UNCERTAINTY-AWARE CONFLICT DETECTION ALGORITHM AND CONFLICT AREA VISUALIZATION FOR AIR TRAFFIC CONTROLLERS

Lennard Nöhren[1], Oliver Ohneiser[1,2], Albin Joy[2]
1. Institut für Flugführung, Deutsches Zentrum für Luft- und Raumfahrt,
Lilienthalplatz 7, 38108 Braunschweig, Deutschland
2. Institut für Informatik, Technische Universität Clausthal,
Julius-Albert-Straße 4, 38678 Clausthal-Zellerfeld, Deutschland

Abstract

Current air traffic management (ATM) systems face rising challenges due to increasing volume of air traffic and shortage of air traffic controllers (ATCOs). Medium-term conflict detection (MTCD) is an important tool to assist ATCOs. Traditional MTCD usually relies on deterministic, trajectory-based models. Hence, uncertainties in flight movements are not considered, potentially leading to false alarms or missed conflicts. Therefore, this paper presents an uncertainty-aware MTCD algorithm and a dynamic representation of conflict areas in ATCO displays. The suggested area-based MTCD approach employs ellipsoidal models to define protected zones around aircraft to identify spatial and temporal overlap zones rather than just points along trajectories. By dynamically adjusting ellipsoid dimensions with Monte Carlo simulations based on variations of wind, aircraft speed, and pilot reaction delays, our model provides a probabilistic MTCD. A horizontal and vertical conflict display augments colour-coded risk indicators for sub-zones of conflict areas to enhance ATCOs' situation awareness. An evaluation with ten ATM experts – including two ATCOs – in a simulated air traffic environment showed conceptual soundness and usability. Participants rated the MTCD model's concept with a score of 8.2 on average on a 10-point scale with high scores in favour. Map visualizations were well received, with all ratings being 8 or more. The evaluation as well identified potential improvements for pilot response modelling and computational speed to advance MTCD and its visualization in future ATM systems.

1. INTRODUCTION

Challenges in the global air traffic industry are expected to increase in the coming years [1], driven by increasing traffic volumes and staff shortages [2], adding significant complexities to air traffic management (ATM). Efficient electronic tools are essential to support air traffic controllers (ATCOs) in managing air traffic flows. As airspace utilization becomes more intensive, the need for advanced conflict detection and resolution [3] systems become critical to ensure safety and efficiency. Medium-term conflict detection (MTCD) plays an important role in this framework by focusing on identifying potential conflicts within a meaningful time horizon, typically spanning up to 20 minutes [4]. Unlike short-term systems that focus on immediate collision avoidance, MTCD excels by identifying conflicts earlier, giving ATCOs sufficient lead time to implement optimized and preventive measures effectively [4]. This capability is particularly valuable in managing en-route air traffic, where the development of aircraft trajectories is influenced by dynamic factors such as wind variability, aircraft performance, and operational constraints.

Conventional MTCD methods usually rely on deterministic models and linear trajectory representations, which inadequately account for uncertainties such as weather conditions, navigation errors, and pilot actions. These limitations result in either false alarms, which burden ATCOs with unnecessary interventions or missed conflicts, which compromise operational safety and efficiency. Traditional ATM situation data displays often represent conflicts using a simplistic binary approach – conflict or no conflict –, lacking a probabilistic depiction of conflict likelihood. Additionally, the conflict is displayed along the trajectories instead of illustrating the complete conflict area, which limits spatial awareness for ATCOs. Traditional displays also fail to represent conflicts as dynamic, four-dimensional areas (space and time). The lack of an integrated, uncertainty-aware system calls for innovative solutions that combine probabilistic conflict detection algorithms with user-centric visualization tools, providing a more comprehensive understanding of potential conflicts and their evolution.

This paper aims to advance MTCD by addressing existing gaps in predictive accuracy, uncertainty management, and user interface design focusing solely on the detection aspect, not the resolution. By incorporating an ellipsoidal model, stochastic modelling, and Monte Carlo simulations, the algorithm enhances predictive four-dimensional accuracy under dynamic conditions. The algorithm accounts for key uncertainties such as wind variability, pilot behaviour, aircraft speed variations, and wake turbulence. A user-centric graphical user interface (GUI) is developed to visualize different aspects of conflict areas dynamically. The proposed system underwent testing in simulated air traffic scenarios with feedback from ten ATM experts to evaluate the concept, the technical accuracy of the implementation, and the GUI usability.

2. RELATED WORK

Conflict detection and resolution has been an active field of research for many years [3]. Many approaches rely on 4D-trajectories [5] [6], a stochastic approach can help to

doi: 10.25967/650017

accurately predict conflicts in the medium-term future due to uncertainties in the flight's behaviour. For that, different methodologies were applied in the past. Some of the most popular are Bayesian optimization algorithms [7] [8], Monte Carlo Simulations [9] [10] [11], Ellipsoidal protection zone models [6] [10] [12], or other probabilistic approaches [13] [14] [15]. These methods are used to incorporate various types of uncertainties into conflict detection. [16] classifies the uncertainties into three categories: human, environmental, technical. Human factors that could be considered for conflict detection are for example pilot reaction delays [17] [18] or ATCO workload [8]. Technical factors are things like aircraft performance [8], positioning errors [19] or speed inaccuracies. The most important environmental factor for conflict detection is wind [20] [21]. It is a major source of trajectory uncertainty, as demonstrated by Dudoit et al. [20], who emphasize its dynamic influence on trajectory predictions. Similarly, Jurado et al. [8] identify disparities in aircraft speeds as critical contributors to conflict prediction errors in dynamic air traffic environments. Lastly, reaction delays in executing speed, altitude, and heading adjustments represent a critical source of uncertainty [17].

In this work we use a combination of the aforementioned stochastic methods to achieve a precise conflict detection, incorporating various types of uncertainties. Furthermore, we explore how the results of these algorithms can be presented in a GUI for ATCOs in an intuitive and understandable manner. Most of the works mentioned above focus on the algorithmic part of the conflict detection. Although there are some works that focus on the human factors of ATC-Software [22] [23] [24] [25], – to our knowledge – there has been no work combining the probabilistic conflict detection approach with the design and evaluation of a fitting ATCO display.

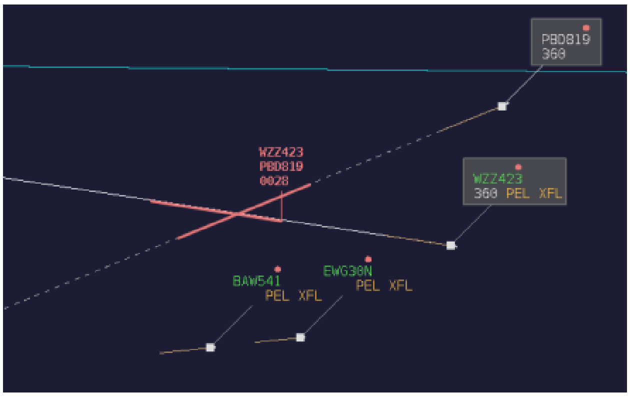

FIG 1. Traditional horizontal conflict view

FIG 1 [26] shows a typical traditional conflict view. It provides a straightforward representation of potential conflicts by displaying intersecting flight paths and highlighting the conflict point with crossing markers. Identifiers, altitudes, and labels for involved aircraft are also displayed to facilitate quick identification of the conflicting flights. However, this method primarily focuses on visualizing individual conflict points of planned trajectories. While it is an effective and simple way to display conflicts between two aircraft, it does not account for uncertainties or dynamic changes in trajectories. The displayed conflict prediction is obsolete, as soon as an aircraft deviates from its trajectory.

