A Heuristic Search Approach to Find Contrail Avoidance Flight Routes

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Abstract. Contrails are line-shaped clouds or "condensation trails," composed of ice particles that are visible behind jet aircraft engines. Contrails can affect the formation of clouds effecting climate change. This paper proposes an integrated model of atmosphere, airspace and flight routing with a Gradient Descent based heuristic search algorithm to find Contrail avoidance trajectories with climb, descent and vector maneuvers. Trade off analysis of Contrails avoidance with fuel burn/CO2 and distance flown is also presented.

Keywords: Heuristic search · Gradient descent · Environmental impact · Air traffic

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) special report on Aviation and the Global Atmosphere has accepted that secondary aviation emissions such as Contrails can have a climate impact comparable to the CO2 from the combustion process and may add to greenhouse gas effect [1].

Recent advances in avionics and onboard computing power on an aircraft may help pilots plan their routes that may mitigate the environmental impact of aviation. In this paper we propose a simple yet effective heuristic search i.e. Gradient descent algorithm to identify contrail avoidance trajectories with route choices for pilots and air traffic planners. The research contribution of this paper is in integrating a heuristic search algorithm with atmospheric, airspace and air traffic route models to generate realistic aircraft trajectories that can be implemented in real time.

2 Background

Contrails (also known as condensation trails) consist of tiny ice particles and are formed by water vapors in the exhaust of the aircraft engine, given the right weather conditions. Contrail formation is well understood by the Schmidt–Appleman criterion [2]. Persistent contrail increases the cloud cover over the Earth and in turn reflects solar radiation. This contributes significantly to greenhouse gas effect [1].

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There are several suggested technological and operational modifications in an aircraft operation that can manage contrail formations. In this paper, we focus on Flight path management as means of avoiding contrail formations as it can be easily achievable yet cost effective. A flight path management option for contrail avoidance includes:

- Alteration of existing flight routes
- Climb/decent and vector based on daily conditions

An integrated approach with a combination of contrail model, atmosphere, airspace and flight route and an effective search strategy on three axes (Climb, Descend and Turn) can be more suitable and adoptable. Tradeoffs between increase in distance flown and additional fuel burn have to be taken into account. The key research problem this paper looks into is how can contrails formation be avoided or minimized by integrating a heuristic search algorithm with atmospheric, airspace and flight route models.

We used Gradient Descent method [3] as heuristic search algorithm to identify contrail avoidance trajectories. Gradient descent is an iterative method that is given an initial point, and follows the negative of the gradient in order to move the point toward a critical point, which is hopefully the desired local minimum. The key research question this paper looks into are:

1. How to integrate atmospheric data with air traffic management to identify alternative flight paths?
2. What are the tradeoffs between avoiding contrail formation and fuel burn/CO2 emissions and distance flown/time?

3 Methodology

Since the problem is two folds i.e. integrating different models and a search algorithm to work over them, proposed methodology consisting of following models:

3.1 Airspace Model

The airspace model consists of geo-spatial data points of the Australian airspace. The data is derived from Aeronautical Information Publication (AIP) for the Australian region and contains airspace specific information such as lateral dimensions, special use airspace, restricted zones, etc.

3.2 Atmospheric Model

The atmospheric model is developed by using data from the Bureau of Meteorology. It provides wind and temperature data for $5° \times 5°$ grids and 12 elevations. Further 3D interpolation is done to obtain data for $1° \times 1°$ grid. Humidity data is then obtained from nearest weather station.

