１5. グラフ探索理論に基づいた軌道最適化について

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1 Introduction

The introduction of area navigation (RNAV) removed the need for aircraft to fly between ground-based radio navigation aids. As air traffic management (ATM) moves towards trajectory-based operations (TBO), flight route flexibility will further increase and the fixed network of Air Traffic Service (ATS) routes will be reduced. In Europe, Free Route Airspace (FRA) [1] exists where operators may plan routes between FRA entry and exit points, either direct or via intermediate points, without reference to fixed routes [2]. In the North Pacific oceanic area (fig. 1), there is a flexible track area in which the Japan Civil Aviation Bureau (JCAB) and Federal Aviation Authority (FAA) publish PACOTS (Pacific Organized Track System) tracks on 24-hour cycles which are computed according to forecast winds and tailored to specific aircraft types and city pairs, and operators may also plan User-Preferred Routes (UPR) between latitude/longitude waypoints.

Aircraft operators can use this increasing routing flexibility to plan routes that are tailored more closely to their operations. For air transport, this typically means reducing operating cost by minimizing distance or time flown. For relatively short flights (say, three hours or less), in the absence of strong winds the fuel saving benefit of a minimum fuel route compared to a minimum time route is relatively small. However, as the distance from origin to destination increases, the benefit of routes that take account of winds aloft grows. Exploiting flexible routing fully requires creating wind-optimal flight plans, but not all aircraft operators have such a capability, and we believe that demand for such a capability will grow. Commercial flight planning services exist, and so practical techniques to create wind-optimal routes have already been developed. However, there is little literature and they are likely to be considered as trade secrets.

Building on research by Kyushu University, we have developed a program that can generate ideal wind-optimal trajectories [3] and used it in various investigations to demonstrate potential benefits of TBO [4, 5]. However, the program can take a long time to converge on the optimal trajectory, and it is difficult to include operational constraints. We propose a method based on shortest-path graph search as a practical means of generating near-optimal trajectories that satisfy operational constraints [6], and apply it to optimal track generation in the North Pacific, which is one of our areas of research.

2 Ideal Trajectory Generation

We have developed a Dynamic Programming (DP)-based optimal trajectory generator that iteratively searches for a trajectory that minimizes a cost function representing a trade-off between fuel burn and flight time [3]. From an initial trajectory (a Great Circle between specified initial and final points with specified altitudes and speeds), it constructs a grid of points around the trajectory in a search space of lateral profile (downrange, cross-range), vertical profile (altitude) and speed. The costs to move from the initial point to each of a set of candidate grid points in the next downrange step are computed using the EUROCONTROL Base of Aircraft Data (BADA) aircraft performance model and performance parameters and atmospheric data, and the point with the lowest cost is selected as the next point on the trajectory. This proceeds downrange until a new trajectory has been created between the terminal points, and its time/distance are compared with the initial trajectory. If the difference is sufficiently small, the created trajectory

