Aircraft Path Planning for UAM Applications

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***Abstract*— Aircraft path planning in urban air mobility context relates to finding of a continuous path/trajectory that will drive the aircraft from a start to an end location knowing the environment map. This map can be a 3D model, including semantic information (no fly zones, aerial corridors) that are constraints for the path planning algorithm. This paper investigates the aircraft path plan dealing with the flight pre-known obstacles in the 3D space, regardless of their static or dynamic characteristics, that syncs with the local path in cases when pre-flight unknown obstacles are detected along the global path by one of the aircraft's sensors to ensure safe flight between flight origin and destination locations. To achieve this, we rely on a combination of A* and Visibility graphs approach.**

Keywords- Unmanned Aircraft Systems (UAS), Drones, Urban Air Mobility (UAM), Aircraft path planning, Path optimisation, A*, Visibility graphs

I. Introduction

Aircraft path planning, within Urban Air Mobility (UAM) context, relates to finding of a continuous path/trajectory that will drive the aircraft from a start to an end location knowing the environment map, which is stored in the navigator's memory. This map can be a 3D model, including semantic information (no fly zones, aerial corridors) that are constraints for the aircraft planning algorithm. To ensure a failsafe operation, the aircraft also has to build a local semantic map at the same time as it moves to avoid potential hazards or obstacles. The perception abilities are obviously the starting point to develop the path planning algorithms and allowing the aircraft to accomplish its mission. In this paper, we will describe in more details the development of an aircraft path planning algorithm for the purpose of the urban air mobility applications.

The structure of the paper is as follows. Section II introduces the flight path planning building blocks. Section III elaborates on flight path planning methodology while Section IV briefly discusses obstacle clearance construction. Section V elaborates on the 3D path construction. Section VI discusses non-holonomic constraint, which is followed by a brief conclusion in Section VI.

II. Aircraft Path Planning Building Blocks

The search space for our path planning problem is an undirected graph in R^3 that is built from the visible vertices of the physical and non-physical objects on the map of the location where the flight task will be deployed. Physical objects refer to buildings, trees, etc. Non-physical objects refer to geometric objects in R^3 defined by the aeronautical authorities within which it is not possible to navigate, and they are flight constraints for our solver (Figure 1). In practice, these objects are defined in Aeronautical Information Exchange Model (AIXM) [1] format and are called Airspace Volume objects.

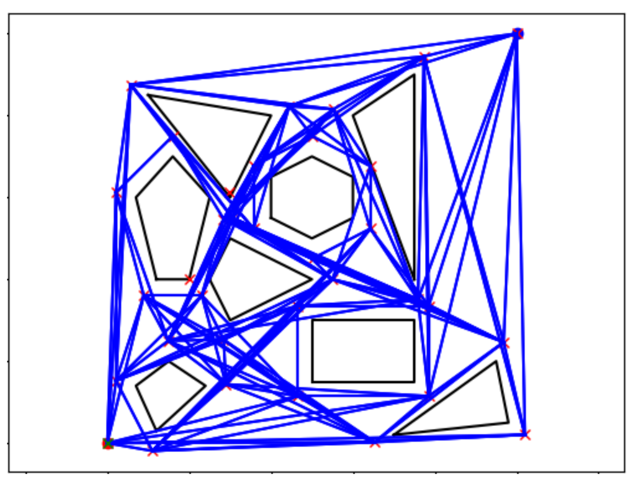

Figure 1. Global path search space example.

In each node of the graph, the geolocation information of the given point in World Geodetic System 84 (WGS84) coordinates and the altitude are placed. The information about the distances for each pair of nodes connected is placed in the corresponding edges.

III. AIRCRAFT PATH PLANNING METHOD SELECTION

Due to the nature of the aircraft path planning problem, the number of possible solutions to it is large. A solution can be modelled as an ordered set of points in space conforming a path whose length is minimum with respect to others. To cut back the solution space, some flight path planning methods search some points that are good candidates for belonging to the optimal solution (or optimal path). One of these methods is the Visibility Graph [2], which only considers the origin, destination and the points belonging to the outline of the obstacle. Indeed, this graph consists of a set of inter-visible locations, i.e., pairs of points in the 2D Euclidean plane that can see each other [3]. Each node in the graph represents a point location, and each edge represents a visible connection between them. That is, if the line segment connecting two locations does not intersect any third obstacle, an edge is drawn between them in the graph. One example of a Visibility Graph among a set of polygons is shown in Figure 2. In the case of polygons, just their vertices are considered as nodes of the constructed graph since any intermediate point of any polygon edge would be part of a suboptimal sub-path.

