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# An ADS-B Aided Dynamic Traffic Alert for Robust Safety Assessment in Controlled Airspace

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*Abstract* - **Aircraft are separated by a specified distance via the instructions of the air traffic control officers (ATCOs), so the trailing aircraft would not be suffering from wake vortex effect nor actual conflicts. However, with the surging air transport volume in the past decades, the current model of terminal manoeuvring area (TMA) could not satisfy the growing demand. Safety might be compensated by the high workload of the ATCOs as they might not be aware of the potential violations. Hence, a novel approach transforming communication-based train control (CBTC) with the aid of flight speed is proposed to enhance the efficiency and the safety of air traffic management (ATM). This study develops mathematical models and an algorithmic framework supporting the terminal traffic flow decision with real-time surveillance-broadcast data. The decision quality and situational awareness in ATC can be enhanced to facilitate the estimation of incoming traffic in the area control jurisdiction.**

*Keywords* - **Safety Enhancement, Human Factors, ADS-B, Air Traffic Management, Conflict Detection**

## I. INTRODUCTION

Several aviation programmes attempt to provide an advanced surveillance and communication infrastructure with the sharing airport and airspace capacities across regions. The emerging surveillance technology contributes to a 40% reduction in general aviation accidents in the Federal Aviation Administration's (FAA) capstone programme. A modern decision support system can assure the high demand for international travel and achieve efficient air traffic service. With automation aids and decision supports, the future TMA operations could be reshaped to cope with the long-term evolution of airspace congestion control. The automatic dependent surveillance-broadcast (ADS-B) was first adopted in 2006 to enhance flight safety. The effectiveness of ATC largely depends on the availability of information communicated to airspace users, collaboration with stakeholders, and en-route sharing on meteorological conditions to resolve traffic flow issues. Hence, an imminent opportunity shall be sought to undergo revolutionary changes of ATM such as the harmonisation between flight trajectory and short-term conflict detection.

The ATC efficiency is significantly impacted by its uncertainty due to the following reasons. First, the prediction of the flying time in approach phases is challenging as the true airspeed is subject to various meteorological factors like wind direction and intensity, atmospheric instability, and cruising altitude. Air route re-direction can also be determined by changing the approach path. Second, ATCOs and pilot airspeed discrepancy are commonly seen and the ATCOs is required to accommodate this in conflict detection and prediction by satellite-based technologies. ATCOs do not have complete control over assigning the approach speed of flights. When flights enter the TMA, ADS-B provides 1-2 signals of three-dimensional geographical coordinate and airspeed in each second. ATCOs can estimate the incoming flight trajectory and the predicted arrival time from the processed ADS-B data.

It is crucial to consider human factors in the ATC system to identify potential conflicts before the actual violation. This research contributes by proposing a safety-oriented alert system using a mathematical model that predicts the position and separations of the flights in controlled airspace. The proposed model contributes by alleviating the cognitive load of ATCOs for conflict detection in real-/near-time for implementing countermeasures. The safety of the controlled airspace is also enhanced with the aid of the safety factor. By the relative approach in flight separations, this research transforms CBTC adopted by railway system to ATM to enhance the overall efficiency of the air traffic.

## II. LITERATURE REVIEW

Extensive research has been conducted in the past decade to address the terminal traffic flow and airspace congestion control, including the resolutions and decisions on runway configuration [1-3], runway scheduling [4-7], approach route [8-11], waypoint merge system [12, 13], aeronautical holding [14], fuel consumption [15], runway and waypoint arrival time determination [16, 17].

The management of flight arrival and departure procedures are key components of an efficient air transportation system [2]. Inaccurate information regarding the approaching time and route might lead to the infeasibility of the planned schedule, sometimes even leading to re-scheduling efforts. Contemporary research in traffic flow management focuses on the recovery approach, which is a reactive approach that handles delays when they arise [18]. Several congestion control methods, such as runway configuration switch [19], ground delay programmes, point-of-merge decision and aeronautical holding assignment can be applied to resolve the contemporary traffic condition, reduce unnecessary delays and offload congested air routes [20]. Therefore, the TTFP schedule should inherently include a certain degree of solution robustness and network resilience to increase the vulnerability of the disruption of airside operations. As a result, an ADS-B aided traffic alert system could give a solid foundation to ensure the robustness of TMA.