3.3 Persistent Contrail Model

Persistent contrails are of interest because they increase the cloudiness of the atmosphere. Persistent contrails often evolve and spread into extensive cirrus cloud cover that is indistinguishable from naturally occurring cloudiness. Changes in cloudiness are important because clouds help control the temperature of the Earth's atmosphere. Persistent contrail model is developed as follows [4]: A region is identified as contrail formation region if the relative humidity $>r_{crit}$

$$where\ r_{crit} = \frac{G\left(T - T_{contr}\right) + e_{sat}^{liq}\left(T_{contr}\right)}{e_{sat}^{liq}\left(T\right)}$$

A region is identified as persistent contrail formation region if relative humidity $>r_{crit}$ and relative humidity with respect to ice $>100\ \%$

$$this\ is\ given\ by\ RHi = (RHw)\frac{6.0612e^{18.102T/(249.52+T)}}{6.1162e^{22.577T/(273.78+T)}}$$

Where:

$$G = \frac{EI_{H_2O}C_pP}{\varepsilon Q\left(1 - \eta\right)} \text{ and}$$

- T = ambient temperature
- $T_{contr} = -46.46 + 9.43\ln(G - 0.053) + 0.72\ln^2(G - 0.053)$
- $G = \frac{EI_{H_2O}C_pP}{\varepsilon Q(1-\eta)}$
- e_{sat}^{liq} = Saturation vapor pressure
- EI_{H_2O} = Emission index of water vapor
- C_p = Isobaric heat capacity of air
- P = Pressure
- ε = Ratio of molecular masses of water and dry air
- Q = Specific combustion heat
- η = Average propulsion efficiency of the jet engine

3.4 Flight Route Model

Upper airspace routes in Australian airspace are obtained from Air Traffic Service Manual and integrated into the airspace model. Only those flight routes are considered that are in the upper atmosphere where contrail formation is possible.

3.5 Integration of Contrail, Flight Route, Atmosphere and Airspace

All four models were integrated and as illustrated in Fig. 1, regions of contrail formation can be seen in the Australian airspace with routes identified.

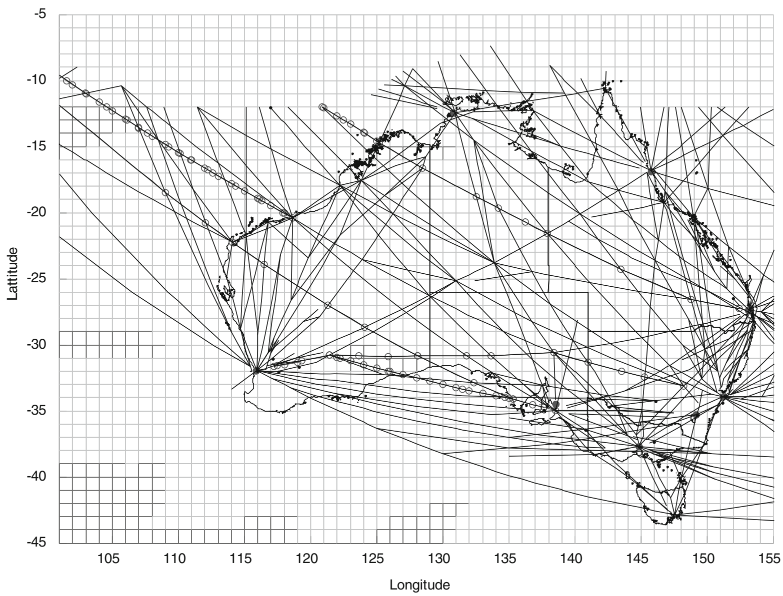


Fig. 1. An integrated view of flight routes, contrail regions, airspace and flights.

3.6 Algorithm Design

We then developed an algorithm for contrail avoidance. There are three maneuvers possible, climb, vector and descent as illustrated in Fig. 2, for a given flight.

The cost function J is developed as follows:

$$\text{MIN } J = \int_{t_0}^{t_f} [(SX(t))^T \dot{X}(t) + C_t + C_f f + C_r r(x, y)]dt$$

Where Ct is Cost coefficient of time

Cf is Cost coefficient of fuel

Cr is Cost coefficient of penalty areas

r(x,y) which is the Penalty function (i.e. Contrails formation regions) is defined as $r(x, y) = \sum_i \frac{1}{d_i^2}$ where di is the distance between the aircraft and centre of the ith region that potentially form persistent contrails.