3. CONFLICT DETECTION

Conflict detection relies on monitoring aircraft trajectories in both spatial and temporal dimensions to identify potential collision risks [4]. In medium-term conflict detection, which this work primarily focuses on, conflicts are predicted several minutes in advance. This time frame, typically spanning 5 to 20 minutes, enables proactive conflict management by allowing sufficient time for controllers to implement strategic interventions while minimizing the urgency associated with short-term tactical decisions. Furthermore, medium term detection allows a balance between computational efficiency and predictive accuracy, particularly when trying to account for stochastic uncertainties such as wind variability, pilot reaction times, and trajectory deviations, as is the goal in this work.

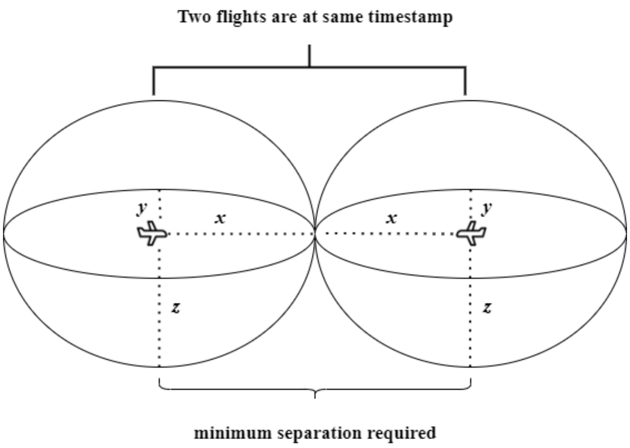

FIG 2. Conflict protection zones of two flights

FIG 2 shows a conflict between two flights, showing overlapping protection zones, which represent a breach of the minimum separation. When such a conflict is detected, a conflict alert can be issued. This alert prompts ATCOs or autonomous systems to take preventive actions, such as changing altitude, heading, or timing, to ensure separation.

The vertical and horizontal separation minima are governed by the ICAO, which prescribes that vertical separation should be 1000 feet for aircraft flying below FL290 (flight level 290) and 2000 feet for aircraft flying above FL290, except when Reduced Vertical Separation Minima (RVSM) applies [27]. Horizontal separation is typically maintained using surveillance systems like radar, with the standard minimum distance being 5 nautical miles between aircraft to avoid potential conflicts. However, this separation is applicable only when radar coverage is available, which is not the case over certain regions such as oceans or large deserts. In these cases, alternative methods or increased separation standards are often employed. In this study, the separation standards are based on vertical separation of 2000 feet and 5 nautical mile horizontal separation, following the guidelines established by ICAO [28].

3.1. Aircraft Protection Area Modelling

A protection area around each aircraft is used to estimate possible conflicts. These protection areas can be represented in several geometric shapes (see FIG 3), each with unique attributes and constraints: where (x_1, y_1, z_1) represent the coordinates of one aircraft, and (x_2, y_2, z_2) represent the coordinates of another aircraft.

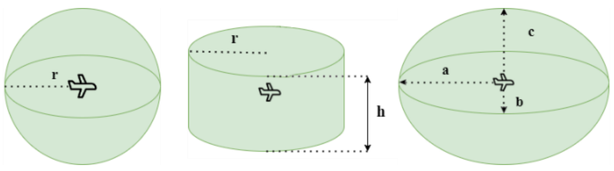

FIG 3. Spherical model (left), Cylindrical model (centre) and Ellipsoidal model (right)

Spherical Protection Area: The spherical model depicts the aircraft's protection area as a sphere, with the distance between the centre and any point on the surface being the same in all directions (FIG 3 left). The radius *r* defines a uniform protection area in both horizontal and vertical dimensions. The conditions for a conflict are [10]:

$$(1)\quad \left(\frac{x_2-x_1}{r}\right)^2 + \left(\frac{y_2-y_1}{r}\right)^2 + \left(\frac{z_2-z_1}{r}\right)^2 \le 1$$

Cylindrical Protection Area: This model takes a cylindrical shape with a defined radius and height (Fig 3 centre). Horizontal separation is defined by the circular radius *r* and vertical separation by the height *h*. The mathematical prerequisites for a conflict between two aircraft are as follows [10]:

$$(2)\quad (x_2 - x_1)^2 + (y_2 - y_1)^2 \le r^2 and -\frac{h}{2} \le z - z_0 \le \frac{h}{2}$$

Ellipsoidal Protection Area: The ellipsoidal model allows for varying separation distances in two horizontal and the vertical dimensions (FIG 3 right). The semi-major axis *a* reflects horizontal separation in the x-direction, while the semi-minor axis *b* accounts for horizontal separation in the y-direction, and the vertical separation is represented by the semi-minor axis *c*. The ellipsoidal protection area is calculated using the following equation [10]:

$$(3)\quad \left(\frac{x_2-x_1}{a}\right)^2 + \left(\frac{y_2-y_1}{b}\right)^2 + \left(\frac{z_2-z_1}{c}\right)^2 \le 1$$

The spherical model has significant limitations for ATM. Because the radius is the same in all directions, it overestimates the required vertical separation, which is typically much smaller than horizontal separation in practical scenarios. While both cylindrical and ellipsoidal models can meet this requirement, the ellipsoidal model offers a distinct advantage. By modifying the horizontal *a*, lateral *b*, and vertical *c* axes independently, the ellipsoidal model provides greater flexibility compared to cylindrical models, which are limited to adjusting only two parameters (*r* and *h*). This additional degree of freedom makes it more effective in reflecting actual air traffic conditions, especially when factors like wind are considered, that don't impact the horizontal uncertainty of each axis to the same degree.

3.2. Conflict Detection through Ellipsoid Overlap

The intersection of ellipsoids representing aircraft protection areas signifies a potential conflict. Instead of using point-based detection, which only measures the distance between the exact predicted positions of the aircraft, the ellipsoid method provides a more comprehensive approach by considering uncertainties in multiple dimensions. This allows for a buffer zone where any overlap signifies that there is a risk, even if the aircraft positions do not perfectly align. In FIG 4, we see two ellipsoids, representing the protection areas of two aircraft, overlapping. The resulting boundary encompasses the entirety of both ellipsoids, not just the overlapping region. This reflects the system's strategy of accommodating the entire protection zones of both aircraft when determining the area of potential conflict, rather than focusing solely on the exact intersection.

