Design of a Real Time Visual Analytics Support Tool for Conflict Detection and Resolution in Air Traffic Control

E. Zohrevandi, C. A. L. Westin, J. Lundberg and A. Ynnerman

Linköping University, Department of Science and Technology, Norrköping, Sweden

Abstract

Air traffic control is a safety critical high-risk environment where operators need to analyse and interpret traffic dynamics of spatio-temporal data in real-time. To support the air traffic controller in safely separating traffic, earlier research has applied real-time visualisation techniques that explore the constraints and solution spaces of separation problems. Traditionally, situation displays for conflict detection and resolution have used visualisations that convey information about the relative horizontal position between aircraft. Although vertical solutions for solving conflicts are common, and often a preferred among controllers, visualisations typically provide limited information about the vertical relationship between aircraft. This paper presents a design study of an interactive conflict detection and resolution support tool and explores techniques for real-time visualisation of spatio-temporal data. The design evolution has incorporated several activities, including an initial work domain analysis, iterative rounds of programming, design, and evaluations with a domain expert, and an evaluation with eight active controllers. The heading-time-altitude visualisation system is developed based on formulating and solving aircraft movements in a relative coordinate system. A polar-graph visualisation technique is used to construct a view of conflicting aircraft vertical solution spaces in the temporal domain. Using composite glyphs, the final heading-time-altitude visualisation provides a graphical representation of both horizontal and vertical solution spaces for the traffic situation.

CCS Concepts

• ***Human-centered computing*** → ***Visual analytics;*** *visualisation design and evaluation methods;* • ***Hardware*** → *Safety critical systems;*

1. Introduction

A core task in air traffic control (ATC) is conflict detection and resolution (CD&R). To ascertain safe separation, air traffic controllers (ATCos) exercise control to keep aircraft apart by at least 5nm (horizontal) or 1000ft (vertical). Currently ATCos are solving 4D CD&R problems on a 2D situation display, where aircraft horizontal position and travel direction is represented graphically on a sector chart (i.e. situation or radar display). Other critical information about the aircraft is provided numerically in a flight label window, including the flight plan, speed, and flight level (the altitude of an aircraft at standard air pressure). While the horizontal separation is straightforward to determine visually on current 2D displays, vertical separation requires that the ATCo reads the flight level information in the flight label and develop a mental model of the vertical relationship between aircraft. While this process is cognitively demanding, research has shown that ATCos often prefer vertical solutions especially for difficult-to-solve cases of conflicts (i.e. mixed of climbing and descending aircraft pair) [RN05].

The goal is to design a visual interactive tool that better supports ATCos' cognitive work in detecting and solving conflicts, especially in the vertical plane. This paper presents the underlying design evolution and development of a final tool known as the heading-time-altitude visualisation system (HTA-Viz). The contributions of the visualisation system we propose are threefold. First, the tool only visualises aircraft that are in conflict, in particular their solution spaces. Second, the polar graph structure in HTA-viz emphasises both the vertical solution space available for solving a conflict and the conflict urgency (time to conflict). Third, the glyph-based visualisation technique is used to integrate multivariate aspects (e.g. rate of climb and descend range and heading) of solution spaces into a single display.

2. Related work

Spatio-temporal analysis of air traffic data have mainly been analysed in the visual analytics (VA) domain [AAB*13]. Of particular interest among the various VA tools developed for the air transportation industry are real-time visualisation of 4D data and visualisation interfaces for CD&R. In relation to the former, the study of [BTD16] explored temporal aspects and vertical profiles of aircraft trajectory data. They provided a pipeline supported with different filtering to create a focus+context visualisation and avoid cluttering. [HTC09] and [AAGS18] developed unique interactive tech-

DOI: 10.2312/evs.20201044

niques to facilitate selection and comparison of trajectories based on various parameters such as altitude or rate of climb/descend. [ALP12] visualised conflict probabilities for flight trajectories on air traffic density maps. All reviewed VA applications are restricted to visualising air traffic data over large scales of time and space, which is more beneficial for air traffic management decisions rather than CD&R decisions.

Some work has specifically explored spatio-temporal data analysis in relation to CD&R decision. From an ecological interface design perspective, [VDMVP08] developed a conflict solution space visualisation system on a 2D display for speed and heading. [LCVPM11] and [BBE*15] further improved this work by providing altitude information on demand. [LDC06] and [BDCP10] developed a CD&R tool visualised in 3D, where the CD&R algorithm depended on the time window selected and did not support continuous detection and visualisation of solution spaces.

