2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

BETA-MESH - A Dynamic 3D Mesh Modelization

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***Abstract*—In this paper, we intend to introduce a new paradigm to ease the path from the optimization research area towards the operational use: how to inject automation in ATM by integrating several constraints without increasing the complexity for the controller ? The fundamental idea is to model the airspace linked to the ground to connect all the possible trajectories through a mesh representing the space of possible trajectories. One objective is to reinforce the realism of the trajectory by combining the aircraft performances to automatic learning and procedural patterns. Thus, the multi criteria shortest path approach with its associated algorithms are used to resolve an instance created from a representative mesh with the possible trajectories for the aircrafts. The question to resolve is then: how to build this instance from the data of a 3D environment by taking into account the uncertainties?**

Keywords: optimization, flow management, graph, mesh, gate to gate, shortest path algorithm

I. INTRODUCTION

With a 15-year horizon, the air traffic management in Europe and the United States will undergo many changes to cope with the increasing number of flights per year. SESAR (Europe) and NEXTGEN (U.S.) initiatives have the ambition to provide a local solution to a worldwide statement.

There are many levers to influence the way traffic is managed: the layout of the airspace, operational procedures, air traffic control system, aircraft equipment, exchange of information, etc. Our overall approach is based on the integration of airspace and operational procedures, represented in a common formalism to be used by the air traffic control system without decreasing the level of flexibility necessary for taking into account the specificity of each context. This approach will take benefit of the air/ground exchange through a better trajectory prediction limiting the uncertainties.

In this paper, we propose to define a new model for the field of civil aviation. This model has the advantage of expressing simply a set of basic concepts of the air traffic control for many stakeholders such as the aircrafts, air traffic controllers and artificial actors without losing expressiveness. We model a reality subject to many disturbances involving a context of uncertainties. The basic idea is based on the notion of dynamic mesh which integrates not only the static airways connected to taxiways, but also the avoidance patterns in front of each aircraft. By doing so, the trajectories are constructed dynamically and are integrated in the mesh. Thereafter, we can use a toolbox of algorithms to decide the best maneuver according to different criteria. These criteria must consider different parameters of the flights but also the complexity of the controller work. Indeed, the modelization of the complexity is essential for the acceptance of the solutions by the controllers. More generally, the model presented here is a part of a top-down approach where we consider many of the works of the literature as solutions to specific air traffic management problems. With the mesh, these solutions can be put together as a global system. Our approach is unique in the sense that the representation is adjusted to the problem to be addressed while maintaining the same algorithmic methods.

To ensure a temporal continuity that is not met today due to the use of different systems and procedures related to the flight phases, this approach allows to supervise an airspace from the planning phase to the tactical phase. Thus, standardization of the techniques (spatial and temporal) allows to capture the full information of a phase and to inject it into the next phase in a natural way. From the planning phase to the tactical phase, the uncertainties will be reduced allowing the controllers to manage the transition from a traffic flow management to a flight management in a continuous way by simply changing granularity.

II. DESCRIPTION OF THE MESH

In this section, the general idea of the mesh is presented by integrating the procedures of the controllers. Initially, the basic assumption states that the aggregation of local optimization methods based on a global entity can conduct to a global optimum. It is a vision between centralized and distributed optimization. The following paragraph describes this model called mesh dividing its components into four categories: static, observation/learning-based, procedural and dynamic.

A. Static Data

1) Airways : The mesh is a discretization of the airspace (approach and enroute phases) connected to the ground movement (airport taxiways and runways). This discretization of three-dimensional space is based on the concept of points and routes. Thus, we assume that aircraft are always positioned on a straight line connecting two points in space that is to say a route. The distance between two points is arbitrary, which can approximate any trajectory. The next sections describe how to generate these points and routes.

First, static data are created from the waypoints and airways that are generated by air traffic control organizations.

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It also adds the taxiways, the runways and gates of airports to have a gate to gate picture [1] [2].