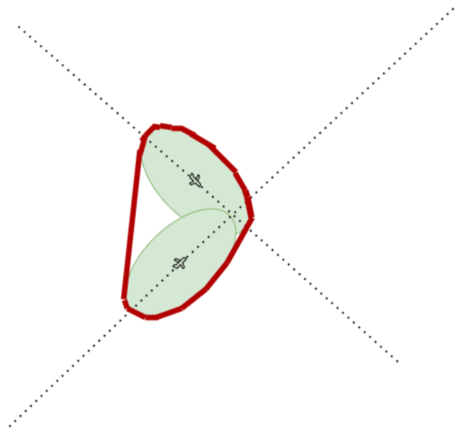

FIG 4. Conceptual conflict zone created by the intersection of two ellipsoidal protection areas. A convex hull of the two ellipsoids is marked in red

The ellipsoids are calculated at each waypoint of the trajectory to perform the conflict detection. It is important to interpolate between waypoints to ensure that the system can identify potential conflicts that may otherwise be overlooked. By producing supplementary waypoints, the method enhances the resolution of the flight route. Given that the horizontal radius of the ellipsoidal model is 2.5 NM (based on ICAO's 5 NM separation standard), additional waypoints with a distance of 1 NM in between ensure sufficient granularity for conflict detection while keeping computations manageable. In FIG 5, aircraft A and aircraft B are represented with their respective trajectories, where the black solid circles indicate the main waypoints for each flight.

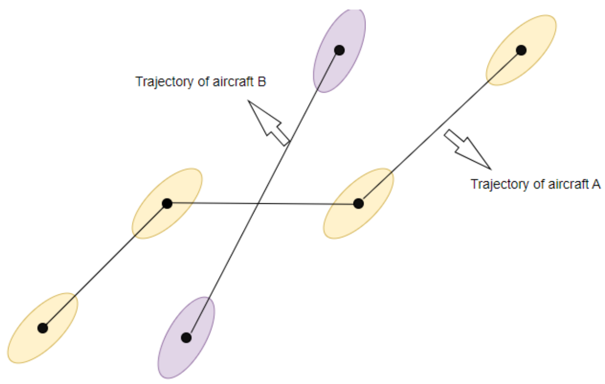

FIG 5. Ellipsoidal conflict detection based on main waypoints only

However, we can see that a conflict check based only on the ellipsoids surrounding these main waypoints, would not detect a conflict between the trajectories. In FIG 6, the white circles indicate the interpolated waypoints added between the primary waypoints. By evaluating the overlap of ellipsoids at both the main and interpolated waypoints, the conflict detection system can successfully identify a conflict at one of the interpolated waypoints, as shown by the overlapping ellipsoids. Linear interpolation can be used to compute intermediate points between established positions [29].

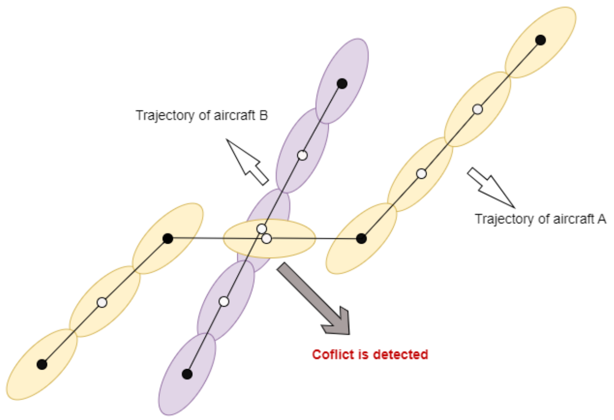

FIG 6. Ellipsoidal conflict detection with interpolated waypoints

To ensure that the correct aircraft heading is considered at each waypoint, a rotation matrix can be used to adjust the ellipsoidal protection zones accordingly. Therefore, a three-dimensional rotation matrix, particularly around the z-axis (representing heading changes), can be used. For heading angle β, the matrix $R_z(\beta)$ is defined as:

$$(4)\quad R_z(\beta) = \begin{bmatrix} \cos(\beta) & -\sin(\beta) & 0 \\ \sin(\beta) & \cos(\beta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

This matrix rotates vectors, allowing the ellipsoid to align with the aircraft's direction of travel. To calculate the heading at each waypoint, including both main and interpolated points, the heading β_p between two following geographical coordinates (latitude lat_1, longitude lon_1) and (latitude lat_2, longitude lon_2) is calculated using the formula:

$$(5)\quad \beta_p = \arctan\left(\frac{\sin(\Delta lon)\times\cos(lat_2)}{\cos(lat_1)\times\sin(lat_2)-\sin(lat_1)\times\cos(lat_2)\times\cos(\Delta lon)}\right)$$

Where $\Delta lon = lon_2 - lon_1$ is the longitudinal difference between the two points.

3.3. Stochastic Modelling

Uncertainties such as variable wind velocities, fluctuating aircraft speeds, and delays in reaction to ATCO commands impact the accuracy of trajectory forecasts and conflict detection. These uncertainties make deterministic models insufficient for capturing complex real-world flight dynamics. Stochastic models address this limitation by incorporating uncertainty into the conflict detection algorithm, providing a probabilistic framework that better reflects the unpredictability of flight operations [7]. By simulating random variations in environmental factors and flight parameters, stochastic modelling allows the system to consider multiple possible outcomes rather than relying on a single, fixed prediction. This broader scope leads to a more comprehensive assessment of conflict risks. In our conflict detection algorithm, stochastic modelling is implemented through Monte Carlo simulation, which estimates the probability of conflicts by running multiple simulations with varying initial conditions.

The selected core uncertainty factors modelled in the algorithm are wind conditions (speed and direction), aircraft speed, and pilot reaction delays to heading, altitude, and speed adjustments. They are chosen due to their significant impact on conflict prediction accuracy, as highlighted in existing research. These selected features cover all three uncertainty categories defined by the FAA [16]. By accounting for these uncertainties in the conflict detection algorithm, the system achieves a more robust and realistic representation of operational conditions, thereby enhancing its reliability for medium-term conflict detection.

3.3.1. Monte Carlo Simulation

The Monte Carlo simulation [7] [10] [11] [13] is a method utilized in the conflict detection algorithm to model the uncertainties in flight dynamics. This method tries to delineate the unpredictability in an aircraft's behaviour and environment by running multiple simulations to assess the probability of conflicts between aircraft paths under varying conditions. The stochastic models for uncertainties in wind, aircraft speed, and reaction delays, as detailed in Section 3.3, are introduced in each simulation of the Monte Carlo process to account for real world variability. These stochastic variations modify the ellipsoid parameters that define the aircraft's protection zone. The algorithm then checks if the ellipsoids of two aircraft intersect in both space and time, indicating a potential conflict. The ratio of simulations that result in a detected conflict to the total number of simulations undertaken determines the probability P_c of conflict after all simulations are complete. We can mathematically express this probability as follows:

$$(6)\quad P_c = \frac{Number\ of\ Simulations\ with\ Conflict}{Total\ Number\ of\ Simulations}$$

This probability-driven assessment of conflict risks enables the system to categorize potential conflicts into high-risk (red), moderate-risk (orange), and low-risk (green) categories.