## III. MATHEMATICAL FORMULATION

In this section, we proposed a novel three-case-of-constraint mathematical model for an approaching scenario to enhance the level of safety, as well as providing a higher level of efficiency. The conflict detection model CD considers both the vertical and longitudinal separation. The conditions of detecting any two flights not conflicting are P1 for vertical separation, P2 for horizontal separation, and P3 for horizontal separation with safety factor.

$$\overline{\mathrm{CD}} = \mathrm{P1} \cup (\mathrm{P2} \cap \mathrm{P3}) \tag{1}$$

A conflict is only be considered resolved if and only if (1) is satisfied. Considering a set of approaching flight $I$ with $i, j \in I$, $i \neq j$, and the leading flight $i$ and the trailing flight $j$ are flying at $\overrightarrow{P_i} = (\lambda_i, \varphi_i, \gamma_i, \theta_i)$ and $\overrightarrow{P_j} = (\lambda_j, \varphi_j, \gamma_j, \theta_j)$ respectively. For every single waypoint on a flight route, a leading flight $i$ and trailing flight $j$ would arrive at the waypoint at $t_i$ and $t_j$ respectively.

TABLE I

NOTATIONS AND DECISION VARIABLES

| Sets with indices | Explanation |
|---|---|
| $I$ | A set of approaching flights in the decision horizon (index $i, j$) |
| $f$ | A collection time of leading and trailing flight |
| $\overrightarrow{P_i}$ | A leading flight (index $\lambda_i, \varphi_i, \gamma_i, \theta_i, t_i, s_i$) |
| $\overrightarrow{P_j}$ | A trailing flight (index $\lambda_j, \varphi_j, \gamma_j, \theta_j, t_j, s_j$) |
| $\rho$ | A set of records in the data in $f$ seconds (index $f_{record}$) |
| $\sigma$ | A safety factor percentage, $\sigma \in [0, \infty)$ |
| **Parameters** | **Explanation** |
| $i, j$ | Flight ID $i, j \in I$ |
| $\lambda_i, \lambda_j$ | Longitude of a flight, $i, j \in I, i \neq j$ |
| $\varphi_i, \varphi_j$ | Latitude of a flight, $i, j \in I, i \neq j$ |
| $\gamma_i, \gamma_j$ | Altitude of a flight, $i, j \in I, i \neq j$ |
| $\theta_i, \theta_j$ | Heading of a flight, $i, j \in I, i \neq j$ |
| $f_{record}$ | The last ADS-B record available, $f_{record} \in \rho$ |
| $t_i, t_j$ | Arrival time of flight at the position $\lambda_i, \varphi_i, \gamma_i, \theta_i$ or $\lambda_j, \varphi_j, \gamma_j, \theta_j, i, j \in I, i \neq j$ |
| $t_i', t_j'$ | Predicted arrived time after $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $\overline{\gamma_i}, \overline{\gamma_j}$ | Mean value of altitude in $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $\underline{\mathrm{v}}_i', \underline{\mathrm{v}}_j'$ | A minimum value of velocity in $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $\bar{\mathrm{v}}_i', \bar{\mathrm{v}}_j'$ | A maximum value of velocity in $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $s_i, s_j$ | Predicted distance after $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $\varphi_i', \varphi_j'$ | Predicted latitude after $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $\lambda_i', \lambda_j'$ | Predicted latitude after $f$ or $f_{record}$ seconds, $i, j \in I, i \neq j$ |
| $t_{record,i}, t_{record,j}$ | The time in the record, $i, j \in I, i \neq j$ |
| $S_{Safety}$ | A safety separation distance with $\sigma \in \mathbb{R}^+$ |
| **Constants** | **Explanation** |
| $S_{Vji}$ | A minimum separation in vertical direction |
| $S_{Hji}$ | A minimum separation in horizontal direction |
| **Decision Variables** | **Explanation** |
| $\tau_{MTOM}$ | The aircraft type deployed for the flight |
| CD | The two flights are under violation/conflict |

