A Conflict-free Trajectory Generation Method for Pre-tactical Phase in Trajectory Based Operation

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Abstract—Trajectory Based Operation (TBO) is the future vision of air traffic management, and provides efficiency, capacity and safety benefits by managing aircraft trajectories cooperatively. According to air traffic operational characteristic of responsibility airspace division, this paper presents a conflict-free trajectory generation for pre-tactical phase in TBO environment. Considering the traffic flow distribution and flight conflict, a detailed conflict-free trajectory planning algorithm based on waypoint trajectory constraint is developed. Some simulation results based on typical operational data are carried out to show the feasibility of proposed method. This work is of great significance to the development of trajectory management and decision tools to support TBO.

1. INTRODUCTION
As the demand of air traffic grows steadily, current air traffic management (ATM) mode is gradually unable to accommodate the high-density airspace operation in a safe and efficient way. Therefore, Trajectory Based Operation (TBO) concept has been proposed as the future vision of ATM by International Civil Aviation Organization (ICAO), Next Generation Air Transportation Systems (NextGen) and the Single European Sky ATM Research (SESAR) program. TBO is different from current “Radar Based Operation” in which the controller attempts to tactically predict flight path and ensure the safe separation tactically using flight plan and current sensed position from surveillance in the responsible airspace sector. TBO provides efficiency, capacity and safety benefits by managing aircraft trajectories cooperatively among the stakeholders, such as Air Navigation Service Provider (ANSP), airlines and airports, and it supports to optimize an individual flight as well as the overall operations of airspace.

The successful implementation of TBO needs the support of many new technologies and systems, such as advanced ATM automation system, Flight Management System (FMS), air-ground data link, high-precision weather forecast. For the ATM aspect, one of the most important tasks is assigning a conflict-free 4D trajectory to each flight during the pre-tactical and tactical phase in TBO environment [1]. Meanwhile, different operational phase has a different emphasis on trajectory management. Pre-tactical phase focuses on the overall traffic efficiency and sequencing, and tactical phase focuses on the maintenance of safety separation for specific aircrafts.

Recent years, several studies have been carried out to develop the trajectory planning models and algorithms for TBO concept. Barriere uses the constraint programming model to solve the trajectory de-confliction problem by adjusting the departure time of flights [2], and further a method to allocate alternative flight levels is also introduced to increase the flexibility of optimization process [3]. Cai
formulates a multi-objective model for network-wide conflict-free flight trajectories planning problem [4]. Ground holding, rerouting and flight level allocation are used to perfect the scheduled trajectories with consideration of the cost and fairness. To solve this large-scale and complicated constrained problem, the hybrid NSGA-II is applied. Aiming at optimizing the efficiency of the ATM system under TBO concept, Fomeni et al. present a trajectory based mathematical model based on the airspace users’ preferences and priorities, and the constraints of the ATM system [5]. This model is formulated as a binary optimization problem and outputs an optimal pre-departure 4D-trajectory for each flight. Cafieri focuses on speed control to separate aircraft and consider two approaches: (i) maximize the number of conflicts resolved and (ii) identify the largest set of conflict-free aircraft [6]. The mixed-integer nonlinear programming model and tailored greedy algorithm is used to solve this problem. To resolve potential conflicts during strategic 4D conflict-free trajectory planning, Tang et al. establish a protection-zone conflict control model according to air traffic control separation constraints [7]. Arrival time and departure time adjustment are considered as the two strategies in this deconfliction of 4D trajectory method. Huang presents a flight sequencing model based on delay allocation to minimize the total weighting delay, and a genetic algorithm is used to solve the designed model [8].

Although various models and algorithms have been developed to optimize the aircraft trajectories and air traffic, there are still many problems to be overcome, such as computation complexity and the application to operational systems. In addition, most of these models only focus on the safety separation between aircraft, the airspace or sector capacity should also be considered when assigning the conflict-free 4D trajectories. At the operational view, a well-designed trajectory management mechanism and decision-aid tools are also necessary to promote the planning and negotiation process of conflict-free trajectories.

According to ATM operational characteristic of responsibility airspace division, this paper focuses on conflict-free trajectory planning and generation in the pre-tactical phase for the large-scale busy airspace or regional control center. In other words, this method refers to traffic planning in the next 30 minutes to 6 hours. Due to operational uncertainties, trajectory management within the next 30 minutes should focus on the compliance monitoring and conflict detection and resolution. This paper is organized as follow. In Section II, the operational concept is explained in detail. Section III provides the conflict-free trajectory planning model and algorithms. In Section IV, some computational results for typical cases are presented to validate this method. The conclusion and future research direction are stated in the Section V.