These data rarely evolve and represent an important basis for next presented techniques. We can already characterize the static data : the routes are either unidirectional or bidirectional and belong to several geometric planes located on different flight levels. Note that, for the moment, there are no roads to realize the changes of levels, because the climb profiles are based on aircraft performances.

The graph obtained is densified to remove the critical segments. A critical segment [A,B] is a route between two points of the mesh defined as follow: the graph connectivity decreases when the segment is removed or, the path to go from A to B is beyond a given threshold in Nautical Miles when the segment is removed

2) Observation and learning: However, static data are related to the ground and steady flight levels and so, the mesh does not cover the ascending/descending phases. To fill this gap, the aircraft performances per aircraft are modeled to integrate in the graph the level change segments based on the learned ROC[1], ROD[2]. Moreover, the assumption that aircraft follows predefined routes does not provide a realistic model. Instead, because of the unknown burden of the aircraft, it is difficult for a controller to estimate the aircraft performances for predicting the trajectory. Furthermore, it is common that we want to reach a point through geodesic on the great circle. Static data do not take into account these uncertainties. In a horizontal plane, the ROT[3] per aircraft obtained by learning is used to improve the turning accuracy by adding segments at each points (calibration points).

To address this problem, we use machine learning tools (e.g. clustering based on k-means) inspired by [3] to draw conclusions about typical trajectories i.e. an average associated with characteristics such as location, time of day, day of the year, aircraft type, airline and weather. Thus, the data learned are associated with a context. For example, when an aircraft initiates a level change, we can calculate its climb profile using the contextual data.

3) Procedures : The beta-mesh approach incorporates some operational procedures. We model the standard procedures developed by the air traffic control organizations to help controllers to optimize the flows. First, the SID[4] and STAR[5] fit into the mesh, because they define the points to follow for takeoff and landing, respectively. Here are some known procedures that can be embedded into the model.

The ”green procedures” (e.g. CDA[6], point-merge [4], tailored arrival [5]) are optimized for the approach phase. These patterns (see Fig. 1) are integrated into the graph to optimize the fuel consumption and to reduce noise by adopting a trajectory with an uniform rate of descend from the cruising flight level to the runway. The modeling of this process will quantify the gain and ensure that the passage of various flight levels is safe globally. The system will automatically promote the green procedures as often as possible. Moreover, the vectoring patterns used by the controllers are also integrated to obtain more realistic routes and thus ensure the traffic fluidity.

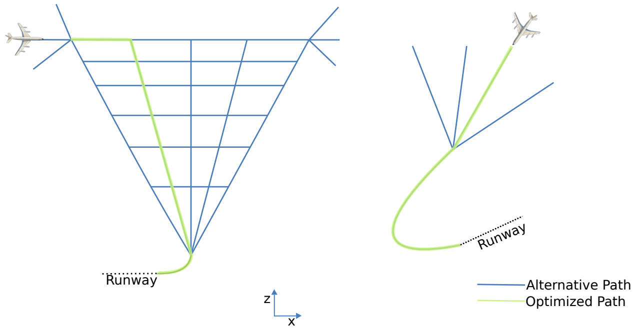

Fig. 1. Green patterns

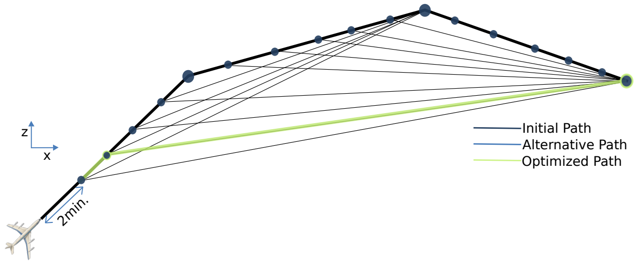

Fig. 2. DCT application

B. Dynamic Data

While the previous strategy builds a coherent mesh with reality, it remains that the near avoidance is not covered by a static representation. Dynamic data cover more the airspace by creating points and roads temporarily and locally. These data are generated by applying the patterns of conflict resolution from air traffic controllers clearances: DCT[7], HDG[8], RTE[9] and CFL[10]. The speed regulation is deliberately not covered in this paper as speed change does not affect the mesh definition. The difference with the procedures is that these patterns are associated to each aircraft and based on operationnal procedures, the mesh is always densified δt minutes(around two minutes) after the current flight position for a near avoidance.

