En-Route Trajectory calculation using Flight Plan Information for Effective Air Traffic Management

Yong-Kyun Kim*, Yun-Hyun Jo*, Jin-Won Yun*, Taeck-Keun Oh*, HEE-CHANG ROH*, SANG-BANG CHOI* and HYO-DAL PARK*

Abstract—Trajectory modeling is foundational for 4D-Route modeling, conflict detection and air traffic flow management. This paper proposes a novel algorithm based Vincenty’s formulas for trajectory calculation, combined with the Dijkstra algorithm and Vincenty’s formulas. Using flight plan simulations our experimental results show that our method of En-route trajectory calculation exhibits much improved performance in accuracy.

Keywords—ATC, ATM, Trajectory Prediction, ATFM

1. INTRODUCTION

Air Traffic Control (ATC) systems improve the safety and efficiency of air traffic by preventing collisions with other aircraft and obstacles and by managing aircraft navigation status [1].

To achieve these purposes, air traffic control systems identify aircraft and display their location, display and distribute flight plan data, provide flight safety alerts, and process controllers' requests [2].

Despite technological advances in navigation, communication, computation and control, the Air Traffic Management (ATM) system is still, to a large extent, built around a rigidly structured airspace and centralized around mostly human-operated system architecture. The increasing demands of air traffic are stressing current ATM practices to their limits and the need for alternatives of higher capacity arises [3].

In keeping with the recent increase in air traffic a more efficient air traffic control method is required. The accuracy of trajectory predictions in En-route airspace impacts ATM conflict predictions and Estimated Times of Arrival (ETA) to control fixes. For the airspace user, inaccurate trajectory predictions may result in less-than-optimal maneuver advisories in response to a given traffic management problem [3, 4].

These include missed advisories and false advisories. Missed advisories refer to the lost opportunity of resolving a traffic management problem in a manner most efficient to the airspace user. False advisories refer to the suggestion of an unnecessary maneuver that may cause an aircraft to depart from its most efficient or user-preferred, trajectory.

A limiting factor in the accurate prediction of aircraft trajectories is the difficulty in obtaining

* This research was supported by a grant (code #07 항공-항행-03) from the Air Transportation Advancement Program funded by the Ministry of Land, Transport and Maritime affairs of the Korean government.
Manuscript received April 22, 2010; accepted July 31, 2010.
Corresponding Author: HYO-DAL PARK
* Dept. of Electronic Engineering, Inha University, Incheon, Korea (kim9902@hanmail.net, cyh0107@naver.com, ozone83@nate.com, augustinooh@gmail.com, eeiicbb@hotmail.com, sangbang@inha.ac.kr, hdpark@inha.ac.kr)
precise trajectory calibration and intent data for individual flights. Trajectory calibration data refers to aircraft state, aircraft performance, and atmospheric characteristics that influence the external forces acting on the aircraft.

Trajectory intent information includes the anticipated route, speed profile, and maneuvering procedure of the aircraft over the trajectory prediction time horizon.

In this paper we propose an efficient method of En-route trajectory calculation using flight plan information.

The remainder of this paper is organized as follows: In the next section, trajectory calculation techniques and theoretical background about trajectory calculation are presented. We describe our En-route trajectory calculation algorithm in Section 3. In Section 4 we present some experimental results of our proposed scheme, and then we end with our conclusions in Section 5.

2. TRAJECTORY CALCULATION TECHNIQUES

2.1 Trajectory calculation theory

Let us first consider a fairly simplified model for our trajectory design problem. The set of flows shall be arbitrarily chosen. A flow is defined as a set of flights between a departure airport and an arrival airport. The following simplifications are made: The airspace is considered as an Euclidean space, where all airports are at altitude 0. Latitudes and longitudes on the ellipsoid earth surface are converted into (x, y) coordinates by a stereographic projection, and the altitude in feet shall be our z coordinate [5].

All aircraft fly with identical performances and follow linear slopes of climb and descent.

2.2 Parameters for trajectory calculation

For trajectory calculation, we must consider the concept of speed, speed variation by altitude adjustment and wind parameters.