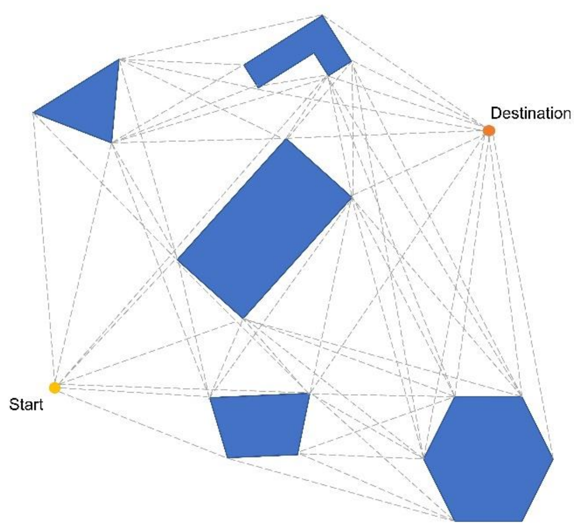

Figure 2. Visibility graph.

The perfect complement for the Visibility Graph is a tree search algorithm, since once the data set is decomposed into a relatively small set of nodes and edges, this type of algorithm can provide a solution in a reasonable amount of time [4]. Among the algorithms that have historically been used for this problem, we find Dijkstra, which is able to compute the optimal solution in O(|E| + |V | log |V |) time complexity (being V the number of vertices and E the number of edges of the graph). However, a generalization of Dijkstra's algorithm has been preferred in this approach. It is called A*, and its main advantage is that it cuts down on the size of the sub-graph that must be explored [5]. It does so by considering a lower bound on the distance to the target, which works well in this case since Euclidean distances are considered. This bound or weight permits us to distinguish promising nodes to explore from nodes that may not be part of the solution. So, with this combination of methods it is possible to exactly solve the problem in 2D and without considering the dynamics of the vehicle.

IV. OBSTACLES CLEARANCE CONSTRUCTION

One of the most critical parts of the aircraft path planning is the integration of the so-called 'horizontal and vertical clearances' constraints [6]. These have been the first studied constraints after the selection of the path planning method, and due to the nature of this problem, their incorporation was laborious.

In the aircraft plan planning problem, just static objects were considered, that is to say, animals or other vehicles that could intersect the studied vehicle's path during the flight would be avoided locally in an online manner. But, in a first approach, the most efficient but safe route should be computed considering objects which would be (with certain guarantee) in the vehicle's path during the flight. The set of obstacles that we have considered in the aircraft plan planning can be defined in 2D as convex or non-convex regions in space, being the most used representations the circle and the polygon in the UAM framework. In fact, the area enclosing these obstacles should be as close as possible to the original shape of the objects, but it is also pretended to define this area with as few numbers of points as possible. Therefore, being the polygon and the circle the two basic shapes whose combination is able to tightly cover almost all possible figures in 2D space, both have been selected as the main obstacle's representations in this research.

Regarding its provenance, there are two types of obstacles. The first are provided by some aviation institutions like EUROCAE in maps defining the Airspace Class of each region of the atmosphere, named Visual Flight Rules (VFR) [7]. In these maps, the restricted areas or No-Fly Zones of a given region are pointed out. Moreover, in our problem, there is a second type of obstacle which fundamentally consists of the rest of objects against which we do not want the vehicle to collide: buildings, trees, bridges, transmission towers, power lines, etc. Considering both type of obstacles, it is possible to gather a set of forbidden zones in space that the aircraft will have to surround.

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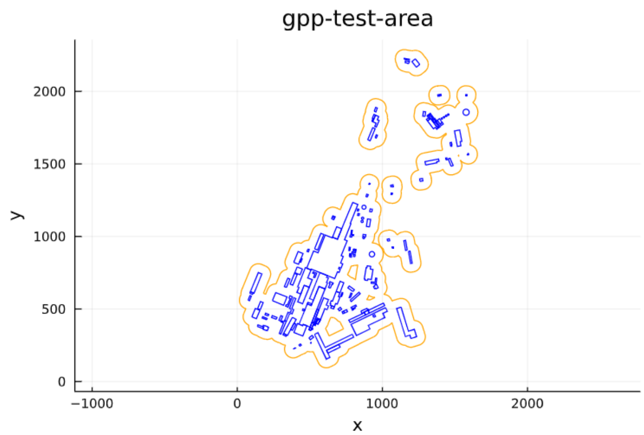

Figure 3. Global path planning test area [8].

By clearance with respect to an obstacle, it is meant to express the distance that the vehicle must respect at all times from each kind of obstacle. There is a distinction between horizontal and vertical clearances in this research, due to the nature of the problem (for example, the aircraft's dynamics). Thus, to guarantee at all times that this constraint is respected, the approach that has been followed is to enlarge the objects, so that the forbidden region is formed by the prism/cylinder volume and the volume which is closer than a given value h_c with respect to the obstacles. In Figure 3 it is possible to see a horizontal projection of these enlarged objects. In blue, a set of buildings that can be encountered in a certain test area for this research are represented. In orange it is possible to see a boundary which is placed at a distance h_c = 60 m from the obstacles, and that contours the forbidden region that must never be trespassed. It is also possible to see that these objects, composed of a set of linear and circular segments, have some holes in their interior.