The DCT (see Fig. 2) is used to guide the aircraft from one point to another on the planned path without going through all the waypoints. The route shortcut reduces the time of flight of the aircraft. The optimization of this procedure is to find the coordinates of the point of application and the coordinates of the point of arrival according to the usual constraints (see Fig. 2).

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[1] Rate Of Climb
[2] Rate Of Descent
[3] Rate Of Turn
[4] Standard Instrument Departure
[5] Standard Terminal Arrival Route
[6] Continuous Descent Approach
[7] Direct routing
[8] Heading change
[9] Route change
[10] Cleared Flight Level change

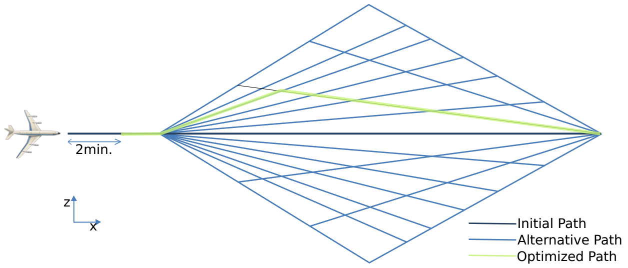

Fig. 3. HDG application

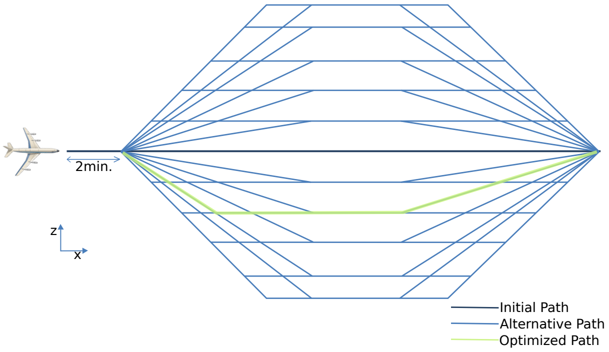

Fig. 4. RTE application

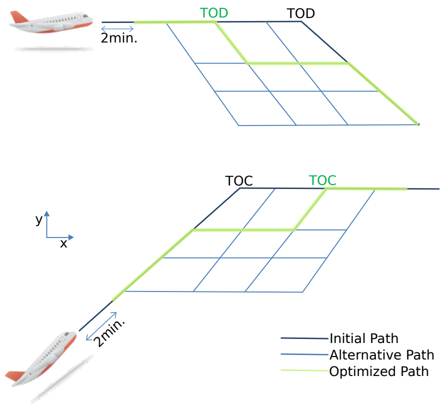

Fig. 5. CFL application

The HDG (see Fig. 3) allows the controller to easily avoid a conflict between two aircrafts. The application of this procedure is to provide a vector of deviation to the aircraft that the pilot must follow until it receives permission to resume its planned path. The parameters to optimize are the coordinates/heading from the point of application and the coordinates/heading from the breakpoint to return to the initial path.

The RTE (see Fig. 4) is used to shape a horizontal offset to create a parallel path to the planned path which allows multiple aircrafts to be side by side.