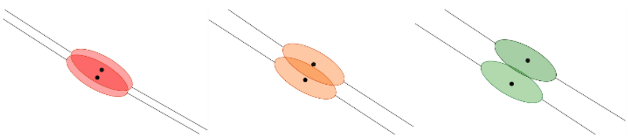

FIG 7. Probability of conflict, i.e. left (red) high probability of conflict, centre (orange) medium probability of conflict, and right (green) low probability of conflict

If the conflict probability P_c between the ellipsoidal protection zones of two aircraft at different waypoints exceeds 90% after all simulations, the conflict is classified as high risk, and the associated ellipsoids are displayed in red (FIG 7 left). If the probability falls between 40% and 90%, the conflict is classified as moderate risk, and the ellipsoids are displayed in orange (FIG 7 centre). If the probability is below 40%, the conflict is classified as low risk, and the ellipsoids are displayed in green (FIG 7 right). The thresholds of 90% and 40% are chosen to define conflict severity based on a balance between sensitivity and interpretability, ensuring that high-risk conflicts are identified with sufficient confidence while maintaining practical usability. These values are assumed for the purposes of this work and can be adjusted depending on operational requirements. The colours red, orange, and green are used for visual convenience to represent high, moderate, and low risks, respectively.

3.3.2. Wind Modelling

The wind conditions are modelled using the Ornstein-Uhlenbeck process, which is widely used to simulate mean-reverting stochastic behaviours [30]. This process is ideal for modelling wind because it allows the wind speed and direction to fluctuate randomly around a predefined mean while gradually reverting back to that mean over time. Mathematically, the Ornstein-Uhlenbeck process is defined by the stochastic differential equation:

$$(7)\quad dX_t = \theta(\mu - X_t)dt + \sigma\, dW_t$$

Where:

- X_t is the variable being modeled (wind speed or direction),
- θ is the rate at which the wind reverts to its mean (μ),
- σ represents the volatility or intensity of random fluctuations,
- dW_t is the Wiener process (representing the randomness introduced into the model).

In this algorithm, the current wind conditions are used as the starting point for each simulation. The wind model evolves over discrete time steps, with each step influenced by two main components: the mean-reversion term and the random fluctuation term. The mean-reversion component pulls the wind speed and direction back towards their mean values at a rate governed by θ, which dictates how quickly the values revert to their average state. The formula for this adjustment is:

$$(8)\quad \theta \times (\mu - X_t) \times dt$$

where μ is the mean value, X_t is the current wind condition, and dt is the time increment. This mechanism ensures that deviations from the mean are corrected over time, preventing the wind values from drifting too far from realistic conditions. On the other hand, the random fluctuation component introduces variability into the model. This is done by sampling random noise from a normal distribution. This term, represented by:

$$(9)\quad \sigma \times random\ noise$$

This reflects the natural, unpredictable variations in wind speed and direction. Together, these two components are used to update the wind values at each time step, following the equation:

$$(10)\quad X_{t+1} = X_t + \theta \times (\mu - X_t) \times dt + \sigma \times random\ noise$$

This approach captures both the predictable (mean-reverting) and unpredictable (random) elements of wind behaviour. The stochastic nature of the model ensures that wind conditions evolve in a realistic and dynamic way, with variability introduced at each time step while still maintaining a tendency to revert to realistic average conditions. By incorporating these stochastic elements, the wind model becomes a robust and flexible tool for simulating environmental conditions in the conflict detection algorithm. Each Monte Carlo simulation reflects a different possible wind scenario, allowing the system to assess conflict risks more comprehensively.

3.3.3. Aircraft Speed Modelling

In this conflict detection algorithm, speed variability is modelled stochastically, ensuring that each Monte Carlo simulation accounts for deviations in aircraft speed. While each aircraft has an optimal cruising speed, real-world conditions such as turbulence, headwinds, and tailwinds cause deviations from this ideal speed. To model this variability, the algorithm introduces speed variations using a random factor that simulates different possible speed conditions during the aircraft's flight. In this algorithm, instead of relying on a single variation range, each simulation accounts for three ranges of speed variation. Specifically, the algorithm first checks the scenario where the speed varies within a range of ±5% of the optimal speed, which refers to the forecasted cruising speed derived from BADA data [31], representing the baseline speed under nominal operating conditions. Next, it checks for variations within ±10%. Lastly, it considers more significant deviations of ±15% from the optimal speed.

Each Monte Carlo simulation run incorporates all three variation ranges. This ensures that the conflict detection algorithm thoroughly examines the possible speed deviations and their impact on the aircraft's trajectory,

3.3.4. Pilot Reaction Delay Modelling

In addition to environmental uncertainties, the algorithm models reaction delays in response to flight control commands. For instance, when an aircraft receives a command to change heading, altitude, or speed, there is a delay before the aircraft actually executes the command. These delays are influenced by factors such as pilot response time and system lag and are modelled as random variables drawn from a normal distribution.

Empirical studies and real-world observations have provided the basis for defining the mean and standard deviation of reaction delays used in this work [17]. These values, presented in TAB 3.1, are based on observed response times across various flight control commands, such as changes in altitude, heading, and speed. A control command refers to a directive issued by an ATCO to the cockpit crew (e.g., verbally). The reaction time is measured starting from when the command is issued, continuing until the cockpit crew reacts, and ending when radar data confirms that the aircraft's behaviour (e.g., altitude, heading, or speed) has changed accordingly.

TAB 3.1. Mean and standard deviation of reaction delays for aircraft control commands.

Control Command	Mean Delay (s)	Standard Deviation (s)
Altitude	17	4
Heading	17	4
Speed	25	4

3.3.5. ETO Ranges and Temporal Overlap

The ellipsoidal model is used to introduce uncertainties to the spatial domain. To also introduce uncertainties to the time domain, Estimated Time of Overflight (ETO) ranges are used instead of single ETO values at each point of the trajectory. This applies not only to predefined main waypoints but also to the interpolated waypoints generated during the simulation. The ETO range essentially represents a time window during which an aircraft is expected to cross a particular waypoint. The algorithm calculates the travel time between waypoints based on the speed selected in the Monte Carlo Simulation. For each simulation, the time to travel between two waypoints is derived from the minimum and maximum speeds observed. By introducing three variations in aircraft speed (±5%, ±10%, and ±15% from the optimal speed), three distinct ETO ranges are generated.

Temporal overlap occurs when two aircraft are expected to arrive at a waypoint within overlapping time windows, signalling a potential temporal conflict. Only if a temporal overlap is detected for any of the three speed variations does the algorithm proceed to the next step of checking for spatial overlap. By conducting the temporal overlap check first, the algorithm avoids unnecessary spatial overlap calculations for waypoints with no potential for conflict, significantly improving computational efficiency.

3.4. Dynamic Adjustment of Ellipsoids

This section explains how the factors such as the uncertainties introduced in the previous section impact the ellipsoidal models. Dynamic adjustments allow the conflict detection system to reflect changing flight conditions and risks accurately. During stable cruising, ellipsoid dimensions remain constant, but external influences necessitate updates to better represent predicted trajectories and ensure effective conflict detection.

3.4.1. Influence of Wake Turbulence on Ellipsoidal Dimensions

Wake turbulence generated by an aircraft significantly impacts the safety margins for nearby aircraft [32]. It primarily affects other aircraft flying within a few nautical miles to the generating aircraft, necessitating adjustments to the protection ellipsoids to ensure adequate separation and reduce the risk of conflicts. For light and medium aircraft, wake turbulence effects are smaller than the chosen 5 nautical mile standard separation, while heavy aircraft produce substantial wake turbulence requiring increased safety buffers to smaller aircraft. EUROCONTROL specifies safe separation between “Upper Heavy” and “Light” aircraft of 7 nautical miles [32]. Therefore, all axes *a, b, c* of the ellipsoid are increased by a factor of 1.5 to account for stronger wake turbulence for heavy aircraft. While the model simplifies these effects, it remains a practical approximation for conflict detection calculations.

