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Commercial Aircraft Lateral Flight Reference Trajectory Optimization

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Abstract: Cruise is normally the longest and most expensive phase in a long-haul flight. Taking advantage of winds to reduce flight time using a constant mach number is of real interest to the aeronautical industry. Reducing flight time will reduce time related costs, help passengers to catch their connections, and reduce fuel consumption. Saving fuel also leads to fewer polluting emissions released to the atmosphere. The “free-flight” concept is adopted here, with the search space area modeled as a graph in which the weather information at each vertex is obtained from predictions from Environment Canada. The Floyd-Warshall optimization algorithm was implemented to allow the flight reference trajectory optimization to have automatic decision making capacities to deliver the shortest path trajectory between departure and destination airports. Simulations showed that flight time savings as high as 19 minutes could be obtained, representing (roughly estimated) a savings of 1.2 tons of fuel.

Keywords: **Air traffic management, decision making, autonomy, mission operations, navigation, guidance, avionics**.

1. INTRODUCTION

The increasing number of airborne aircraft is beginning to saturate the air space in parts of the world. This has motivated a number of efforts to fund and launch programs to look for alternatives to expand the useable airspace while guaranteeing security as a means to improve overall flight performance. The leading programs upgrading air space traffic procedures are the Next Generation of ATM systems (NextGEN) in the United States, and the Single European Sky ATM Research (SESAR) in Europe. Both of these programs are based on the Trajectory/Intent Based Operations (TBO/IBO) concept. Within the TBO/IBO, an aircraft can take any trajectory they prefer that improves its performance as long as they adjust to meet some safety rules required by Air Traffic Management (ATM).

The TBO concept is important, as it will allow more aircraft to fly at their optimal speed and altitudes. According to (Jensen et al., 2014, Jensen et al., 2013, Jensen et al., 2015, Turgut et al., 2014), many aircraft do not fly at their optimal speed and altitudes. This could be due to a lack of planning by airlines or to ATM restrictions. However, to maximize their profits, airlines are motivated to fly at their optimal profiles to reduce fuel consumption and polluting emissions, and it is expected that future regulations will tax polluting emissions, adding to the airlines’ motivation to reduce fuel burn. The aeronautical industry is already aware of the pollution problem, as 2% of the total carbon dioxide (CO_2) liberated to the atmosphere from all human operations is attributed to aeronautics (ICAO, 2010). CO_2 emissions are a growing concern as they are linked to global warming. The industry has set itself ambitious goals to reduce the CO_2 emission levels until they are comparable to the levels recorded in 2005. Certain flight phases consume more fuel and occur closer to population centers, such as taking-off and landing, and some of the operations that fall within these phases should be avoided as much as possible due to their high fuel requirements, such as the missed approach procedure (Murrieta-Mendoza et al., 2014).

1.1 Related Work

(McConnachie et al., 2013) present a study of potential procedures to be followed by airlines to reduce fuel consumption. Current aircraft have undergone modifications, such as the implementation of winglets, which have proven to reduce fuel consumption as well as noise (Freitag, 2009). New fuel options have been proposed, such as biofuel (IATA, 2009). Some airlines, including Porter Airlines, Air Canada, Aero Mexico, and GOL (ICAO, 2012) have tested biofuel in real flights to evaluate its potential.

From the trajectory perspective, notable fuel consumption and noise production reductions have been reported for the descent phase with the development of the Continuous Descent Approach (CDA), in which an aircraft descends using minimal engine power (Kwok-On et al., 2003). This procedure has been tested in many different airports, even at busy airports such as Los Angeles International (Clarke et al., 2013).

For the cruise phase, optimization has been carried out using Optimal Control for multiple objectives such as the most economical trajectory when also accounting for the formation of contrails – water vapor that forms clouds at irregular altitudes (Soler et al., 2014). Optimal control has also been analyzed by respecting current ATM contrail regulations, as in (Valenzuela and Rivas, 2014).

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Dynamic programming was developed by (Sidibe and Botez, 2013) to be implanted in the Flight Management System (FMS). Dynamic programming for the next-generation of trajectories (i4D) was developed and implemented by (Hagelauer and Mora-Camino, 1998) and (Miyazawa et al., 2013).