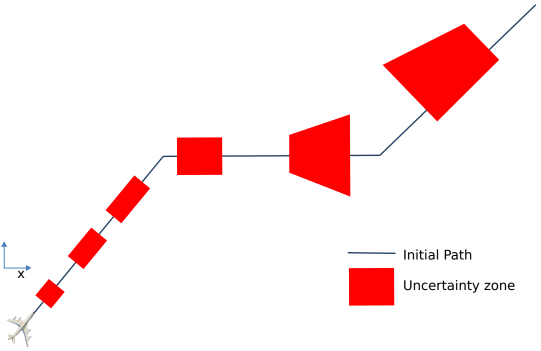

Fig. 6. Definition of the margins

Finally, the CFL (see Fig. 5) is a method for resolving conflicts in approach phases. The system anticipates the descent phase (TOD[11] change), or delays the climbing phase by creating an intermediate flight level (i.e. TOC[12] change). The optimization parameters are coordinates of the point of application and flight level to reach.

III. UNCERTAINTY MANAGEMENT

The uncertainty is part of automation systems, so how to optimize trajectories and manage uncertainties at once? Due to the large number of complex factors such as weather forecast, aircraft performances, human decisions (pilots and controllers), and unexpected situations, it is impossible to anticipate each situation beyond a given duration. To manage this uncertainty, learning methods are used to gain in information accuracy on *what usually happens under certain conditions*. This expression describes the pragmatic aspects of the air traffic controller in which it explicitly does not assess the degree of uncertainty it faces. It is rather based on his experience. Through learned trajectories, we can statistically know, based on aircraft performance database, the typical trajectories that should be used by the aircrafts. The purpose of the approach is to use at any time the most likely trajectory based on the flight intent analysis, i.e. the last reported aircraft position extrapolated using the learning database. Moreover, the uncertainties in terms of trajectory prediction are represented by convex polygons (based on the longitudinal, lateral and vertical errors). The size of the polygons is directly correlated to the uncertainty at a given time (see Fig. 6).

The trajectory will be represented as a polyline connected to the 3D mesh and the uncertainties will be directly correlated to the separation parameters. The most obvious feature is the use of safety margins as do the controllers. These margins are used in the detection of conflicts in defining radius which greatly exceeds the minimum distance of separation. The uncertainty is then absorbed in the margins because a plane cannot accidentally deviate from its trajectory to the point where it exceeds the safety margins. The separation parameters are function to the uncertainty with a predefined acceptance threshold. Thus, the system will automatically integrate the level of confidence of the proposed solution. This, therefore, anticipates the uncertainties as soon as possible, because we know in advance what will potentially happen

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[11] Top Of Descend

[12] Top Of Climb

with the past situations (global behavior by analyzing the last days of traffic and local behavior by the last minutes of flight).

IV. MODELIZATION

In this section, we propose a theoretical approach for implementing the concepts presented so far.

A. Atemporal Network

For the sake of simplicity, we first present the airspace without the temporal dimension. We refer to the next set of definitions as the atemporal network.

Definition 1: A waypoint is a couple in $\mathbb{R}^2$ which corresponds to its latitude and longitude. We note that there is no flight levels associated to it. The set of all waypoints is denoted by E.

Definition 2: An air route is a quadruplet in $E^2 \times \mathbb{R}^2$ where the first two elements are the source and the destination waypoints and the last two elements are the initial and final flight levels.

Definition 3: An airspace is modelized by a directed-graph $\mathcal{A} = (V, E, w_E, w_{FL\uparrow}, w_{FL\downarrow})$ where V is a set of waypoints, E is a set of air routes, $w_E : E \to \mathbb{R}^+$ is the distance associated to two waypoints linked by an air route, $w_{FL\uparrow} : E \to \mathbb{N}$ (respectively $w_{FL\downarrow} : E \to \mathbb{N}$) is the difference in flight levels for an ascending (descending) air route.