3.4.2. Influence of Wind on Ellipsoid Shape

Effect on the Semi-Major Axis *a*: When the wind blows at an oblique angle, it introduces a forward (or backward) component along the aircraft’s trajectory. This component affects the longitudinal *a* axis, elongating the ellipsoid in the forward direction. The degree of elongation depends on the angle and strength of the wind.

Effect on the Lateral Axis *b*: The lateral component of an oblique wind affects the lateral *b* axis, causing the ellipsoid to expand laterally to account for potential drift.

Effect on the Vertical Axis *c*: Even with an oblique wind, the vertical axis *c* remains largely unaffected unless vertical turbulence is present, which is typically negligible in these models. Thus, no significant adjustments are made along the vertical axis.

3.4.3. Influence of Reaction Delays on Ellipsoid Shape

When a pilot or system responds to an ATCO command, the ellipsoid dynamically modifies to represent the uncertainty in the aircraft’s future position resulting from these manoeuvres. These modifications guarantee that the conflict detection system accommodates potential delays and changes in aircraft movement. The impact on the ellipsoid transpires as outlined below:

Heading Change: Changes in heading affect both the width (*b* axis) and length (*a* axis) of the ellipsoid. This adjustment compensates for lateral drift and forward trajectory deviations, reflecting greater uncertainty in both lateral and forward directions.

Speed Change: Increases the longitudinal axis of the ellipsoid, represented by the *a* axis. A variation in speed alters the aircraft’s rate of ground coverage, thereby extending the ellipsoid’s forward projection to account for the increased uncertainty in its future position.

Altitude Change: Increases the vertical axis of the ellipsoid, represented by the *c* axis. A variation in altitude extends the ellipsoid’s vertical projection, capturing the increased uncertainty in the aircraft’s altitude position over its future trajectory.

4. GRAPHICAL USER INTERFACE

This work introduces a GUI for conflict detection, aimed at offering a user-friendly tool for ATCOs to visualise potential conflicts between two aircraft. The primary aim of this interface is to properly visualise the conflict probability zones and allow ATCOs to make an informed decision on how to handle the conflict.

4.1. Convex Hull Algorithm

To visualise the conflict zones that were determined using ellipsoids, a Convex Hull algorithm [33] can be used. It constructs a boundary around ellipsoidal zones grouped according to conflict probability categories. Instead of drawing individual boundaries for each conflicting ellipsoid, a single convex boundary is generated for each risk category, which results in a cleaner and more efficient representation. The algorithm works by creating the smallest convex polygon that encompasses all relevant ellipsoids within a category, effectively reducing visual clutter. This approach is particularly useful when many conflict zones overlap, creating complex geometric shapes due to the large number of factors that are considered in their calculation. These zones are influenced by factors like speed variation, wind, and reaction delays as discussed in previous chapters. Furthermore, Graham's Scan [33] is efficient and ensures computational scalability, making it suitable for real-time applications where conflict zones need to be dynamically generated for multiple aircraft simultaneously. It operates with a worst case runtime complexity of O(n log n) [33].

4.2. Horizontal Conflict View

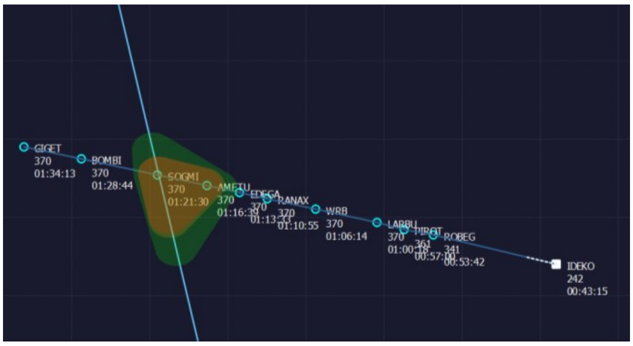

FIG 8. Area based horizontal conflict view

The horizontal conflict view (FIG 8) developed in this work introduces a visualisation tool specifically designed for enhanced, probability-based conflict detection. It has many similarities to the classical conflict view (FIG 1), for example the display of trajectories, trajectory waypoints and flight markers. But unlike traditional displays, which often highlight only the immediate conflict points along the aircraft trajectories, this tool provides a view of entire conflict zones that were calculated with the convex hull algorithm in geographic space. This feature provides ATCOs witch additional information to find the most efficient solution to conflicts. Conflict zones are clearly marked with colour-coded overlays to represent risk levels. This visual scheme enables ATCOs to quickly assess the likelihood and severity of potential conflicts, allowing them to decide on a case-to-case basis whether an early avoidance of the conflict zone is necessary or whether they prefer to wait and observe how the conflict zones develop over time.

4.3. Vertical Conflict View

The vertical conflict view (FIG 9) is designed to visually represent potential conflicts between aircraft on the height profile of the aircraft trajectories over time. Effectively capturing the third and fourth dimensions (altitude on the y-axis and time on the x-axis) necessary for comprehensive 4D conflict detection. It can be opened on demand in a separate window.

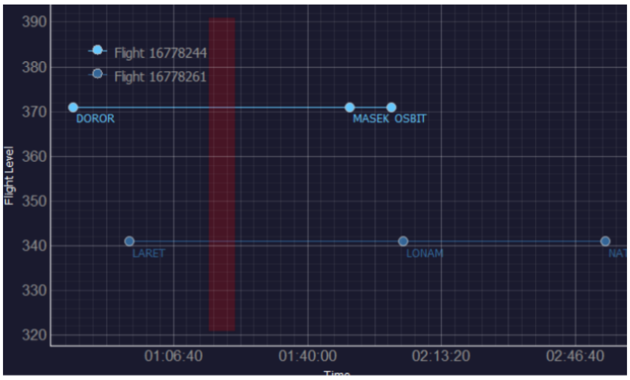

FIG 9. Vertical conflict view

FIG 10 shows how the vertical conflict view complements the horizontal conflict view, which displays only the spatial dimensions (latitude and longitude). In this view, ATCOs can monitor conflicts based on ETO at specific altitudes. Conflicts are highlighted with a single protection zone, displayed as a red bar in the vertical view. Unlike the horizontal conflict view, which distinguishes between high, medium, and low-risk zones using different colour-coded overlays, the vertical graph simplifies the representation by consolidating all potential conflicts into a single "protection zone".

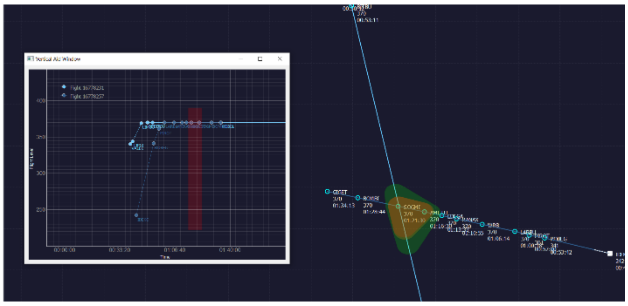

FIG 10. The horizontal conflict view and the vertical conflict view in a separate window

5. EVALUATION

The main objective for the assessment of the conflict detection algorithm and its GUI was to evaluate the functionality and user-friendliness. This section outlines the evaluation process and explains the findings derived from both quantitative and qualitative data.