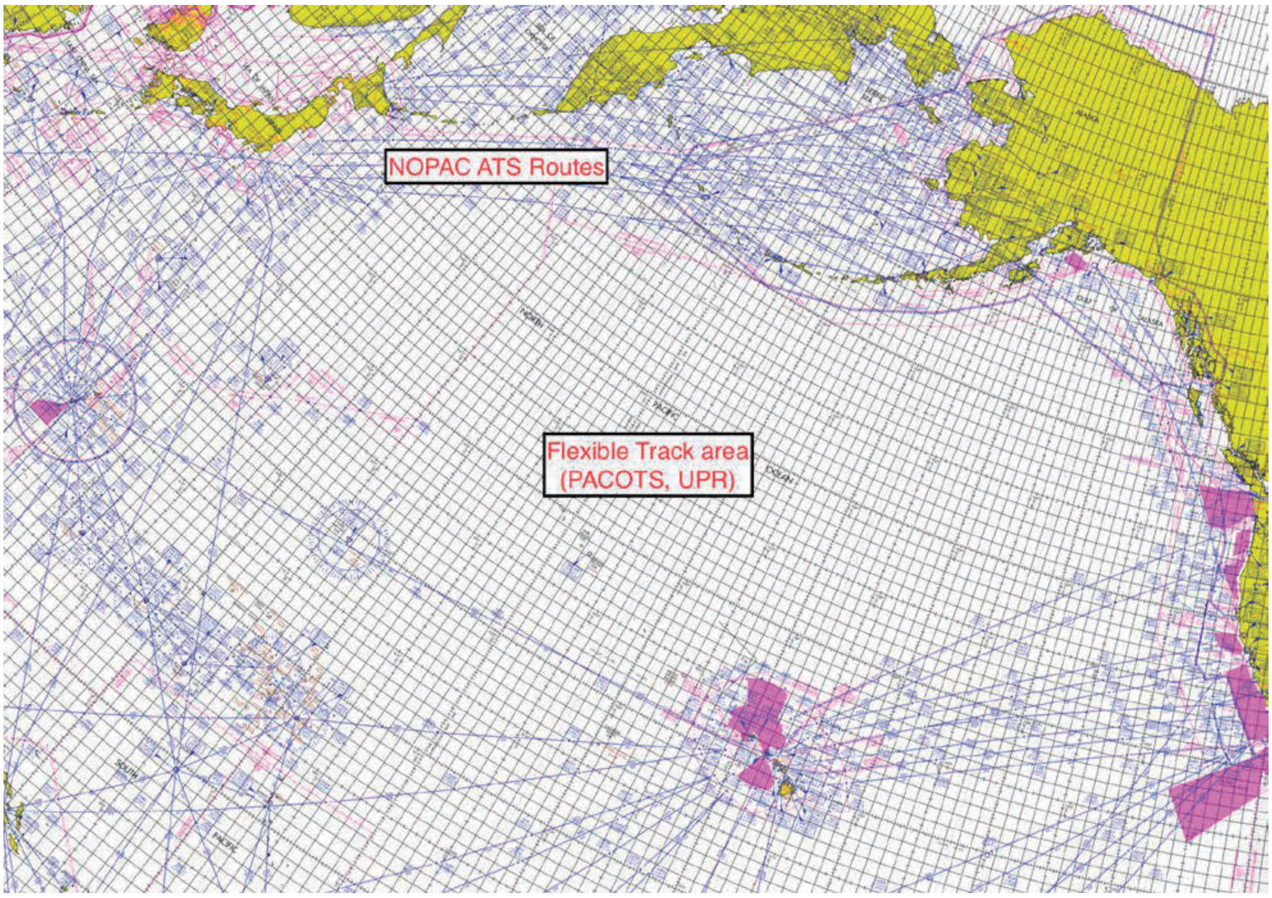

Figure 1: North Pacific oceanic airspace (from [6])

is considered the optimal solution and the process terminates; otherwise the created trajectory is set as the new initial trajectory and the process iterates.

This algorithm is useful for generating ideal optimal trajectories, but it is difficult to apply constraints such as the need to avoid certain airspaces or to follow a specified vertical or speed profile. We have attempted to modify the cost function to give a very high penalty if such a constraint is exceeded, but this can lead to trajectory anomalies such as lateral or vertical zig-zagging, and is hard to apply in general. Moreover, the optimization is computationally intensive, and the number of iterations required seems to be somewhat sensitive to atmospheric conditions (a sample of 147 flights from Tokyo to Honolulu on 12 different days with six aircraft types took between 1h45m and 19h24m per trajectory, with an average time of 9h9m on an Intel Xeon processor-based cluster). These drawbacks make the algorithm impractical for flight planning.

3 Shortest-Path Graph Search

For flight planning purposes, searching a large parameter space is too time-consuming at present, so it is necessary to limit the search space and make simplifications. Although the resulting trajectories may not be strictly optimal, they may be sufficiently close that estimation errors due to uncertainties in weather, takeoff weight and departure time will be generally larger than the gap between a generated trajectory and the true optimum.

Our idea is to represent possible lateral flight routes between departure and arrival points as a two-dimensional graph of vertices (nodes) and edges. This greatly reduces the lateral search space, can be easily made compatible with existing flight planning and navigation systems (by using as vertices existing significant points or radio navigation aids, or latitude/longitude coordinates), and makes it easy to apply certain types of ATM restrictions; for example, route direction and altitude constraints along particular edges, and avoiding restricted-use airspaces or areas of forecast severe weather, turbulence or volcanic ash. These constraints could be dynamic.

Finding an “optimal” route then involves computing the shortest path through the graph between origin and destination vertices using a standard graph-search algorithm, but using a cost function (fuel burn, flight time, or a combination thereof) as the metric in place of Euclidian distance.

4 Implementation and Results

To test the feasibility of the concept, we applied it to a study of North Pacific oceanic flight operations. The North Pacific free route area (in which UPR is permitted) was represented as a mesh of east-west edges between a grid of vertices at intervals of 1º latitude and 5º longitude. This was connected to oceanic gateway points off the east coast of Japan and the west coast of North America.

We made the following further simplifications.

(1) Calculate the cruise phase only.

(2) Constant altitude.

(3) Constant true airspeed or Mach number.