Definition 4: A path $\pi = \langle e_1, ..., e_n \rangle$ must respect the following constraints :

- $\forall i \in [1, n-1] \subset \mathbb{N}, e_i.\text{fw} = e_{i+1}.\text{iw}$
- $\forall i \in [1, n-1] \subset \mathbb{N}, e_i.\text{ffl} = e_{i+1}.\text{ifl}$

where 'iw' is the initial waypoint, 'fw' is the final waypoint, 'ifl' is the initial flight level and 'ffl' is the final flight level. The length of the path is computed by $l(\pi) = \sum_{i=1}^{n} w_E(e_i)$. Furthermore, the set of all possible paths is $\mathcal{P}$ and can be restricted to any sets of paths from e_1 to e_n by $\mathcal{P}(e_1 \rightsquigarrow e_n)$. Then, for any shortest path π^*, we have $l(\pi^*) = \min_{\pi \in \mathcal{P}(e_1 \rightsquigarrow e_n)} l(\pi)$. Finally, we define a distance function by $d_E(u, v) : V^2 \to \mathbb{R}^+$:

$$d_E(u,v) = \begin{cases} \min_{\pi \in \mathcal{P}(e_1 \rightsquigarrow e_n)} l(\pi) & \text{if } \pi \text{ exists} \\ +\infty & \text{otherwise} \end{cases} \quad (1)$$

When $d_E(u, v) \neq +\infty$, we can compute the difference in flight levels by :

$$\begin{aligned} d_{FL}(\pi) : \mathcal{P} &\to \mathbb{N}^2 \\ \pi &\mapsto \sum_{i=1}^{n} (w_{FL\uparrow}(e_i), w_{FL\downarrow}(e_i)) \end{aligned} \quad (2)$$

Otherwise, these values are equals to +∞. By an aggregation, one can now optimize a path according to these three distances.

B. Dynamic Network

Now that we have an atemporal network, we want to modelize an airspace in action. The following definitions are about the dynamic network. We were inspired by the work of [6].

Definition 5: A 4D point is a quadruplet in $\mathbb{R}^2 \times \mathbb{N}^2$ where the first two elements are the latitude and longitude and the last two elements are the flight level and the time. We note that by associating the time to $\mathbb{N}$, we discretize the time with an arbitrary granularity e.g. a second or a half minute.

Definition 6: A trajectory is a set of 4D points associated to a single aircraft from takeoff to landing. It is a discretization of the real trajectory with a timestamp to every points.

Now, we will link the 4D point to the atemporal network for constructing the dynamic network. A 4D point is always located on an air route. This means that we need an interpolation function :

$$\begin{aligned} \mathcal{I} : E \times [0,1] &\to \mathbb{R}^2 \times \mathbb{N} \\ (v, r) &\mapsto (lat, long, fl) \end{aligned} \quad (3)$$

with the constraints :

$$\mathcal{I}(e, 0) = (e.\text{iw}, e.\text{ifl})$$
$$\mathcal{I}(e, 1) = (e.\text{fw}, e.\text{ffl})$$

An example of the interpolation function can be a simple linear interpolation with a ratio determined by the average speed of the plane and the elapsed time. Then, it is very easy to create a new 4D point by adding the current timestamp.

V. OPERATIONAL CONCEPTS

In this section, we will add some operational concepts to the temporal network defined so far. Their modeling can optimize the trajectories while taking into account additional constraints caused by the loss of separation among aircrafts, segregated areas, storms, sectorization and coordination among controllers. At first glance, the operational constraints can be modeled simply by activating/deactivating the conflicted air routes. Thus, the mesh integrates automatically the operational constraints and the multi-objectives optimization algorithms are applied on a graph which is qualified as "free of conflicts" and minimizing the following objectives :

- Risks
- Delays
- Controller workload and complexity
- Fuel consumption
- Airport Capacity

Thereafter, we can use different strategies for assuring that the importance of these objectives are respected.

A. Flights and Sectorization

The sectorization is a fundamental concept in air traffic control used to manage the complexity inherent to the work of the controllers. By dividing the airspace into elementary volumes constituting sectors and belonging to the FIR[13], the complexity is shared among several control positions. Each control position has the responsibility to maintain a high level of security and to ensure the flow of aircrafts through their

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[13] Flight Information Region

sector and in its periphery. The sectors have a capacity related to the controller workload which is calculated by the ANSP[14].