5.1. Evaluation Methodology

The assessment included a total of ten participants, out of whom eight were ATM scientists and two were master students from DLR. While the DLR scientists provided valuable technical and theoretical insights, it is worth noting that two of them have ATCO qualifications, and one is still an ATCO. The evaluation was conducted by structured questionnaires and observational techniques, with a specific emphasis on three aspects:

- **Conceptual Soundness:** Assessing the comprehensive design of the conflict detection system, including its integration of wind data, pilot responses,

and speed uncertainties in the context of conflict identification. Furthermore, participants offered recommendations for further uncertainty that should be taken into account.
- **Computational Performance:** Assessing the tool's calculations and effectiveness of its computing procedures. Recommendations were collected regarding possible opportunities for enhancing computational efficiency and resource utilisation.
- **User Interface:** Assessing the design and usability of the GUI, focussing on the lucidity of visual depictions, the efficiency of maps, and the operational capabilities of interactive components such as window switching and conflict severity indicators differentiated by colour.

Each session began with a brief presentation introducing the tool, its objectives, and the underlying algorithms, followed by a demonstration of its key functionalities, including conflict detection capabilities and the graphical user interface. Participants were then guided through example scenarios illustrating potential conflicts, allowing them to interact with the tool and explore its features in detail. During this phase, participants were encouraged to ask questions and discuss their observations.

The tool was evaluated through individual sessions with participants. The participants were asked to rate 13 statements using a Likert scale ranging from 1 (very poor) to 10 (excellent). They also answered open-ended questions to gather detailed feedback on strengths and areas requiring improvement. Each session lasted approximately 30 to 45 minutes, allowing sufficient time for exploration, interaction, and thoughtful feedback.

5.2. Evaluation Results

The following part provides an overview of the main conclusions derived from the assessment. The results incorporate both numerical evaluations with graphical representations and qualitative comments. The average rating scores of the ten participants are visualized as blue bars for each statement with the standard deviation indicated by vertical black lines for each blue bar in the three bar diagrams of the following subsections.

5.2.1. Conceptual Soundness

The participants had to rate six different statements regarding conceptual soundness. The following list provides the abbreviated statement name and the full statement category:

- [Cncpt] General Concept of Conflict Detection Tool
- [FrqUs] Practical Application Frequency of Tool in Decision-Making
- [WindI] Wind Data Inclusion
- [Pilot] Pilot Reactions Modelling
- [AcftS] Aircraft Speed Uncertainties

The average ratings on the conceptual soundness statements are shown in FIG 11.

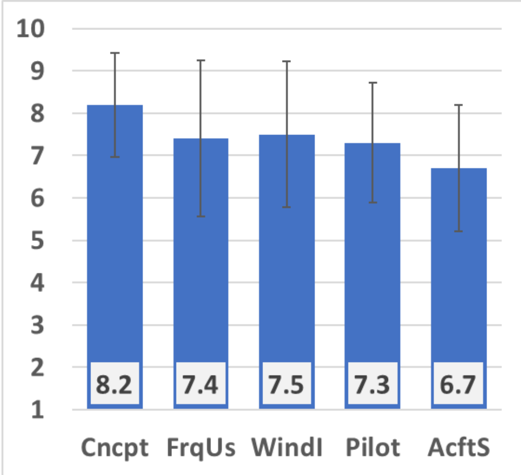

FIG 11. Participants' average ratings for five concept statements

In response to the *Cncpt* question on the overall concept of the conflict detection tool, the majority of participants expressed a high appraisal of the tool, with 80% assigning scores of 8 or higher—specifically, 50% rated it 8, and 20% rated it a perfect 10. This indicates a strong level of confidence in the tool's design. The absence of ratings below 6 confirms the basic acceptance of the tool's underlying design. The *FrqUs* question asked participants to indicate how frequently they would use the tool in their decision-making process. Most of the responses were favourable, with 60% assigning it a rating of 8 or higher.

The integration of three data types into the concept were investigated as follows: how effectively wind data was used [*WindI*], how pilot responses were represented [*Pilot*], and how aircraft speed uncertainty was handled [*AcftS*]. The incorporation of wind data was regarded well by the majority of participants. 90% of participants rated with 7 or higher. The pilot response representation received a wider range of evaluations. All ratings were 6 or higher, however, only 40% of participants assigned a rating of 8 or higher. The assessment of aircraft speed uncertainty received favourable responses with 70% of ratings being 7 or higher suggesting a positive view of the integration of speed uncertainty into the conflict detection capabilities of the tool. However, three ratings were in the range of 4 to 5.

Participants offered a variety of insightful recommendations in answer to the open-ended inquiry about possible supplementary uncertainty that may be included into the conflict detection algorithm. A crucial suggestion was to incorporate descent/climb rates, especially during changes in altitude, as these fluctuations might produce substantial vertical displacement that may not be completely accounted for by the existing model. Another proposal included incorporating vertical wind speed, which impacts aircraft performance during both climb and descent and may lead to conflicts, particularly in turbulent weather situations.

A number of contributors emphasized the significance of considering pilot execution delay or agility, which refers to the duration it takes for a pilot to identify and react to a conflict alert. The influence of human factors can have a substantial effect on the result of a possible conflict situation. In addition, velocity fluctuations resulting from variations in flight level were observed, as the speed of an aircraft can differ based on its altitude, which might impact the precision of conflict predictions. Participants also emphasized the need of taking into account the likelihood of not making a turn at the next waypoint. Within intricate air traffic situations, deviations from predetermined waypoints can result in unforeseen conflicts. Considering this unpredictability would enhance the resilience of the tool. Ultimately, several participants highlighted the need to incorporate uncertainty associated with the unique manoeuvring features of the aircraft types and crisis situations, which may involve emergencies. Adverse events can lead to sudden deviations in the path of an aircraft, while different types of aircraft display distinct performance attributes, such as differing turn radii or response times, which should be considered in conflict detection.

5.2.2. Computational Performance

The participants had to rate two statements regarding computational performance of the conflict detection algorithm. The following list provides the abbreviated statement name and the full statement category:

- [RlCal] Realism of Calculation Results
- [SRCal] Speed and Responsiveness of Calculations

The average ratings on the computational performance statements are shown in FIG 12.

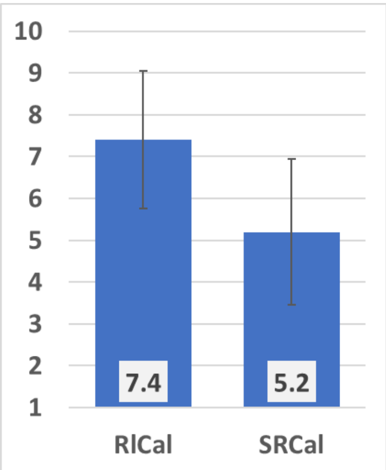

FIG 12. Participants' average ratings for two computation statements

80% of participants expressed a high level of confidence in the results, with assigning a score of 7 or higher. Since the algorithm's precision was assessed through visual representations rather than direct measurement, this feedback likely reflects users' trust in the tool's general accuracy rather than a confirmed evaluation of its precision. However, two ratings marked a score of 6 and 4, respectively.