2. OPERATIONAL CONCEPT
As described in ICAO Doc9854, ATM system consists of the ATM concept components Airspace Organization and Management (AOM), Demand/Capacity Balancing (DCB), Aerodrome Operations (AO), Traffic Synchronization (TS), Conflict Management (CM), Airspace User Operations (AOU) and ATM Service Delivery Management (ATM-SDM). TBO is part of ATM-SDM and enables globally consistent performance-based 4D trajectory management. And it will enhance the planning and execution of efficient flights, reduce potential conflicts and resolve upcoming network and system demand/capacity imbalances early.

The characteristics of TBO concept are defined as follows according to ICAO Air Traffic Management Requirements and Performance Panel (ATMRPP) [9].

- Sharing of the most accurate trajectory information eventually leading to a common view of the trajectory.
- Managing trajectory information using Collaborative Decision Making (CDM).
- The shared and managed trajectory is used as reference for the flight by providing a common intent to be achieved during execution of the flight.
Trajectory management processes in TBO

Figure 1. Trajectory management processes in TBO

Trajectory management process in TBO involves the use, modification, sharing and coordination of trajectories to achieve the objectives of the concept components across multiple Air Navigation Services Providers (ANSPs). These concept components all act on the same trajectory by adding or removing lateral, vertical or time trajectory constraints. The proposed method in this paper focuses on the traffic optimization and sequencing, which is encircled in green in Figure 1.

In the TBO environment, when pre-tactical and tactical trajectory management seek to modify individual trajectories, coordination between airspace users and Air Traffic Control (ATC) unites across the ANSPs is required. Therefore, trajectory negotiation is an important part of future ATM. Several different actors may participate in trajectory negotiation, including ATC controllers, Air Traffic Flow Management (ATFM) managers on ANSP side, and flight crews and dispatcher from Airline Operation Center (AOC) on the airspace user side. Figure 2 shows the general trajectory negotiation process among different participants for pre-tactical operations. When an ANSP carries out the pre-tactical trajectory management for its responsible airspace, time and/or space constraints may be proposed for specific flights by concept components DCB (usually conducted by ATFM) and TS (usually conducted by ATC). These trajectory constraints will be shared among the related ANSPs and airspace users. Due to the difference in flight time, the flights involved in the pre-tactical trajectory management process have the different operational status, some flights have already in the air or active, and some flights are still inactive. For the inactive flights, the proposed trajectory constraints from the related ANSPs are delivered to AOC, and then AOC submits the re-planned and updated trajectory to ANSPs to generate an agreed trajectory as the common reference. Furthermore, AOC delivers the updated trajectory to aircraft before departure. For flights in the air, the current ATCs unit of the flights collect trajectory constraints from the down-stream ATC units, and uplink these constrains by data link to conduct a trajectory negotiation. The airborne flight management system will compute a new trajectory and downlink it to the current ATC automation system in the form of Extended Projected Profile (EPP). Then the current ATC shares the updated trajectory to the down-stream ATC units to realize the “closed-loop” trajectory management. It should be pointed out that AOC may also participate in the trajectory negotiation for the second case, when the trajectory needs to be adjusted to a great extent, such as the re-routing under abrupt weather.

Figure 2. Trajectory negotiation among different participants
3. CONFLICT-FREE TRAJECTORY GENERATION

In this section the proposed conflict-free trajectory generation method is outlined, based on the operational concept in Section 1. From the perspective of an ANSP, the trajectory planning process is introduced. The trajectory negotiation and trajectory constraint description method is also elaborated.

3.1. Basic Principles of Conflict-free Trajectory Planning

The problem considered in this paper is the conflict-free trajectory planning of large-scale airspace in a busy ACC, which may cover several sectors and airports. To satisfy the operational requirements and minimize the frequency of trajectory adjustment in tactical phase, a conflict-free trajectory in the target airspace for each aircraft is computed. The basic principles of this trajectory planning process are the follow:

- There are two goals of the conflict-free trajectory process: 1) balancing demand and capacity in each time interval; 2) solving the potential flight conflicts.
- Considering the complexity of calculation, the solution only considers the traffic distribution and flight conflicts at the main waypoints in the target airspace.
- When the number of predicted flights in one time interval exceeds the pre-defined capacity value, according to the “first come first served” principle, the extra flights will be moved to next time intervals.
- The assigned CTO for flight is usually after its Estimated Time of Over (ETO), unless there is no available time slot between the ETO and end of the time interval. This case is contributed to maximize the usage of capacity.
- The assigned CTO at different waypoints for a flight should be compatible with aircraft performance.

3.2. Trajectory Planning Algorithm

With the basic principles previously described, a trajectory planning process is outlined.