First, airspeed is the speed of a trajectory calculation relative to the air. The common conventions for qualifying airspeed are: indicated airspeed (IAS), calibrated airspeed (CAS), true airspeed (TAS), and ground speed (GS).

Indicated airspeed (IAS) is the Airspeed Indicator Reading (ASIR) uncorrected for instrument, position, and other errors. From current EASA definitions: Indicated airspeed means the speed of an aircraft as shown on its pitot-static airspeed indicator calibrated to reflect standard atmosphere adiabatic compressible flow at sea level uncorrected for airspeed system errors.
Most airspeed indicators show the speed in knots (i.e. nautical miles per hour). Some light aircraft have airspeed indicators showing speed in miles per hour.

Calibrated airspeed (CAS) is indicated airspeed corrected for instrument errors, position error and installation errors.

Calibrated airspeed values less than the speed of sound at standard sea level (661.4788 knots) are calculated as follows:

\[
V_C = A_0 \sqrt{\left(\frac{Q_c}{P_0} + 1\right)^{3/2} - 1} 
\]  

Where

- \( V_C \) is the calibrated speed.
- \( Q_c \) is the impact pressure sensed by the pitot tube.
- \( P_0 \) is 29.92126 inches Hg; static air pressure at standard sea level
- \( A_0 \) is 661.4788 knots; speed of sound at standard sea level

This expression is based on the form of Bernoulli’s equation applicable to a perfect, compressible gas. The values \( P_0 \) and \( A_0 \) are consistent with the International Standard Atmosphere (ISA).

True airspeed (TAS) is the physical speed of the aircraft relative to the air surrounding the aircraft. The true airspeed is a vector quantity. The relationship between the true airspeed \( (V_t) \) and the speed with respect to the ground \( (V_g) \) is represented thusly:

\[
V_t = V_g - V_w 
\]  

Where

- \( V_w \) is Wind speed vector.

Aircraft flight instruments, however, don't compute true airspeed as a function of groundspeed and wind speed. They use impact and static pressures as well as a temperature input. Basically, true airspeed is calibrated airspeed that is corrected for pressure altitude and temperature. The result is the true physical speed of the aircraft plus or minus the wind component. True Airspeed is equal to calibrated airspeed at standard sea level conditions.

The simplest way to compute true airspeed is using a function of Mach number

\[
V_t = A_0 \cdot M \sqrt{\frac{T}{T_0}} 
\]  

Where \( M \) is Mach number, \( T \) is Temperature (Kelvins) and \( T_0 \) is Standard sea level temperature (288.15 Kelvins)

Second, speed variation by altitude adjustment refers to when aircraft are climbing or descending.

The Rate of Climb (RoC) is the speed at which an aircraft increases its altitude. This is most often expressed in feet per minute and can be abbreviated as ft/min.; elsewhere, it is commonly expressed in meters per second, abbreviated as m/s. The rate of climb in an aircraft is measured with a Vertical Speed Indicator (VSI) or Instantaneous Vertical Speed Indicator (IVSI). The rate of decrease in altitude is referred to as the rate of descent or sink rate. A decrease in altitude
corresponds with a negative rate of climb.

There are two airspeeds relating to optimum rates of ascent, referred to as Vx and Vy.

Vx is the indicated airspeed for best angle of climb. Vy is the indicated airspeed for best rate of climb. Vx is slower than Vy.

Climbing at Vx allows pilots to maximize the altitude gain per unit ground distance. That is, Vx allows pilots to maximize their climb while sacrificing the least amount of ground distance. This occurs at the speed for which the difference between thrust and drag is the greatest (maximum excess thrust). In a jet airplane, this is approximately minimum drag speed, or the bottom of the drag vs. speed curve. Climb angle is proportional to excess thrust.

Climbing at Vy allows pilots to maximize the altitude gain per unit time. That is, Vy, allows pilots to maximize their climb while sacrificing the least amount of time. This occurs at the speed for which the difference between engine power and the power required to overcome the aircraft's drag is the greatest (maximum excess power). Climb rate is proportional to excess power.

Vx increases with altitude and Vy decreases with altitude. Vx = Vy at the airplane's absolute ceiling, the altitude above which it cannot climb using just its own lift.