Participants were also instructed to assess the speed and responsiveness of the tool's computations, therefore determining the effectiveness with which the system handles conflict detection tasks. The feedback encompasses a wide variety of experiences. While 60% of participants assessed the tool's responsiveness as low, assigning it ratings ranging from 3 to 5, the rest of participants expressed more positive evaluations of 6 to 8, suggesting a moderate to high level of satisfaction with the tool's computational efficiency. The lack of ratings above 8 indicates that although the tool functions satisfactorily, there are yet possibilities for enhancing its calculating speed and responsiveness.

The respondents were requested to share their opinions on whether the system displayed excessive processing time or resource use and to propose potential enhancements. Numerous comments emphasized the necessity of improving the efficiency of computations. In order to enhance the overall speed of the system, one participant suggested optimizing the map rendering process by generating the map immediately after the computations were finished, rather than during processing. Another persistent issue was the sluggish execution of the Monte Carlo simulations, which are essential for the conflict detection capability of the instrument. Notably, the conflict zones exhibited a latency of over 10 seconds in updating, therefore impeding users' ability to make prompt decisions. This delay was perceived as a significant issue that impeded the operational effectiveness of the tool. Furthermore, a participant suggested the optimization of the conflict detection process by pre-calculating 4D flight trajectories using waypoints from flight plans. This strategy would mainly tackle time constraints that arise when directions or altitudes are altered within brief time periods. One further proposal for enhancing processing speed entailed the possible implementation of multiprocessing to optimize job execution.

5.2.3. User Interface

The participants had to rate six statements regarding the user interface for conflict visualization to evaluate the intuitiveness of the design, the navigability, and the level to which the interface facilitates real-time situational awareness. The following list provides the abbreviated statement name and the full statement category:

- [SatUI] Satisfaction with User Interface Design and Layout
- [EfMap] Effectiveness of Maps in Conveying Conflict Detection Information
- [HoriD] Horizontal Display
- [VertD] Vertical Display
- [ExWin] Clarity in Managing Extra Windows within User Interface
- [Color] Colour-Coding in Indicating Conflict Severity

The average ratings on the user interface statements are shown in FIG 13. For the *SatUI* statement all participants rated with a score of 7 or higher indicating a general satisfaction with the interface. Several participants offered comments to further improve the interface even if many of them are outside the immediate focus of this thesis and will be discussed in Section 6 on future work.

The *EfMap* statement received the highest score of all 13 statements with 8.9 with all scores being 8 or higher. This indicates a high degree of confidence in the clarity and usefulness of the visual map representations.

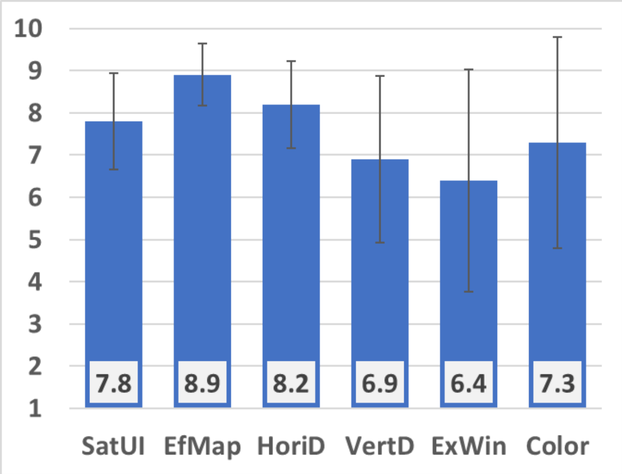

FIG 13. Participants' average ratings for six user Interface statements

During the evaluation of the clarity and informativeness of both horizontal and vertical visual representations of conflicts in the tool, participants offered comments that emphasized the positive aspects and possible areas for enhancement of the user interface. The horizontal conflict visualizations [*HoriD*] were generally well-received, with 80% of the participants giving it a rating of 8 or higher.

On the other hand, the vertical conflict visualizations [*VertD*] achieved a more diverse range of responses. Although 50% of the participants assessed the vertical display with a rating of 8 or higher, the other 50% of participants scored it at 6 or below. This suggest that while some individuals value the vertical visualizations, there is potential for boosting their clarity and informativeness.

The statement regarding the clarity of showing and hiding extra windows [*ExWin*] received a very mixed distribution of responses with a noticeable spread of ratings across the lower end of the scale. The majority of participants rated this feature between 4 and 7, indicating that there might be some confusion or difficulty in managing extra windows within the tool. One participant even rated the feature as 2, suggesting a significant need for improvement in this area.

When evaluating the effectiveness of colour coding [*Color*] (green, orange, red) in indicating the probability of conflicts, the majority of participants gave a positive response. Specifically, 60% of the participants gave a score of 8 or higher. Yet, there was also invaluable constructive criticism, notably on the green area. According to several participants, the colour green, commonly linked to "safe" areas, may be deceptive when used to the assessment of conflict likelihood. Consequently, the lower ratings were evident, as 30% of participants assigned a rating of 3 to 5 to the colour coding, so suggesting a certain level of ambiguity over the significance of the green colour within this particular setting. However, the general idea of utilising clearly defined colours to indicate different degrees of conflict likelihood was still considered a lucid and efficient strategy. Feedback indicates that making slight modifications in colour selection could improve the clarity of the tool and minimize any possible misunderstandings.

6. CONCLUSION AND FUTURE WORK

We proposed an approach for medium-term conflict detection (MTCD) considering uncertainties in different input parameters and a dynamic four-dimensional visualization of its output in air traffic controller (ATCO) displays. A core part of this work is the probabilistic MTCD algorithm, which incorporates Monte Carlo simulations to model uncertainties, such as wind variability, speed variations of aircraft, and pilot response delays. By utilizing Graham's algorithm, the algorithm dynamically generates convex polygons of conflict zones.

An evaluation with ten participants from the air traffic management (ATM) domain was conducted. The evaluation results show confidence with conceptual soundness, the horizontal conflict view, and the maps with rating scores of 8 and beyond on a 10-point scale with high scores in favour.

Qualitative feedback of participants encouraged for further advancements such as a graphical interface that provides the ATCO with conflict-free zones, safe altitudes, and alternative trajectories. Numerical conflict probabilities could be integrated alongside colour-coded representations to support the assessment of conflicts. The MTCD algorithm could be enhanced by integrating additional uncertainty factors, such as descend and climb rates during flight level changes, vertical wind variability, pilot response delays, speed adjustments during transitions, and the likelihood of deviations at waypoints.

The evaluation results demonstrate the system's potential to improve situational awareness, enhance decision-making processes, and ultimately contribute to safer and more efficient operations if integrated in future ATM systems.

7. REFERENCES

[1] EUROCONTRONTOL, "Traffic Forecast," 2025.

[2] IFATCA, "ATCO SHORTAGE: The Perfect Storm," 2025. [Online]. Available: https://ifatca.org/article/atco-shortage-the-perfect-storm/. [Accessed 08 09 2025].

[3] J. Tang, "Conflict Detection and Resolution for Civil Aviation: A Literature Survey," *IEEE Aerospace and Electronic Systems Magazine,* vol. 34, pp. 20 - 35, 2019.