(a) Generate the 4D trajectories set to be optimized, according to the ETOs at the selected waypoints in the target airspace. In full TBO environment, the original 4D trajectories are submitted by the airspace users and the updated data may also be provided by the up-stream ANSPs.

(b) For one selected waypoint, calculate the number of flights $N^F_i$ which will fly over it in each time interval (usually 15mins), and determine the flights distribution in each time interval according to the capacity value $C_i$ and the sequence of ETOs, guaranteeing the number of flights $N^F_i$ reserved in the time interval should no more than $C_i$.

(c) For each time interval at selected waypoint, assign the CTOs to the flights which violating the minimum time separation $T_{\min}$. The CTOs of flights in $i$-th time interval $[t_{\text{begin}}, t_{\text{end}}]$ satisfies the follow conditions:

$$\begin{align*}
\forall 2 \leq j \leq N^F_i, \ CTO_{i,j} - CTO_{i,j-1} & \geq T_{\min} \\
\forall 1 \leq j \leq N^F_i, \ t_{\text{begin}} \leq CTO_{i,j} \leq t_{\text{end}} \\
CTO_{i+1,j} - CTO_{i,N^F} & \geq T_{\min}
\end{align*} \tag{1}$$

where $j$ is sequence number ordered by the assigned CTOs in the time interval $[t_{\text{begin}}, t_{\text{end}}]$, $CTO_{i,j}$ is the assigned CTO of the $j$-th flight in $i$-th time interval. The CTO is calculated in order of the flight’s ETO. When assigning CTO can’t solve all the conflicts, adjusting the flight levels is used. Adjustment range of flight level is the adjacent available levels.

(d) For each time interval at selected waypoint, assign the CTOs to the flights which violating the minimum time separation $T_{\min}$. The CTOs of flights in $i$-th time interval $[t_{\text{begin}}, t_{\text{end}}]$ satisfies the follow conditions:

$$\begin{align*}
\forall 2 \leq j \leq N^F_i, \ CTO_{i,j} - CTO_{i,j-1} & \geq T_{\min} \\
\forall 1 \leq j \leq N^F_i, \ t_{\text{begin}} \leq CTO_{i,j} \leq t_{\text{end}} \\
CTO_{i+1,j} - CTO_{i,N^F} & \geq T_{\min}
\end{align*}$$

(e) Check the assigned CTOs of flights which fly over more than one selected waypoint and confirm whether the CTOs are not compatible with aircraft performance or exceed the predefined
speed adjustment range. If so, the flight will be add a delay time at every waypoint, and the value is maximum of the difference between CTO and original ETO at each selected waypoint for this flight. Then the trajectory and ETOs in step a) are updated.

(f) Perform the above steps again until the assigned CTOs meet the requirements and generate the conflict-free trajectories.

3.3. Trajectory Constraint Description
The generated conflict-free trajectories include a set of trajectory constraints and these constraints will be shared and negotiated with the up-stream ANSPs and airspace users/aircraft. Trajectory constraints contain several types, for example waypoint trajectory constraint, procedure constraints, and region-based trajectory constraints [10]. Waypoint trajectory constraint is used in this paper and it may optionally specify altitude, and/or time requirements that apply at that waypoint. The formats of trajectory constraints are shown as follow:

- `<CROSS Waypoint AT ALTITUDE Altitude>`
- `<CROSS Waypoint AT TIME Time>`
- `<CROSS Waypoint AT ALTITUDE Altitude AT TIME Time>`

The above formats are intended for the purpose of describing the assigned trajectory and its data elements in a text document. Operationally, ATC clearances will be issued using the Controller Pilot Data Link Communication (CPDLC) messages to the aircraft. Trajectory constraint data will be exchange among the ANSPs and airspace users on ground using Flight Information Exchange Model (FIXM).

4. SIMULATION RESULTS
The typical operational data of Shanghai ACC is applied to validate the feasibility of the proposed method in this paper. The 4 busy waypoints in south of Shanghai ACC is selected as the trajectory constraint points, the location diagram is shown in Figure 3.

![Figure 3. Location diagram of the selected waypoints](image)

In order to eliminate flight conflicts and smooth the traffic flow, the minimum time separation $T_{\text{min}}$ is set as 90s for flights at the same level and 45s for flights at different level when flights merge at the selected waypoints. The time interval of DCB is set as 15min and the corresponding capacity value is 7. Table I shows the computational results for waypoint KHN and 11 flights have been assigned CTOs which are different from their ETO. The assigned CTOs are created by 3 different reasons, for example:

1) As the predicted flow in the first time interval exceeds the capacity, flight DKH1050 is scheduled in the second time interval with a CTO.
2) Flight CSN6547 is assigned a CTO to maintain the minimum time separation from the flight ahead of it.

