C_{ij}^k} r_k^{ij}
\]

\[
r_k^{ij} = \max_{(k', l') \in C_{ij}^k} r_k^{ij}
\]

For one conflict set \( C_{ij}^k \), bounds of a forbidden interval
for the difference of times \( \theta_k^i - \theta_j^i \) at the waypoint can then be
computed by cumulating the inequations over the pairs of
conflicting points \( (k', l') \in C_{ij}^k \):

\[
r_k^{ij} = \min_{(k', l') \in C_{ij}^k} r_k^{ij}
\]

\[
r_k^{ij} = \max_{(k', l') \in C_{ij}^k} r_k^{ij}
\]

Moreover, the bounds on the speed of each aircraft fur-
ther constrain the \( \theta_k^i \) variables for two consecutive waypoints
\( \omega_k^i \) and \( \omega_k^{i+1} \):

\[
\forall k \in [1, n_i - 1], \theta_k^{i+1} - \theta_k^i \in \left[ \frac{d_k^i}{\pi \nu_0^i}, \frac{d_k^i}{\alpha \nu_0^i} \right]
\]

with \( d_k^i = \sigma_k^{i+1} - \sigma_k^i \), the distance between \( \omega_k^i \) and \( \omega_k^{i+1} \).

In the following, these bounds on the travel time of flight \( i \)
between two consecutive waypoints are respectively noted
\( T_k^i = \frac{d_k^i}{\pi \nu_0^i} \) and \( T_k^i = \frac{d_k^i}{\alpha \nu_0^i} \).

IV. MODEL

The conflict detection processing of the previous sections
can now be sum up with a more standard (and concise)
combinatorial decision problem formulation, with variables \( \theta_k^i \) representing the RTA of flight \( i \) on waypoint \( \omega_k^i \), for a
set of \( n \) potentially conflicting flights over the time window
considered:

\[
\text{Find: } \forall i \in [1, n], (\theta_k^i)_{k \in [1, n_i]}
\]

\[
s.t.: \forall (i, j) \in [1, n_i]^2, i < j,
\]

\[
\forall (k, l) \in [1, n_i] \times [1, n_j] \text{ s.t. } C_{ij}^k \neq \emptyset,
\]

\[
\theta_k^i - \theta_j^i \notin \left[ r_k^{ij}, r_k^{ij} \right]
\]

\[
\forall i, \forall k \in [1, n_i - 1], \theta_k^{i+1} - \theta_k^i \in \left[ T_k^i, T_k^i \right]
\]

The first set of constraints are derived from the conflicts
between two potentially conflicting flights \( i \) and \( j \), \( r_k^{ij} \) and \( r_k^{ij} \) being the bounds of the forbidden values for the differ-
ence of fly times over the conflicting waypoint \( \omega_k^i = \omega_j^i \).
The second one characterizes the speed limitation for each
aircraft as stated in equation \( 4 \).

OPTIMIZATION

Among the admissible solutions of this decision problem,
the ones that minimize airlines costs should be preferred. To
optimize their operating costs, airlines generally tune the
Cost Index (CI) parameter (used by the FMS to optimize the
flight parameters along its trajectory) for each flight, which
represents the relative importance of the cost of fuel with
respect to the cost of flight time, i.e.:

\[
\text{CI} = \frac{\text{cost}_\text{time}}{\text{cost}_\text{fuel}}
\]

where \( \text{cost}_\text{time} \) is in $ per time unit, and \( \text{cost}_\text{fuel} \) in $ per
mass unit.

For a given flight \( i \), we can therefore consider that the
airline cost is the sum of the extra cost of time and of the
extra cost of fuel multiplied by CI, (the Cost Index of flight
\( i \)), compared to the reference trajectory at the reference
speed:

\[
\text{cost}_i = \text{CI}_i \times \text{cost}_\text{fuel} + T_i^0 - (\theta_i^\text{opt} - \theta_i^0)
\]

where \( T_i^0 = \sum_{k=1}^{n_i-1} \frac{d_k^i}{\alpha \nu_0^i} \) is the total flight time of flight \( i \)
at its reference speed \( \nu_0^i \).

If we assume that \( v_0^i \) is the optimal speed of the flight
and that a discrepancy from \( v_0^i \) leads to a proportional increase of
fuel consumption during the time flown at this speed, then:

\[
\text{cost}_\text{fuel} = \sum_{k=1}^{n_i-1} \frac{|v_k^i - v_0^i|}{v_0^i} (\theta_k^{i+1} - \theta_k^i)
\]

\[
= \sum_{k=1}^{n_i-1} \frac{|d_k^i}{\alpha \nu_0^i} - (\theta_k^{i+1} - \theta_k^i)
\]
The longer the conflict lasts, the closer remaining conflicts with the operational one, so as to take equation 7 with suitable weighting to balance the cost of solutions with as few violated constraints as possible. Furthermore, when a conflict constraint is violated, the longer the conflict lasts, the more hazardous is the operational situation, so it is interesting as well to search for solutions that minimize the duration of all actual conflicts, as proposed in [4].

As the conflict constraints of our model enforce that \( \theta_i - \theta_j \) does not belong to \([r_{ij}, r_{ij}^L]\), we have to compute the “distance” of the time difference from the center of the interval \(M_{ij}^{kl} = \frac{1}{2}(r_{ij}^{kl} + r_{ij}^{kl})\):  
\[ \text{dist}_{ij}^{kl} = \left| (\theta_i - \theta_j) - M_{ij}^{kl} \right| \]

The longer the conflict lasts, the closer \( \theta_i - \theta_j \) is to \(M_{ij}^{kl}\), and the smaller is \(\text{dist}_{ij}^{kl}\). So to obtain a measure of the duration of the conflict, the distance is subtracted from the half of the length of the interval \([r_{ij}^{kl}, r_{ij}^{kl}]\), i.e. from \(L_{ij}^{kl} = r_{ij}^{kl} - r_{ij}^{kl}\). Moreover, the cost should be 0 outside the conflict interval:  
\[ \max(0, \frac{1}{2}L_{ij}^{kl} - \left| (\theta_i - \theta_j) - M_{ij}^{kl} \right|) \]

The total cost over all remaining conflicts is the sum of all the actual conflicts durations, for all pairs of flights in potential conflict (i.e. \( \forall i < j \) s.t. \( \exists (k, l), C_{ijkl}^{kl} \neq \emptyset \)):  
\[ \text{cost}_{\text{conflict}} = \sum_{i<j} \sum_{k,l,i,j} \max(0, \frac{1}{2}L_{ij}^{kl} - \left| (\theta_i - \theta_j) - M_{ij}^{kl} \right|) \]

This cost could be combined with the cost defined in equation 3 with suitable weighting to balance the cost of remaining conflicts with the operational one, so as to take both criteria into account for overconstrained instances.

V. CONCLUSIONS AND PERSPECTIVES

To overcome the traffic growth predicted by current ATM research programs in Europe, we propose a novel deconfliction model based on small speed regulations, following the mixed integer program presented in [4] with a conflict model that generalizes the work presented in [3]. The associated centralized solver would output new RTAs to dynamically adjust the flight plans during the flight, taking operational costs for airlines and for ATC into account. The resolution would be iteratively performed over a rolling horizon (20–30 min) to handle the uncertainties inherent to trajectory prediction.

The described model is currently being implemented using Constraint Programming and Local Search as optimization techniques. Simulations will be carried out with Europe-wide traffic data.

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