Definition 7: A flight is a triplet $\mathbb{N}^2 \times \mathcal{P}$ where the first two elements are the callsign and the takeoff time and the latter is the flight plan represented as a path.

Definition 8: A sector is a subgraph of $\mathcal{A}$ where we cut the air routes crossing the frontier between two sectors by adding a junction (COP point).

The next concepts will be explained with a computer-based approach because of their computing nature. Foremost, the complexity is a measure on the physical world and the cognitive aspect of the air traffic controller. Many indicators on the physical world are presented in [7] [8]. In our work, we have implemented so far the ones defined in [9]. These indicators are :

1) Volume of the sector
2) Number of aircrafts
3) Average vertical speed
4) Incoming flows with time horizons of 15 minutes and 60 minutes
5) Number of crossings with an angle greater than 20 degrees

Furthermore, we add some constraints to reduce the cognitive workload of the controllers :

1) Balance the controller workload among multiple sectors (e.g. with letters of agreement) based on the physical world indicators
2) The controller underload is also verified to avoid a hypovigilance situation.
3) Foresee at least two minutes between the clearances to integrate the controller/pilot exchange time
4) Minimize the number of controllers involved in a clearance (e.g. use of a pattern)

The method used for computing the indicators is based on the trajectories. Indeed, in a given sector, we can retrieve an array of 4D points for a period of time. Every cell of the array describes the position of a flight at a time t. Afterward, it is easy to compute the indicators from the analysis of the geographic positions.

B. Aircrafts separation

To ensure the aircrafts separation, we use a two-step approach. The first step is the detection of potential loss of separation. We compute the orthodromic distance and the vertical distance by pairs of flights. To do so, we use the arrays of 4D points of each flight and determine if these two distances are under thresholds of security for any given time t. These thresholds depend on the uncertainty. We note that this method is centralized and not distributed among the sectors. In this sense, we avoid the difficulties occurring at the frontiers of the sectors mentioned in [10]. Of course, the complexity of the detection is function of the period of the time horizon $|T|$ and the number of flights n and is equal to $\mathcal{O}(n^2 \times |T|)$.

The second step is the resolution of the conflicts. When a loss of separation between two aircrafts is detected, we decide which flight trajectory will be modified with several criteria (e.g. number of modifications received and complexity of the clearance). Afterward, the shortest path algorithm is run on a copy of the graph without the segment containing the two aircrafts in conflict. Also, the algorithm minimizes the global number of conflicts, the global number of "clearances", the number of clearances per aircraft and the complexity by sector. For now, we do not have results for the guarantee of convergence toward a mesh without any conflict because of the dynamic aspect of the graph.

C. Segregated areas and storms

Civil aircraft cannot fly over the military areas which are temporary or permanent segregated areas (TSA). This will result in removing the segments of the mesh overlapping the restricted areas represented by polyhedrons, thus the shortest path algorithm will bypass the segregated areas implicitly. To optimize the trajectories, avoidance segments are added to the graph to increase the mesh density around the restricted zones. Moreover, the storms are modelized as moving polyhedrons. Consequently, the storms are considered as moving TSA. Therefore, the segments overlapping the storms polygons are also automatically removed from the graph to ensure the storm avoidance in the same way.