Last, we consider wind parameters. Wind parameters can be divided into two components (weather fronts and thermal winds) on a large scale.

Weather fronts are boundaries between two masses of air of different densities, or different temperature and moisture properties, which normally are convergence zones in the wind field and are the principal cause of significant weather. Within surface weather analyses, they are depicted using various colored lines and symbols.

The air masses usually differ in temperature and may also differ in humidity. Wind shear in the horizontal occurs near these boundaries. Cold fronts feature narrow bands of thunderstorms and severe weather, and may be preceded by squall lines and dry lines.

Cold fronts are sharper surface boundaries with more significant horizontal wind shear than warm fronts. When a front becomes stationary, it can degenerate into a line which separates regions of differing wind speed, known as a shear line, though the wind direction across the feature normally remains constant. Directional and speed shear can occur across the axis of stronger tropical waves, as northerly winds precede the wave axis and southeast winds are seen behind the wave axis.

Horizontal wind shear can also occur along local land breeze and sea breeze boundaries.[

Thermal wind is a meteorological term not referring to an actual wind, but a difference in the geostrophic wind between two pressure levels p1 and p0, with p1 < p0; in essence, wind shear. It is only present in an atmosphere with horizontal changes in temperature.

In a barotropic atmosphere, where temperature is uniform, the geostrophic wind is independent of height. The name stems from the fact that this wind flows around areas of low (and high) temperature in the same manner as the geostrophic wind flows around areas of low (and high) pressure.

\[ f_{rr} = k \times \nabla (\phi_x - \phi_o) \]  

(4)

where the \( \phi_x \) are geopotential height fields with \( \phi_x > \phi_o \); f is the Coriolis parameter, and k is the upward-pointing unit vector in the vertical direction. The thermal wind equation does not determine the wind in the tropics. Since f is small or zero, such as near the equator, the equation
reduces to stating that \( \mathbf{v}(a_i - a_j) \) is small. This equation basically describes the existence of the jet stream, a westerly current of air with maximum wind speeds close to the tropopause which is (even though other factors are also important) the result of the temperature contrast between equator and pole.

3. PROPOSED EN-ROUTE TRAJECTORY CALCULATION ALGORITHM

This section describes the method for computing the various parameters used to compute a flight plan and our En-route calculation algorithm.

First of all, we need to extract route information from the flight plan. The flight plan message format is shown in the table below.

By enumerating type 15 route information among Parsed flight plans, we can find a particular confirmed aircraft’s waypoints and altitude (or speed) variations.

Waypoints consist of latitude and longitude. In accordance, for measuring the distance between waypoints over a flight information region, the curvature of the Earth must be taken into consideration.

As a rough estimate, we could assume the Earth is a sphere.

\[
dN = R\theta \\
dE = R\cos\theta \lambda
\]  

(5) \hspace{2cm} (6)

Where \( R \) is the radius of the Earth (average of 6378.1 km) and the differences in latitude and longitude are in radians, the distance is 447.47 km. This method is a valid assumption over very small distances, however, over large distances we need to account for the non-uniformity of the Earth. The Earth is not actually a sphere; it is an ellipsoid of revolution, 21 km shorter on the North - South direction than the East - West direction.

The flattening at the poles is caused by the centrifugal force of the spinning Earth. Because of this flattening, the radius of the Earth is not a constant value as we assume for Spherical Earth coordinates.

Table 1. Flight plan message format
A more accurate method of measuring the distance between two points on the surface of the Earth is Vincenty's Formula. It is accurate to 0.5 mm over a distance of a few centimeters to nearly 20,000 km.

Given the coordinates of the two points \((\phi_1, \lambda_1)\) and \((\phi_2, \lambda_2)\) the Vincenty’s inverse method finds the azimuths \(\alpha_1, \alpha_2\) and ellipsoidal distance \(s\).