Gradient Descent algorithm is adopted as follows to minimize the cost function:

(a) Checks if a given route between two successive waypoints crosses or enters a contrail formation region
(b) If route segment crosses contrail formation region then either the latitude or the altitude of the second point is randomly increased or decreased by a small delta.

(c) Latitude is chosen based on the shortest distance to the next waypoint.
(d) This process is repeated until the distance between the aircraft and centre of the ith region that potentially forms persistent contrails becomes less than an epsilon value.

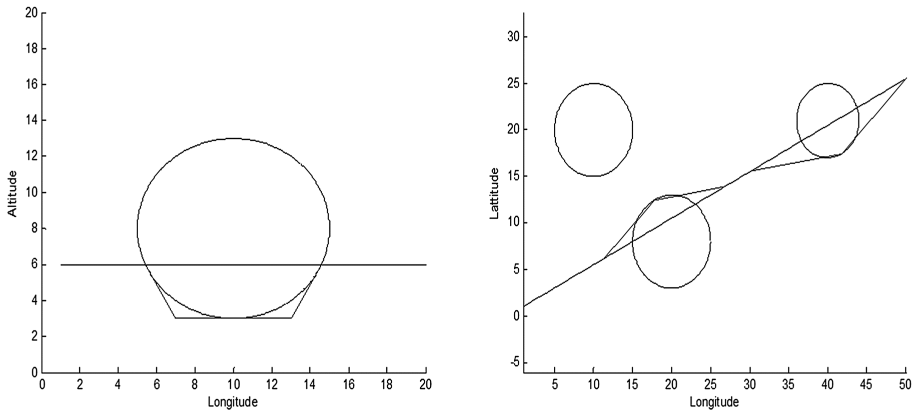


Fig. 2. Climb/descent and vector maneuvers on sample data by Gradient Descent. Straight lines (original trajectory), circumventing line (contrail avoidance trajectory), contrail regions (circles).

4 Experiment Design

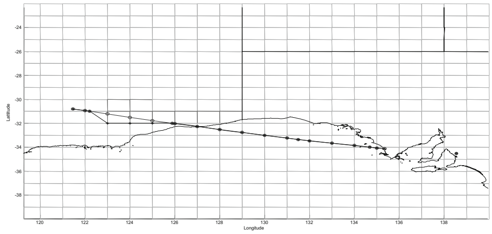
In experiments we first identified routes which were crossing the contrail formation regions. Routes passing through regions of expected persistent contrail formation at the flight level altitude of 33,000 ft are highlighted with blue colored waypoints in Fig. 1. Three of these identified Air Traffic Service routes were chosen, J141, T97 and B340; for application of our algorithm.

5 Results

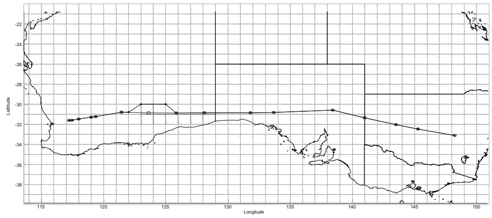
Simulation results show that the contrail formation regions were successfully avoided by employing different strategies such as climb, descent, vector and combination of them. Figure 3 shows different maneuvers generated by the Gradient Descent algorithm for contrail avoidance for some selected routes identified in Fig. 2.

The top section of Fig. 3 shows a Descend maneuver for contrail avoidance. However, it leads to 2.48 % increase in distance flown and fuel burn.

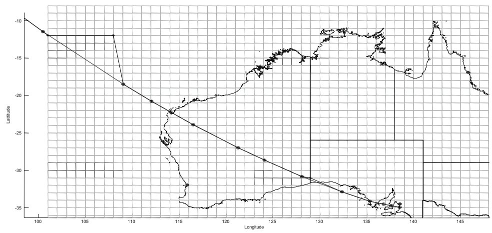
The middle section of Fig. 3 shows a vector (Turn) maneuver for contrail avoidance. However, it leads to 2.04 % increase in distance flown and fuel burn. The bottom section of Fig. 3 shows a Climb maneuver for contrail avoidance. However, it leads to 5.56 % increase in distance flown and fuel burn.