As commented previously, some difficulties have arisen during the conceiving of this specific part of the algorithm. As the objects represented in 2D can be concave polygons, some exceptions appeared when searching some criterion in order to extract the single contour of this kind of figures. Also, as some objects are adjacent (interior and exterior) with respect to others, some errors were being obtained since these figures were intersecting at several points. By merging these overlapping figures in the first place, it was possible to solve the mentioned problem. Another set of exceptions appeared when integrating the vertical constraint, as it was needed to update the heights of the merged figure and the single ones, so that there was no overlapping among prisms. In this way, it was possible to compute the obstacle clearances at different heights in an efficient manner.

V. 3D Path Construction

In the previous section, the main challenge when integrating the vertical constraint has been stated. As said, this was related to the clearance construction of the objects in the vertical domain. If it was possible to specify the range of heights among which the polygons were extended, then it was possible to compute 2D forbidden area contours (as represented in Figure 4) for several discrete height values. In this manner, it was possible to compute a 3D version of the forbidden areas.

The next step in the pursuance of integrating the third dimension was to update the optimization method. The Visibility Graph together with the A* worked well in 2D but when used within a 3D environment, edges were converted into planes and path must be optimized among these planes. For this reason, the complexity of an integral 3D Visibility Graph algorithm increased a lot. By integral, it is intended to mean a method which computes all the Visibility Graph edges between all the 2D obtained figures even if they belong to different height cuts. In this approach, while a higher degree of freedom is given to the vehicle, certain properties of the problem are not taken into account. These can be found by studying Urban Air Mobility framework, like the height distribution that a vehicle under these conditions would delineate or even the speed distribution [9]. So, by simplifying our model or making some assumptions, it has not only been possible to cut time complexity of the algorithm, but to help it in the resolution of the problem. In Figure 4, it is possible to see some 3D obstacles in blue, the computed obstacle clearances in orange and a path in red which goes under a floating obstacle. The top surfaces of the obstacles and the orange contours are not colored for visualization purposes.

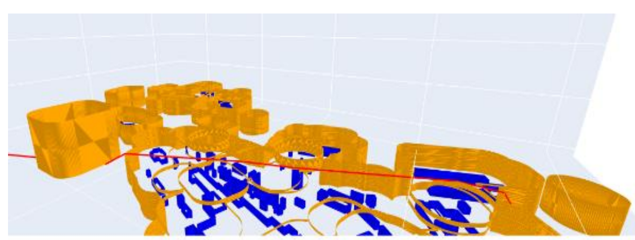

Figure 4. Clearance construction.

VI. Non-Holonomic Constraint

Once the third dimension is added, there is another challenge to face: how to integrate the vehicle's dynamics into the problem. In fact, this constraint prevents some paths or some maneuvers from being valid. Thus, by applying this constraint, it is possible to say that the vehicle follows a non-

 ISBN: 978-1-61208-994-2

holonomic system, which in physics and mathematics is a physical system whose state depends on the path taken in order to achieve it. In other words, the vehicle's orientation at a given point depends on the path taken. So, in this way, steep climbs and turns must be eliminated from the solution space.

The approach taken for the purpose of adding this new restriction has been to discretize the flight or the path into some phases. The considered flight phases are the following ones:

- take-off,
- climb,
- cruise,
- approach, and
- landing.

During the cruise phase, the 2D Visibility Graph and A* method is used in order to calculate the optimal path at a constant height. This height is determined a priori based on several criteria: length of the path, safety, time complexity, etc. Like this, it is possible to calculate routes in large datasets including a high number of obstacles. The other flight phases are computed using a heuristic algorithm, tailored to the application. In short, several take-off trajectories are computed considering different azimuths and the ones that are non-valid are removed. Afterwards the transition between the take-off phase and the cruise one is computed. For the landing heuristic, the procedure is almost the same. Like this, steep climbs are removed from the model, while turn radius can be regulated by adjusting the parameter hc, which was the horizontal clearance of the obstacles. In Figure 5, it is possible to see a 3D path which complies with the non-holonomic constraint.

Figure 5. 3D path which complies with the non-holonomic constraint.

VII. Conclusion

Challenge of introducing urban air mobility relates to the aircraft path planning and optimization in low airspace area characterized with the presence of multiple obstacles. This requires introduction of adjusted aircraft path planning in 3D environment as well as integration of relevant constrains, including non-holonomic ones, in order to introduce safe operations and reliable flight path plans. This paper briefly introduces one of such approaches based on the visibility graphs method.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme (H2020-MG-3-6-2020 Research and Innovation Action "Towards sustainable urban air mobility") under Grant Agreement No. 101007134.

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