Calculate reduced latitude \(U_1 = \arctan[(1 - f) \tan \phi_1]\), \(U_2 = \arctan[(1 - f) \tan \phi_2]\), and \(L\), and set initial value of \(\lambda = L\). Then iteratively evaluate the following equations until \(\lambda\) converges.

\[
\sin \sigma = \sqrt{(\cos U_2 \sin \sigma)^2 + (\cos U_1 \sin U_2 - \sin U_1 \cos U_2 \cos \lambda)^2} \tag{7}
\]
\[
\cos \sigma = \sin U_1 \sin U_2 + \cos U_1 \cos U_2 \cos \lambda \tag{8}
\]
\[
\sigma = \arctan \frac{\sin \sigma}{\cos \sigma} \tag{9}
\]
\[
\cos(2\sigma_m) = \cos^2 \sigma - \frac{\tan U_1 \tan U_2}{\cos^2 \sigma} \tag{10}
\]
\[
sina = \frac{\cos U_1 \cos U_2 \sin \sigma}{\sin \sigma} \tag{11}
\]
\[
\cos^2 \alpha = 1 - \sin^2 \alpha \tag{12}
\]
\[
C = \frac{L}{16} \cos^2 \alpha [4 + f(4 - 3 \cos^2 \alpha)] \tag{13}
\]
\[
\lambda = L + (1 - C) \sin \sigma \cos \sigma \cos(2\sigma_m) + C \cos(\alpha \cos(2\sigma_m)) \tag{14}
\]

When \(\lambda\) has converged to the desired accuracy, evaluate the following:

\[
u^2 = \cos^2 \alpha \frac{a^2 - b^2}{b^2} \tag{15}
\]
\[
A = 1 + \frac{u^2}{16384} [4096 + u^2 (-768 + u^2 (-320 - 175u^2))] \tag{16}
\]
\[
B = \frac{u^2}{1024} [256 + u^2 (-128 + u^2 (74 - 49u^2))] \tag{17}
\]
\[
\Delta \sigma = B \sin \sigma \cos(2\sigma_m) + \frac{1}{4} B [\cos(\alpha \cos(2\sigma_m) (-3 + 4 \sin^2 \alpha) (-3 + 4 \cos^2(2\sigma_m))] \tag{18}
\]
\[
s = bA(\sigma - \Delta \sigma) \tag{19}
\]
\[
\alpha_1 = \arctan \left( \frac{\cos U_1 \sin \alpha}{\cos U_1 \sin U_2 - \sin U_1 \cos U_2 \cos \lambda} \right) \tag{20}
\]
\[
\alpha_2 = \arctan \left( \frac{\cos U_2 \sin \alpha}{-\sin U_1 \cos U_2 + \cos U_1 \sin U_2 \cos \lambda} \right) \tag{21}
\]

We can compute azimuths \((\alpha_1, \alpha_2)\) and distance \(s\).
4. EXPERIMENTAL RESULTS OF PROPOSED SCHEME

Performance of the trajectory calculation algorithm was measured using a real flight plan.

The original message and Parsed results are shown in the table below.

Table 2. Original message and Parsed results

<table>
<thead>
<tr>
<th>Original message</th>
<th>Parsed results</th>
</tr>
</thead>
</table>

Using Departure aerodrome, cruising speed (or Mach number), route and arrival aerodrome, trajectory calculation results are shown in the table below.