### A. P1 Vertical separation conflict detection

A fixed minimum vertical separation is applied between every flight. Therefore, P1 is dedicated to checking whether flight $i$ and $j$ attained the minimum vertical separation distance. The moving average was applied to estimate the altitude of the flight at a certain timestamp, as shown in (5). The vertical minimum separation is regulated as,

$$S_{Vji} = 1000 \text{ ft} \tag{2}$$

At time point $t_i$,

$$f = 15\text{s} \tag{3}$$

$$t_i' = t_i + f, \forall i \in I \tag{4}$$

$$\overline{\gamma_i} = \begin{cases} \overline{\gamma_i} \in [t_i, t_i - f] & if\ \rho \notin \emptyset \\ \overline{\gamma_i} \in [t_i, t_i - f_{record}] & otherwise \end{cases}, \forall \mathrm{i} \in \mathrm{I} \tag{5}$$

Hence, the following shall be satisfied,

$$|\gamma_j - \gamma_i| \geq S_{Vji} \tag{6}$$

such that flights $i$ and $j$ is not considered under conflict.

### B. P2 Horizontal separation conflict detection

If vertical separation is violated, horizontal separation shall be applied to avoid actual collision and the wake vortex effects caused by $i$ on $j$. The current distance-based model for wake turbulence separation is illustrated in TABLE II, TABLE III.

TABLE II

DISTANCE-BASED WAKE TURBULENCE SEPARATION MINIMA

| | | Trailing flight $j$ | | | |
|---|---|---|---|---|---|
| | $\tau_{MTOM}$ | SUPER | HEAVY | MEDIUM | LIGHT |
| Leading flight $i$ | SUPER | **3 NM** | **5 NM** | **7 NM** | **8 NM** |
| | HEAVY | **3 NM** | **4 NM** | **5 NM** | **6 NM** |
| | MEDIUM | **3 NM** | **3 NM** | **3 NM** | **5 NM** |
| | LIGHT | **3 NM** | **3 NM** | **3 NM** | **3 NM** |

TABLE III

CRITERIA OF MASS FOR DEFINING THE TYPE OF AIRCRAFT

| $\tau_{MTOM}$ | Criteria for Mass (kg) |
|---|---|
| SUPER | MTOM ≥ 560000 |
| HEAVY | 136000 < MTOM < 560000 |
| MEDIUM | 7000 < MTOM ≤ 136000 |
| LIGHT | MTOM ≤ 7000 |

By maintain a separation not less than the distance value specified in TABLE II, two flights are successfully separated. The minimum separation distance varies with the type of aircraft $\tau_{MTOM}$ for both flight $i$ and $j$. A relative distance concept between flight $i$ and $j$ would be applied. A moving minimum-maximum approach is used as described in (7) and (8). In a dynamic system, conflict detection is defined by the timestamp of the event at time point $t_i$. A time event in a discrete value is defined as a positive integer. Therefore, with (3) and (4), in each iterative process, the model at a time point $t_i$ is shown as follows.