[4] EUROCONTROL, "EUROCONTROL Specification for Medium-Term Conflict Detection (MTCD). Tech. rep. Version 2.0.," 2017.

[5] R. A. Paielli, H. Erzberger, D. Chiu and K. R. Heere, "Tactical Conflict Alerting Aid for Air Traffic Controllers," *Journal of Guidance, Control, and Dynamics,* vol. 23.1, pp. 92-99, 2009.

[6] J. A. Pérez-Castán, Á. Rodríguez-Sanz, L. Pérez Sanz, R. M. Arnaldo Valdés, V. F. Gómez Comendador, C. Greatti and L. Serrano-Mira, "Probabilistic strategic conflict-management for 4D trajectories in free-route airspace," *Entropy,* vol. 22, 2020.

[7] D. T. Pham, Y. Guleria, S. Alam and V. Duong, “Probabilistic conflict detection using heteroscedastic gaussian process and bayesian optimization.,” *IEEE Access,* vol. 11, 2023.

[8] R. D. A. Jurado, V. F. G. Comendador, M. Z. Suárez, F. P. Moreno, C. E. V. Gallego and R. M. A. Valdés, “Most influential factors in the detection of potential conflicts between en-route aircraft by ATCO,” *Journal of Physics: Conference Series,* vol. 2526, 2023.

[9] A. Warren, “Medium term conflict detection for free routing: Operational concepts and requirements analysis,” *16th DASC. AIAA/IEEE Digital Avionics Systems Conference. Reflections to the Future. Proceedings ,* 1997.

[10] Z. Hu, X. Gan, Y. Wu and F. Liu, “Research on Conflict Detection in Terminal Area based on Monte Carlo Method,” *2022 IEEE International Conference on Advances in Electrical Engineering and Computer Applications (AEECA),* pp. 455-459, 2022.

[11] A. L. Visintini, W. Glover, J. Lygeros and J. Maciejowski, “Monte Carlo optimization for conflict resolution in air traffic control,” *IEEE Transactions on Intelligent Transportation Systems,* vol. 7, pp. 470-482, 2006.

[12] R. P. Patera, “Space vehicle conflict probability for ellipsoidal conflict volumes,” *Journal of guidance, control, and dynamics,* vol. 30, pp. 1819-1822, 2007.

[13] M. Prandini, J. Hu, J. Lygeros and S. Sastry, “A probabilistic approach to aircraft conflict detection,” *IEEE Transactions on intelligent transportation systems,,* pp. 199-220, 2002.

[14] X. Li and F. Gong, “Improved Prandini Conflict Detection Algorithm Based on Trajectory Prediction,” SAE Technical Paper., 2023.

[15] I. Hwang and C. E. Seah, “Intent-based probabilistic conflict detection for the next generation air transportation system,” *Proceedings of the IEEE,* vol. 96, pp. 2040-2059, 2009.

[16] Federal Aviation Administration (FAA), “Pilot’s Handbook of Aeronautical Knowledge, FAA-H-8083-25C,” 2023. [Online]. Available: https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/faa-h-8083-25c.pdf. [Accessed 02 09 2025].

[17] M. Lutz, G. B. Chatterji and H. R. Idris, “Characterization of response times based on voice communication and traffic surveillance data,” *AIAA AVIATION 2022 Forum,* p. 3762, 2022.

[18] N. Wüstenbecker, J. Renkhoff, D. Zeppenfeld, M. Jameel and S. Schier-Morgenthal, “Analysis and prediction of pilot response time to air traffic control clearances,” *CEAS Aeronautical Journal,* 2025.

[19] P. Zhao, H. Erzberger and Y. Liu, “Multiple-aircraft-conflict resolution under uncertainties,” *Journal of Guidance, Control, and Dynamics,* vol. 44, pp. 2031-2049, 2021.

[20] A. Dudoit, V. Rimša and M. Bogdevičius, “Investigation of Aircraft Conflict Resolution Trajectories under Uncertainties,” *Sensors,* vol. 24, 2024.

[21] M. M. Temme and C. Tienes, “Factors for Pilot's Decision Making Process to Avoid Severe Weather during Enroute and Approach,” *IEEE/AIAA 37th Digital Avionics Systems Conference (DASC),* pp. 1-10, 2018.

[22] S. Mejdal, M. E. McCauley and D. B. Beringer, “Human factors design guidelines for multifunction displays (No. DOTFAAAM0117)”.

[23] G. Rottermanner, V. A. de Jesus Oliveira, P. Lechner, P. Graf, M. Kreiger, M. Wagner and P. Judmaier, “Design and evaluation of a tool to support air traffic control with 2D and 3D visualizations,” *IEEE conference on virtual reality and 3D user interfaces (VR),* pp. 885-892, 2020.

[24] S. Huber, J. Gramlich, S. Pauli, S. Mundschenk, E. Haugg and T. Grundgeiger, “Toward user experience in ATC: exploring novel interface concepts for air traffic control,” *Interacting with Computers,* vol. 34, pp. 43-59, 2022.

[25] L. Nöhren, L. Tyburzy, M.-M. Temme, K. Muth, T. Hofmann, D. Heßler, F. Tenberg, E. Viet and M. Wimmer, “New Approaches for the Use of Extended Mock-Ups for the Development of Air Traffic Controller Working Positions,” *Aerospace,* vol. 12, 2025.

[26] Deutsches Zentrum für Luft- und Raumfahrt (DLR), “Envision Project,” 2024. [Online]. Available: https://www.dlr.de/en/fl/research-transfer/projects/envision. [Accessed 02 09 2025].

[27] International Civil Aviation Organization (ICAO), “AFI REDUCED VERTICAL SEPARATION MINIMUM (RVSM) SAFETY POLICY,” 04 2006. [Online]. Available: https://www.icao.int/sites/default/files/ESAF/Documents/RVSM/safety_policy.pdf. [Accessed 02 09 2025].

[28] International Civil Aviation Organization (ICAO), “Procedures for Air Navigation Services:Air Traffic Management (PANS-ATM), Fifteenth Edition (Doc 4444-ATM/501), Amendment No. 1.,” International Civil Aviation Organization (ICAO), Montral, Canada, 2012.

[29] D. Delahaye, S. Puechmorel, P. Tsiotras and E. Féron, “Mathematical models for aircraft trajectory design: A survey,” in *Air Traffic Management and Systems: Selected Papers of the 3rd ENRI International Workshop on ATM/CNS (EIWAC2013)*, Tokyo, Japan, 2014.

[30] R. A. Maller, G. Müller and A. Szimayer, “Ornstein–Uhlenbeck processes and extensions,” *Handbook of financial time series,* pp. 421-437, 2009.

[31] EUROCONTROL, “Base of aircraft data,” [Online]. Available: https://www.eurocontrol.int/model/bada. [Accessed 11 09 2025].

[32] EUROCONTROL, “RECAT-EU,” 2024. [Online]. Available: https://www.eurocontrol.int/archive_download/all/node/9681. [Accessed 02 09 2025].

[33] M. Golin and R. Sedgewick, “Analysis of a simple yet efficient convex hull algorithm,” *Proceedings of the fourth annual symposium on Computational geometry,* pp. 153-163, 1988.