Table 3. Original message and Parsed results

<table>
<thead>
<tr>
<th>Waypoint1</th>
<th>Waypoint2</th>
<th>Distance [Km]</th>
<th>Speed (knot/km/h)</th>
<th>Flight Level</th>
<th>Elapsed time[min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 SARPA</td>
<td>BULGA</td>
<td>82.061</td>
<td>N0448(628.34)</td>
<td>F340</td>
<td>7.83</td>
</tr>
<tr>
<td>2 BULGA</td>
<td>KPO</td>
<td>31.739</td>
<td>N0448(628.34)</td>
<td>F340</td>
<td>3.03</td>
</tr>
<tr>
<td>3 KPO</td>
<td>PAROT</td>
<td>69.024</td>
<td>N0448(628.34)</td>
<td>F340</td>
<td>6.59</td>
</tr>
<tr>
<td>4 PAROT</td>
<td>CUN</td>
<td>57.008</td>
<td>N0448(628.34)</td>
<td>F340</td>
<td>5.44</td>
</tr>
<tr>
<td>5 CUN</td>
<td>BIGOB</td>
<td>17.585</td>
<td>N0448(628.34)</td>
<td>F340</td>
<td>1.67</td>
</tr>
<tr>
<td>6 BIGOB</td>
<td>GOTLO</td>
<td>23.082</td>
<td>N0472(873.75)</td>
<td>F380</td>
<td>1.58</td>
</tr>
<tr>
<td>7 GOTLO</td>
<td>BULLS</td>
<td>34.007</td>
<td>N0472(873.75)</td>
<td>F380</td>
<td>2.33</td>
</tr>
<tr>
<td>8 BULLS</td>
<td>KAKSO</td>
<td>21.221</td>
<td>N0472(873.75)</td>
<td>F380</td>
<td>1.45</td>
</tr>
<tr>
<td>9 KAKSO</td>
<td>KALMA</td>
<td>35.692</td>
<td>N0472(873.75)</td>
<td>F380</td>
<td>2.45</td>
</tr>
<tr>
<td>10 KALMA</td>
<td>SEL</td>
<td>19.772</td>
<td>N0472(873.75)</td>
<td>F380</td>
<td>1.35</td>
</tr>
<tr>
<td>11 SEL</td>
<td>DAPTO</td>
<td>36.956</td>
<td>N0472(873.75)</td>
<td>F380</td>
<td>2.53</td>
</tr>
<tr>
<td>12 Total</td>
<td></td>
<td>428.147</td>
<td></td>
<td></td>
<td>36.25</td>
</tr>
</tbody>
</table>
En-Route Trajectory calculation using Flight Plan Information for Effective Air Traffic Management

Fig. 2. Simulation results

Fig. 3. Aircraft trajectory presentation on map
5. CONCLUSION

In this paper we propose efficient En-route trajectory calculation using flight plan information. Experimental results show that our En-route trajectory calculation exhibits much improved performance in accuracy. The applicability of the proposed algorithm is manifold in the trajectory prediction and modeling of such things as Rocket positioning control and Aeronautical Traffic Flow Management systems (ATFM).

It is further suggested that henceforth the proposed algorithm be extended to trajectory modeling, as it may further enhance 4D trajectory predictions.

REFERENCES


Yong-Kyun Kim
He received an M.S degree in Electronic engineering from Inha Univ. in 2007. He is currently a PhD. candidate in electronic engineering from Inha Univ. His research interests include avionics systems, air traffic management systems and 4D Trajectory modeling.

Yun-Hyun Jo
He received an M.S. degree in Electronic Engineering from Inha Univ. in 2009. He is currently completing doctorate courses at Inha Univ. since 2009. His research interests are in the areas of Avionics and Radar Systems.
Jin-Won Yun
He received a B.S. degree in Electronic Engineering from Inha University, Incheon, Korea, in 2009. He is currently an M.S candidate in Electronic Engineering from Inha University. His research interests include computer networks, fault tolerant systems and parallel and distributed computing.

Taeck-Keun Oh
He received a B.S. degree in Electronics Engineering from Inha University in 2010. He is currently a M.S course with Electronic Engineering in Inha University. His research interests are in the area of Microwave system, Microprocessors and Control Engineering.

Hee-Chang Roh
He received a B.S. degree in Electronics Engineering from Hanyang University in 2009. He is currently a M.S candidate with Electronics Engineering from Inha University. His research interests are in the area of Microwave system and Wireless communication system.

Sang-Bang Choi
He received the M.S and Ph.D. degrees in Electrical Engineering from the University of Washington, Seattle, in 1988 and 1990, respectively. He is currently a professor of Electronic Engineering at Inha University, Incheon, Korea. His research interests include computer architecture, computer networks, wireless communication, and parallel and distributed systems. He is a member of the IEEE and IEEE Computer Society.

Hyo-Dal Park
He received a Ph.D. degree in Electronics Engineering from ENSAE in 1987. He has been a professor at Inha Univ. since 1992. His research interests are in the area of Avionics and Microwave System, Radar System, Antenna. He is a member of the ATCA.