$$\underline{\mathrm{v}}_{\mathrm{i}}' = \begin{cases} \operatorname{argmin}\{v(t): t = t_i, .., t_i - f\} \; if \; \rho \notin \emptyset \\ \operatorname{argmin}\{v(t): t = t_i - f_{record}\} \; otherwise \end{cases}, \forall \mathrm{i} \in \mathrm{I} \tag{7}$$

$$\bar{\mathrm{v}}_{\mathrm{i}}' = \begin{cases} \operatorname{argmax}\{v(t): t = t_i, .., t_i - f\} \; if \; \rho \notin \emptyset \\ \operatorname{argmax}\{v(t): t = t_i - f_{record}\} \; otherwise \end{cases}, \forall \mathrm{i} \in \mathrm{I} \tag{8}$$

$$\Delta t = \begin{cases} t_i' - t_{record,i} & if \; \rho \notin \emptyset \\ t_i + \mathrm{f}_{\mathrm{record}} - t_{record,i} & otherwise \end{cases}, \forall \mathrm{i} \in \mathrm{I} \tag{9}$$

$$s_i = v_i' \Delta t \,, \forall v_i' \in [\underline{v}_i', \bar{v}_i'], \forall i \in I \tag{10}$$

$$t_i \in \mathbb{Z}^+, \forall i \in I \tag{11}$$

$$\varphi_i' = \arcsin\left[\sin(\varphi_i)\cos(s_i) + \cos(\varphi_i)\sin(s_i)\cos(\theta_i)\right], \forall i \in I \tag{12}$$

$$\lambda_i' = \begin{cases} \lambda_i & if \; \varphi_i' = 0 \\ \bmod\left[\dfrac{\lambda_i - \arcsin\left(\dfrac{sin(\theta_i)\, sin(s_i)}{\cos(\varphi_i)}\right) + \pi}{2\pi}\right] - \pi & otherwise \end{cases}, \forall i \in I \tag{13}$$

If the following is satisfied,

$$s_j - s_i = 2\left(\frac{180 \times 60}{\pi}\right) \arcsin\sqrt{\sin^2\left(\frac{\varphi_j - \varphi_i}{2}\right) + \cos\varphi_i \times \cos\varphi_j \times \sin^2\left(\frac{\lambda_j - \lambda_i}{2}\right)} \tag{14}$$

$$s_j - s_i \geq S_{Hji} \,, \forall i, j \in I, i \neq j \tag{15}$$

flights $i$ and $j$ is not considered under conflict.

### C. P3 Horizontal separation conflict detection with safety factor considered

The model in P2 has demonstrated the minimum requirement for horizontal separation conflict detection. However, human response time accounts for a few seconds to initiate appropriate remedial actions. Additional time is also needed for making decisions on remedial actions. To further enhance the safety level, an advanced alert shall be made before the actual violation.

The safety factor percentage $\sigma$, or the safety factor $(1 + \sigma\%)$, is added to the model of P2 for formulating P3. In application, ATCOs could specify the value themselves to fit and relieve their workload on determining potential conflicts. This extends the relative distance required in every two adjacent flights, conceptually shown in Fig. 1.

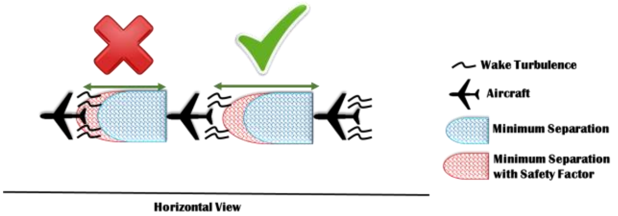

Fig. 1. Concept of minimum horizontal separation with safety factor considered

Similarly, with (3), (4) and (7) – (14), in each iterative process of time point $t_i$, if (16) and (17) are satisfied,

$$S_{Safety} = S_{Hji} \times (1 + \sigma\%) \tag{16}$$

$$s_j - s_i \geq S_{Safety} \,, \forall i, j \in I, i \neq j \tag{17}$$

flights $i$ and $j$ is not considered under conflict.

## IV. CASE STUDY

### A. The analysis setting

In the following, a case study of the Hong Kong International Airport (HKIA)'s TMA would be illustrated. Despite the flight speed is regulated, the actual speed varies with the pilot's behaviours in the descent region. Therefore, potential conflicts, particularly horizontal violations, might occur. Also, flights from different routes would joint at a certain waypoint before proceeding to the final approach. A higher risk is expected in merging. Our main area of interest is the air route passing through air routes ABBEY, serving flights from East Asia and America. Three air routes would merge at the waypoint MAGOG, with their nearest waypoint are DOTMI, MALKA/LELIM, and ELATO.