D. Additional features

We have mentioned so far the use of algorithms without explicitly describe the problem of shortest path. Actually, clearly we are in a multi-objective optimization framework because of all the goals that we have enumerated through this article. We have assigned a value to every edge of the graph in the modelization section but we can go further. The graph can be enhanced with contextual data. The valuation of the edges of the graph becomes dependent of the flights but also of the meteo, turbulence, the environmental impact and so on. A valuation model is associated with every flights and will return a vector of values for every air routes. The value associated to a path is the vector sum of the value of every air routes contained in it. After that, we can use a multi-objective optimization strategy :

1) Lexicographic Order
   This is the easiest method which transforms the problem into a mono-criterion approach. For the equality of the value on the criterion i, we choose the solution with the best value on $i + 1$. By cons, in a context where modeling the preferences of the controller is important, its expressiveness is very limited.
2) Lexicographic order with compensation
   It is a relaxation of the first method involving compensation. If the criterion value $i + 1$ of a solution is very high compared to other solutions, we can choose this solution as it compensates for the lower value of its criterion i. This method is more expressive, but the research for the compensation function which is often non-linear can be very difficult.

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[14] Air Navigation Service Provider

3) Multicriteria optimization with Pareto front
This method seeks simply Pareto front of the vector of criteria. Choosing the best solution is left to the user. In terms of freedom of choice, it is antagonistic to the lexicographic order which is determined statically.

This broad definition has the advantage that the valuation model can be defined later on. For example, a model will encourage routes with prevailing winds that are in the same direction as the heading vector of the aircraft and penalize those whose winds are contrary to this direction. Depending on the situation, we can define various operational issues to be resolved while keeping the same mesh.

VI. IMPLEMENTATION

We will describe the implementation carried out until now. First, because of its substantial size, we stored the graph in a database. To describe the entire European airspace, we used:

- 8591 waypoints
- 20,639 air routes
- 2804 sectors

These data are from the software Skyview2 and were enriched to improve the connectivity of the graph except for the number of sectors. Here, there are many sectors because they are elementary; we must use many elementary sectors to define a sector for an air traffic controller. For the aspect of simulation, we generate a random traffic up to 500 aircrafts a day. The time has a granularity of 15 seconds and we make a prediction of trajectory (4D points) over 30 minutes for each plane. Then, it performs the optimization by detecting conflicts over this horizon. For resolution, we have an A* algorithm that works with the great circle distance as an estimate of the distance minimizer. For now, the algorithm performs a multi-criteria optimization with lexicographic strategy. We solve more than 98% of the potential conflicts in less than 200ms per cluster but given the low density of aircrafts and the number of degrees of freedom, we must work to enhance the performances of the program by taking benefit of new GPU technology to give more realistic results. The goal is to simulate a real daily traffic of thousands of airplanes.

VII. FURTHER RESEARCH AND DEVELOPMENT

Although the beta-mesh approach appears promising, it requires thorough evaluation. The 3D graph set-up connecting ground and air is essential to validate the concept introduced here above. The trajectory prediction is a key pre-requisite to the beta-mesh concept, the ADD[15] will certainly contribute to reinforce the potential of the concept. The beta-mesh will serve a global optimization algorithm based on a multi-criteria cost function combining heterogeneous parameters. The next steps will be dedicated to the multi-criteria algorithm implementation taking benefit of an evolutionary algorithm. This work will be a new perspective to previous works [11] [12] [13].

In general, there are four major research questions which need to be addressed:

- Does the graph provide a good representation of the admissible routes by the aircrafts?
- Is the approach valid in a high uncertainty condition: how to make the balance between uncertainty and optimization?
- Are the criteria correctly separated between absolute rules (correctly formalized and modelized) and subjective rules (letting the controller take the decision or handled by a learning mechanism)?
- What kind of clearance do the system have to promote for a given situation? How to propose it to the controller?

VIII. CONCLUSION

Air traffic control is a stressful job, involving many tasks within a limited time. The final goal is to ensure that aircraft in their sector are safely separated, and promote the traffic fluidity. The beta-mesh is an attempt to use mathematical concepts to help controllers solve this complex cognitive challenge. As the complexity is directly correlated to the airspace segmentation, the beta-mesh approach aims to supervise the airspace to ease the controller work to increase the sectors/airports capacity by preparing globally the traffic. This paper is a first contribution to the automation system studies towards a harmonious human-machine cohabitation.

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