Search reduction techniques to quickly converge to the optimal trajectory of reference were explored in (Gagné et al., 2013) and in (Murrieta-Mendoza and Botez, 2014b). These algorithms improved the reference trajectories when compared to the solutions provided by a commercial FMS.

Due to the high number of solutions available, to solve the vertical reference trajectory, more common methodologies such as branch and cut (Murrieta-Mendoza and Botez, 2015) and genetic algorithms (Felix Patron et al., 2013) have been explored.

Accounting for weather parameters has been explored for some time. It is known that there are currents at high altitudes, especially over the Pacific and Atlantic oceans. These routes are normally very crowded and it might be difficult to obtain clearance from ATM to access those routes. It would be worthwhile to develop algorithms that explore the routes surrounding the reference trajectory to search for favorable winds. Dijsktra's algorithm proved to reduce the flight time in a way similar to that of the paper presented here (Murrieta-Mendoza and Botez, 2014a); optimal control was also analyzed in conjunction with wind, as in (Ng et al., 2014). (Félix-Patrón and Botez, 2015) coupled the vertical and the lateral reference trajectories to explore the optimization opportunities. These algorithms provided good results, showing that it is worth performing these computations to find the weather pattern that most reduces the flight time.

In a different context, taking wind into account is important to respecting time constraints. Recent studies have investigated the time constraints of future flight regulations (Vilardaga and Prats, 2015, Johnson, 2011, Murrieta Mendoza et al., 2015b). (Johnson, 2011) studied how the wind effect affects the CDA, and (Oliveira et al., 2014) explored a n methodology to reduce the wind uncertainty using the Monte-Carlo and Gaussian methods.

1.2 Objectives and limitations of this work

The objective of this work is to implement and evaluate the Floyd-Warshall deterministic algorithm potential to find the combinations of waypoints in the cruise phase that will reduce the flight time. The space search is modeled as a graph search where the edges' weights are the flight times between two consecutive waypoints. The flights under evaluation were at constant Mach number and at constant altitude.

This paper is organized as follows. First, the flight time computation between two waypoints is explained, followed by a detailed description of the weather information source. The search space's representation as a graph is explained next, followed by the Floyd-Warshall implementation. Finally, the results evaluating the different flights are presented and discussed.

2. METHDOLOGY

2.1 Flight Time Computation

The flight time is estimated considering the average ground speed and the "rhumb line" distance between two nodes. The rhumb line is defined as the line linking two points with a constant azimuth. Because the distances considered to compute the Flight Time are short enough, they do not introduce an error in the computations.

$$Flight\ Time = \frac{Distance}{\overline{GS}} \tag{1}$$

The ground speed (GS) is calculated using the True Air Speed (TAS), ϕ added to the wind speed (W_S) at the wind angle (W_A).

$$GS = TAS + W_S * \cos(\phi - \mathrm{W_A}) \tag{2}$$

2.2 Weather Information

The wind information was obtained from open source weather predictions provided by Environment Canada. The data is provided in the form of a 0.6° x 0.6 ° (or 0.24 ° x 0.24 °) grid at 3h time blocks for different isobaric pressures. In order to obtain the information at the specific geographic/temporal point, linear and bi-linear interpolations are required. These interpolations are described in (Murrieta-Mendoza, 2013) and are used in this paper to obtain the wind speed and the wind direction.

2.3 Modeling the Search Space

In a free trajectory, an aircraft can go to any particular coordinate in the search space, a situation that implies an infinite number of possibilities. To reduce the possible coordinates where the aircraft can fly to, the search space is modeled as a grid. The aircraft can only fly from its current point to a neighboring forward point in the grid, as aircraft do not travel backwards. This grid can be seen as a directional graph – G (E, V)-, where the lines connecting the points are the edges (E), and the points are the vertexes (V). For the rest of the document, every point in the graph will be referred as a "waypoint"

The graph provides the advantage that the aircraft can change its direction only when it reaches a waypoint, thereby limiting the number of options.

Placing the graph waypoints too close to each other could lead to a somewhat chaotic trajectory, as the aircraft can find more convenient conditions in a waypoint with a totally different direction. For this reason, the waypoints' separation