The ADS-B data of HKIA on 3 April 2018 were used for analysis with dense traffic that day as it is within the easter holiday. The total number of approaching flight movements to HKIA on 3 April 2018 was 486. Hence, more potential violations are expected. A 15-minute interval between 20:45 to 21:00 was selected for analysis. Flight passing through latitude 22°N to 24°N and longitude 116°E to 118°E would be filtered to filter flights passing through ABBEY. After filtering, ten flights were found. By visualising the trajectory in Google Earth, flights from all three air routes were observed as shown in Fig. 2, confirming our analysis covers the whole area of interest by considering the merging of flights in a certain waypoint.

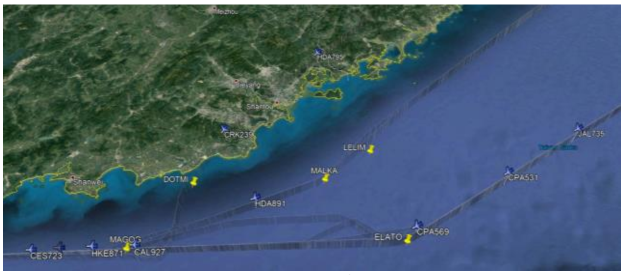

Fig. 2. Flights filtered

## B. Computational analysis

The mathematical model formulated in Section III was coded in Python 3.0 scripts. As illustrated by Fig. 3, the algorithm predicts each flight's location every 15 seconds.

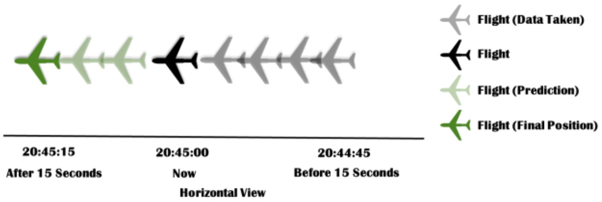

Fig. 3. Concept of position prediction in each 15 seconds

Conflicts would be evaluated for each combination of every two flights at a timestamp irrespective of the air routes. That is, if $n$ flights are observed at a certain timestamp, the combinations possible is $C_2^n$ . Hence, computational analysis was undergone by feeding the filtered data in Section IV.A, including the accuracy measurement and the safety factor analysis.

## C. Accuracy measurement

When feeding real ADS-B data into the model without additional safety factor, no conflicts shall be observed. For a timestamp $t_i$, all combinations of flights are evaluated at an iteration rate of 15 seconds. If there is only a single flight entered our area of interest in that timestamp, conflict detection is omitted. Reversely, if multiple flights exist in our area of interest, all combinations are checked. The number of warning over the whole study period is aggerated. The first record occurs at 20:30:45 while the last record occurs at 21:25:30. At a safety factor of 1.0, the result demonstrated a 100% accuracy by having no warnings, as no flights shall be under conflict with real data fed.

## D. Safety factor analysis

After validating by checking the nominal safety factor at 1, the analysis is now extended to other safety factor values. The number of potential conflicts by varying the safety factor value, and followed by visualizing the trend of varying the safety factor value over the study period. When the safety factor value is raised to 3.0, 16 conflicts are observed. The distribution of warnings over the period is aggregated to the nearest minute in Fig. 4.