These simplifications eliminate the vertical and speed dimensions from the search space. (The PACOTS tracks published daily by the United States Federal Aviation Authority and the Japan Civil Aviation Bureau are generated with similar simplifications.)

As the search algorithm, we used Dijkstra's algorithm as it is easy to implement. For wind data, we used Global Spectral Model (GSM) numerical forecasts published by the Japan Meteorological Agency (JMA). Aircraft performance was calculated using BADA version 3. The program was implemented in python.

Figure 2 shows published PACOTS tracks in the North Pacific flexible track area on a day in January 2017 (gray), corresponding minimum-time tracks computed by our program (orange) and the track of a Boeing 767-300 aircraft flying from Honolulu to Tokyo that executed a Dynamic Re-Route Procedure (DARP), changing its flight plan en route to take advantage of more recent wind forecasts (purple, obtained from Quick Access Recorder (QAR) data). The minimum time tracks were computed using the same cruise flight level, aircraft type and weather forecast assumptions as

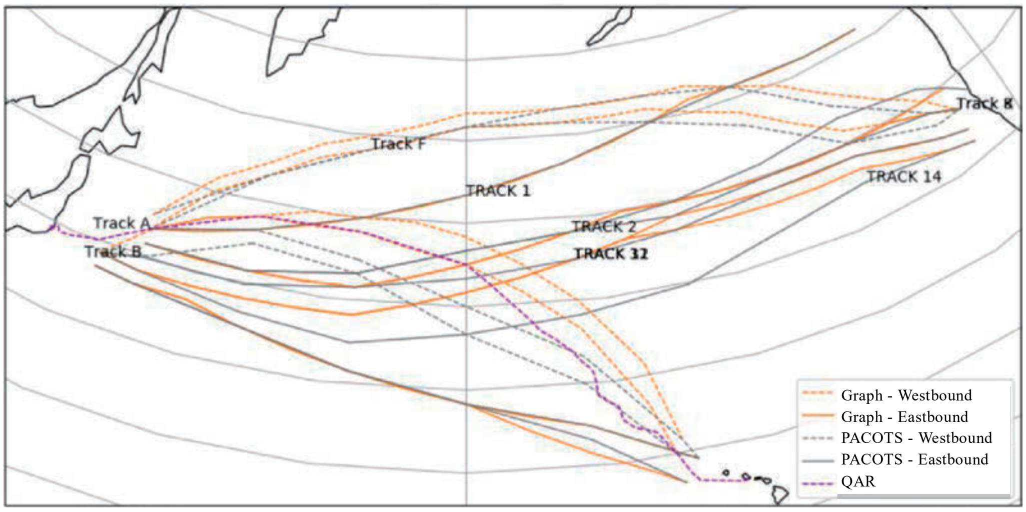

Figure 2: Minimum time tracks generated by our program (orange), PACOTS tracks (gray) and track of an aircraft executing DARP (purple).

the corresponding PACOTS tracks. Eastbound tracks are shown by solid lines and westbound tracks by dashed lines. It should be noted that PACOTS tracks are adjusted to ensure separation with other tracks, and their degree of optimality depends on the order of generation, while our tracks were not so adjusted.

Figure 2 shows good qualitative agreement between the tracks created by our graph search algorithm and PACOTS tracks. Our eastbound track corresponding to PACOTS Track 14 was well north of that track, but this could be due to the fact that PACOTS tracks are adjusted to ensure separation. Although our tracks from Honolulu to Tokyo were north of the PACOTS tracks, it is interesting to note that the DARP aircraft started following the PACOTS track, but then diverged from it and converged with our computed track west of 180º.

We then applied the program in a JCAB study examining reorganization of the NOPAC fixed track system. Figure 3 compares flight plan routes of trans-Pacific flights through the Fukuoka Flight Information Region (FIR) on 20 January 2018 (white) with computed minimum time tracks (red) using a search graph which combined a mesh in the North Pacific free route area with the NOPAC fixed ATS routes. Again, there was good qualitative agreement overall between the flight plan and computed optimal tracks, although the winds used for the calculated tracks were “nowcast” wind forecasts valid during the actual flight times (and therefore close to the winds actually encountered in flight) while flight plans were necessarily based on much less recent, and therefore less accurate, forecasts. Each optimal track took only a few minutes to compute (generally less than 10 minutes), one or two orders of magnitude faster than the DP-based optimizer.

5 Issues and Future Works

In the tests described in the previous section, our graph search-generated tracks appeared qualitatively reasonable compared to existing flight plan generation systems and PACOTS despite its greatly reduced search space. However, this did not show the optimality of the generated tracks, since the PACOTS track generation systems in the USA and Japan use similar simplifications. We plan to make a more quantitative analysis by comparing the tracks produced by our system with ideal tracks created by our DP-based optimizer.