Route Name	Original Route				Modified Route				Additional distance, time, fuel, CO_2 (%)
	Distance (km)	Time (hours)	Fuel (kg)	CO2 emitted (kg)	Distance (km)	Time (hours)	Fuel (kg)	CO2 emitted (kg)	
ATS ROUTE T97	1357	1.56	7267	22978	1390	1.60	7444	23538	2.48



Route Name	Original Route				Modified Route				Additional distance, time, fuel, CO_2 (%)
	Distance (km)	Time (hours)	Fuel (kg)	CO2 emitted (kg)	Distance (km)	Time (hours)	Fuel (kg)	CO2 emitted (kg)	
ATS ROUTE J141	2985	3.44	15983	50539	3046	3.51	16309	51570	2.04



Route Name	Original Route				Modified Route				Additional distance, time, fuel, CO_2 (%)
	Distance (km)	Time (hours)	Fuel (kg)	CO2 emitted (kg)	Distance (km)	Time (hours)	Fuel (kg)	CO2 emitted (kg)	
ATS ROUTE B340	5624	6.48	30112	95217	5937	6.84	31786	100508	5.56

Fig. 3. Top (Descend maneuver), middle (Vector maneuver) and bottom (climb maneuver)

6 Analysis and Future Work

Gradient Descent approach efficiently minimized the cost function and successfully managed to avoid contrail formation regions. However, the flight path modification also leads to increased fuel burn/CO2 emissions (2.0–5.0 %) and distance flown.

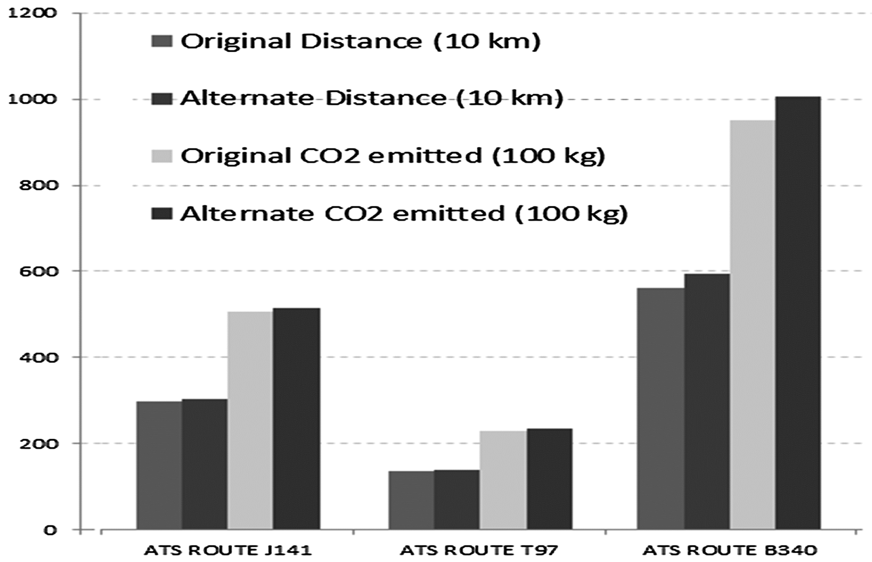


Fig. 4. Distance flown and CO2 emissions in contrail avoidance routes as compared to original routes in the three respective routes with three different routing strategies.

Results indicate that turn maneuvers were cost effective strategy in contrail avoidance. As illustrated in Fig. 4, contrail avoidance on longer routes (ATS Route 8340) has shown increase in distance flown and CO2 emission as compared to smaller routes (T97). For future work we will combine contrail avoidance trajectories with other traffic flow management strategies and employ multi-objective optimization approach.

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