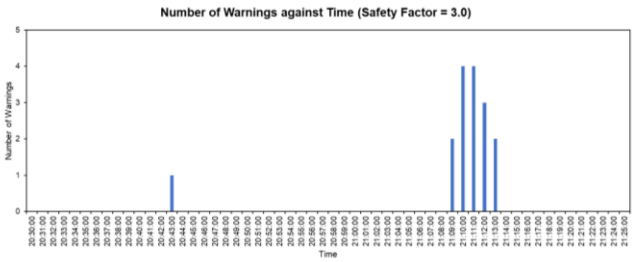

Fig. 4. Warnings incurred against time (Safety factor = 3.0)

As observed, alerts located between 21:09 and 21:13 are generated from the same flight combination. The warning is made to ATCOs 15 seconds before the predicted time. The ATCOs could then have 15 seconds to respond to the situation. Moreover, the ATCOs shall start tackling from the first warning in multiple warnings. The latter warnings shall be eliminated in the real scenario. The safety factor could be adjusted for early intervention.

Although an early warning could reserve sufficient time for decision-making, over-alerting would also cause disturbances to ATCOs and might obstruct their performance. Hence, the number of alerts incurred by the rising value of safety factor shall be properly analysed.

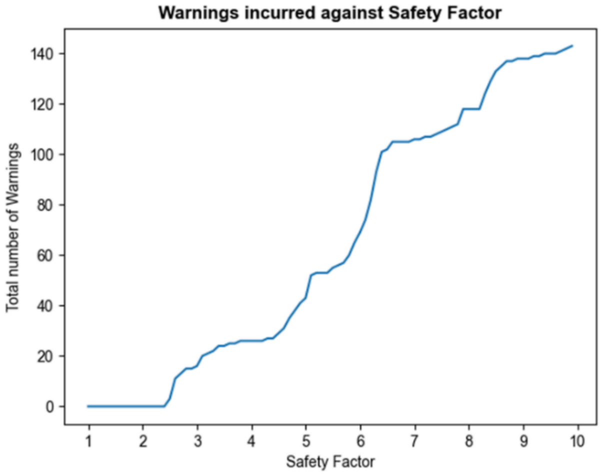

Fig. 5. Warnings incurred against safety factor

Fig. 5 illustrates the warnings incurred against the value of the safety factor. It is observed the trend is non-linear and no warnings are incurred before safety factor 2.5. A safety factor at 6.0 could result in approximately 60 warnings, implying only a warning per minute on average even the minimum separation distance is raised to six times the required. Hence, a good balance shall be achieved via observation during ATC operations.

## V. CONCLUDING REMARKS

This research proposed an alerting mechanism for ATCOs to acknowledge potential conflicts earlier using ADS-B data-predicted position. With this non-critical safety measurement aid, potential violations could be noticed at a glance and proceed to resolve. The earlier appearance of warnings partially shifts conflict detection to computational effort and reduce the cognitive load to monitor a huge traffic volume flow. With a novel approach considering the relative separation distance, CBTC could be utilised in ATM to transform to a relative system. Hence, continuous monitoring of violations could dynamically scale down unoccupied airspace and enhancing the safety level.

Several interesting limitations could lay a good ground for conducting future work. To begin with, the iteration rate is set as 15 seconds. The rationale is to ensure reasonable accuracy of the predicted aircraft position. If the rate is reduced, more moving minimum-maximum/average data is results in reduced accuracy of flight's position estimation. Reversely, the ADS-B data might yet to be available with a raised computational load. However, as a real-/near-time environment, the warning computation time shall be minimised. A balance shall strive between high accuracy and low computation time. Hence, with further advancement of ADS-B, further works could focus on determining a suitable iteration rate to suit the real needs.

Another possible direction for future work is to develop an adaptive-dynamic safety factor. In the proposed model, the safety factor is introduced for non-critical alerts of potential violations to sustain operations under abnormal conditions like extreme weather, heavy traffic, or lack of manpower. Despite it is currently user-defined in nature, a data-driven approach with an adaptive safety factor could enhance ATM safety. The safety factor is ideally adjusted automatically with traffic flow, weather, and the stress level of the ATCOs to reduce the workload of ATCOs.

All these efforts could assure safety in the controlled airspace and further relief the ATC workload. Shifting the process from human-centred to automated could trim the effect of human factors in ATM, while human intelligence is still the core of the robust-in-nature ATM operations.

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