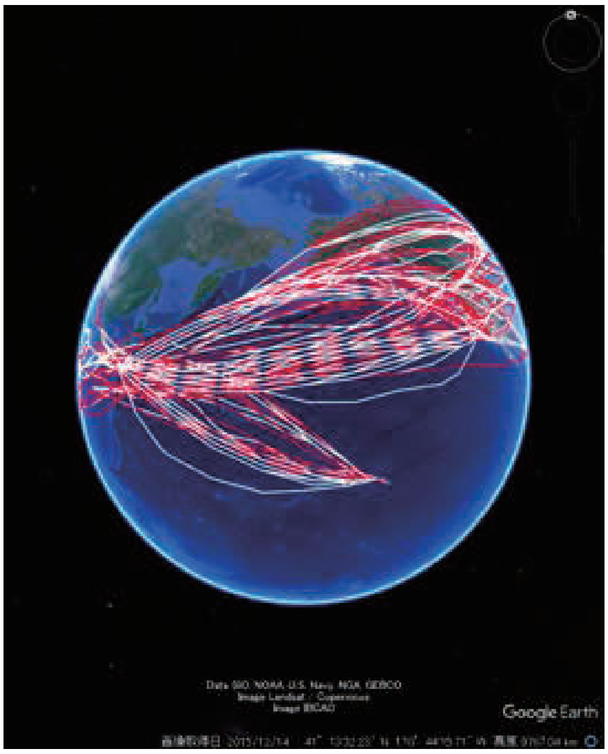

Figure 3: Comparison between flight plan routes (white) and calculated minimum time routes (red).

In the practical application of our track generator, we found that generating reasonable search graphs was more labor-intensive than anticipated. If there is a free route area defined by a mesh on a grid of points, as in the North Pacific, the mesh must be connected to existing route structures through gateway points, which must be connected to the origin and destination airports. Our program does not currently reference a database of ATS routes and navigation aids, so in support of the NOPAC restructuring study mentioned above, for each city pair investigated, we generated the route search graph by combining the flight planned routes of all flights during a one-year period in 2018 from the origin airport to the free route entry gateway and from the free route exit gateway to the destination airport. This process could be automated and use a navigation database of ATS routes and significant points, but this is a research topic in itself and there might be complex operational factors involved in flight route planning through dense airspace, possibly requiring knowledge-based approaches in addition to purely numerical algorithms.

Optimal trajectory generation in a free/flexible route environment raises issues with flight plan specification and processing. It is possible to specify a flight plan waypoint in terms of latitude and longitude coordinates, but the precision is limited to degrees and whole numbers of minutes, which may be inadequate for some purposes (e.g. planning routes with minimum lateral separation from ATS routes or airspaces). Numerical coordinate waypoints also have human factors issues of high potential for errors in data entry, interpretation and communication. Airspace designers can create significant points consisting of a five-character identifier (and ICAO region code) with an associated position with sub-arcsecond precision. Such “named” points typically have pronounceable names (e.g. SEALS, MELON, LAGER) for easier use in verbal air traffic control communication. The FAA has addressed some of these issues in its High Altitude Redesign (HAR) Routing initiative by creating a grid of points at intervals of 30' latitude and 2° longitude over the contiguous United States that are referenced by five-character identifiers (e.g. KD54W) [7], and we believe that an equivalent global system is desirable, although the HAR grid interval might not be the most appropriate in some FIRs.

To generate more operationally realistic trajectories, we are considering adding a step climb function. This is conceptually easy to implement by extending the search graph to the vertical dimension, but to avoid excessive branching and search space inflation, we propose to permit only one step climb during the flight and to restrict the climb point to graph vertices (rather than at points along an edge). A more interesting extension from a research point of view would be to enable time-based control by specifying time constraints along a route.

We plan to next apply the program to study a free route airspace concept covering Fukuoka FIR radar-controlled airspace as well as oceanic, with possible extension to neighboring FIRs, as well as to continue using it to support North Pacific operations considerations by JCAB and the Informal Pacific ATC Coordinating Group (IPACG).

6 Conclusion

This paper described our approach and initial efforts towards creating a practical optimal trajectory generation algorithm that can be used in flight planning to exploit the increased route freedom promised by TBO and FRA concepts. We proposed a graph search-based approach to drastically reduce the search space and to allow easier application of operational constraints compared to our DP-based optimizer. Qualitative proof-of-concept tests and application to an airspace restructuring study have demonstrated its feasibility and value in research.

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