3) Flight CXA8617 is assigned a CTO which creates an additional time separation compared with minimum separation. This is caused by the more flights and conflicts at waypoints TOL. The assigned CTO of CXA8617 at TOL is shown in Table II.

### TABLE I. COMPUTATIONAL RESULTS FOR WAYPOINT KHN

| Time  | Capacity | Predicted Flow | Flight   | Projected Level (m) | Assigned Level (m) | ETO       | CTO       | Delay(s) |
|-------|----------|----------------|----------|---------------------|-------------------|-----------|-----------|----------|
| 15:15 | 7        | 8              | CQH8772  | 9500                | 9500              | 15:15:49  | 15:15:49  | 0        |
| 15:30 |          |                | CHB6364  | 9800                | 9800              | 15:19:47  | 15:19:47  | 0        |
|       |          |                | CXA8279  | 7800                | 7800              | 15:24:18  | 15:24:54  | 36       |
|       |          |                | CXA8242  | 9200                | 9200              | 15:22:59  | 15:25:39  | 160      |
|       |          |                | UE2205   | 7500                | 7500              | 15:25:37  | 15:26:24  | 47       |
|       |          |                | CESS424  | 7500                | 7500              | 15:25:36  | 15:27:54  | 138      |
|       |          |                | CXA8281  | 9500                | 9500              | 15:26:15  | 15:28:39  | 144      |
| 15:15 | 7        | 6              | DKH1050  | 8900                | 8900              | 15:29:56  | 15:30:00  | 4        |
| 15:30 |          |                | OKA2766  | 8400                | 8400              | 15:34:12  | 15:34:12  | 0        |
|       |          |                | CSN3873  | 7500                | 7500              | 15:35:19  | 15:35:19  | 0        |
|       |          |                | CCA1749  | 7200                | 7200              | 15:37:37  | 15:37:37  | 0        |
|       |          |                | CHH7244  | 9200                | 9200              | 15:41:33  | 15:41:33  | 0        |
|       |          |                | CSN6547  | 7800                | 7800              | 15:41:55  | 15:42:18  | 23       |
|       |          |                | CCD8933  | 9200                | 9200              | 15:42:07  | 15:43:03  | 56       |
| 15:45 | 7        | 6              | CSC8984  | 9200                | 9200              | 15:49:57  | 15:49:57  | 0        |
| 16:00 |          |                | CHH7055  | 8100                | 8100              | 15:51:40  | 15:51:40  | 0        |
|       |          |                | CSC8997  | 9200                | 9200              | 15:54:26  | 15:54:26  | 0        |
|       |          |                | CHH7740  | 9200                | 9200              | 15:50:30  | 15:55:11  | 281      |
|       |          |                | CESS499  | 8900                | 8900              | 15:54:57  | 15:55:56  | 59       |
|       |          |                | CXA8617  | 9200                | 9200              | 15:56:23  | 15:59:09  | 166      |

### TABLE II. COMPUTATIONAL RESULTS FOR WAYPOINT TOL

| Time  | Capacity | Predicted Flow | Flight   | Projected Level (m) | Assigned Level (m) | ETO       | CTO       | Delay(s) |
|-------|----------|----------------|----------|---------------------|-------------------|-----------|-----------|----------|
| 15:30 | 7        | 10             | CCA4519  | 8400                | 8400              | 15:27:06  | 15:30:00  | 174      |
| 15:45 |          |                | CES767   | 9200                | 9200              | 15:28:30  | 15:30:45  | 135      |
|       |          |                | CSN3843  | 9200                | 9200              | 15:28:59  | 15:32:15  | 136      |
|       |          |                | CXA8371  | 9200                | 9200              | 15:30:08  | 15:33:00  | 172      |
|       |          |                | CXA8617  | 6600                | 6600              | 15:28:44  | 15:33:45  | 301      |
|       |          |                | FZA65764 | 9500                | 9500              | 15:32:21  | 15:34:30  | 129      |
|       |          |                | CSH9397  | 9200                | 9200              | 15:30:21  | 15:39:31  | 550      |

5. CONCLUSION
This paper presents a conflict-free trajectory planning and generation method in the pre-tactical phase for TBO environment. The concept and process of trajectory management in TBO is introduced to explain the application scenario of this method. According to ATM operational characteristic, a detailed conflict-free trajectory planning algorithm based on waypoint trajectory constraint is developed. The
trajectory constraint description used in trajectory negotiation is also explained. Finally, the simulation results based on typical operational data are carried out to show the feasibility of proposed method. In the follow-up work, integrating this method into ATC decision-assistant tools is a key research topic. In addition, more performance parameters will be considered in the planning model, such as overall flight delay, controller workload.

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