3. Design of analyser for ATC conflict detection

The propagation of a lateral separation violation between an aircraft pair, based on the relative speed vector, is explained in [VDMVP08]. In this paper, we first formulate conflict criteria by analytically exploring the temporal domain. Using the temporal domain as a constraint, formulas can be derived to obtain solution space criteria for horizontal and vertical dimensions separately.

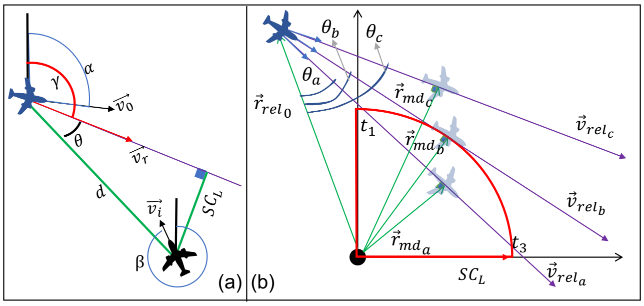

Figure 1: *Geometry of conflict criteria in (a) a 2D absolute coordinate system and (b) a relative coordinate system.*

The geometrical terminology of Figure 1(b) presents temporal evolution of a conflict between the reference aircraft (shown with black dot) towards the passing aircraft. As can be seen from the figure, the relative velocity line of the passing aircraft, for different vectors, may or may not infringe the lateral separation criteria (circle centred on the reference aircraft) of the reference aircraft. With state conditions of both aircraft being known, the beginning t_1 and end of the volume of space where separation is lost t_3 (i.e. less than 5nm) is obtained from solving the quadratic equation (1) for intersection of the relative velocity vector and the separation circle.

$$0 = v_{\text{rel}}^2 t^2 + 2\vec{v}_{\text{rel}}\vec{r}_{\text{rel}_0} t + (r_{\text{rel}_0}^2 - SC_{\text{l}}^2) \quad (1)$$

Where SC_{l} is the 5nm lateral separation criteria. The solution for the equation results in either of the following:

- Two positive values for t_1 and t_3 predicts that the aircraft will lose separation (less than 5nm apart) for (t_3-t_1) minutes (v_{rel_a} line in Figure 1(b)).
- One distinct value (equals to 5nm) predicts that the aircraft will not lose separation (v_{rel_b} line Figure 1(b)).
- One negative value for t_1 and one positive value for t_3 indicates that separation was lost $-t_1$ seconds ago (less than 5nm apart).
- No value indicates that the aircraft are not in conflict and will remain safely separated (v_{rel_c} line in Figure 1(b)).

We derived conflict criteria for heading using a geometrical representation of Figure 1(a) in an absolute (rather than relative) coordinate system. As can be seen in Figure 1, ($v_r \cos\gamma = v_i \cos\beta - v_0 \cos\alpha$) and ($v_r \sin\gamma = v_i \sin\beta - v_0 \sin\alpha$), from which equation (2) is obtained:

$$\tan\gamma = \frac{\cos\phi \sin\beta - \sin\phi \sin\alpha}{\cos\phi \cos\beta - \sin\phi \cos\alpha} \quad (2)$$

Where α and β are heading angles of the passing and the reference aircraft. d is the initial distance between the aircraft pair, v_i and v_o are their respective velocity vectors, v_r is the relative velocity vector ($\cos\phi = \frac{v_i}{\sqrt{v_i^2+v_0^2}}$) and ($\sin\phi = \frac{v_0}{\sqrt{v_i^2+v_0^2}}$). Based on Figure 1(a), conflict occurs when $|\gamma - \alpha| \leq \arcsin(\frac{SC_l}{d})$, which leads to:

$$\alpha - \arcsin(\frac{SC_l}{d}) \leq \gamma \leq \alpha + \arcsin(\frac{SC_l}{d}) \quad (3)$$

Knowing that the heading of the passing aircraft(α) is known, the conflicting heading criteria for the known aircraft(β) is obtained from solving equations 2 and 3.

To derive the vertical separation criteria (SC_{V}), time to separation loss for aircraft relative motion in the vertical plane is considered from the following formula: ($|\vec{v}_{\text{rel}}(\text{vertical}) \times t - \vec{r}_{\text{rel}}(\text{vertical})| < SC_{\text{V}}$). Where SC_{V} is the 1000ft vertical separation criteria. The intersection between time-to-conflict criteria found from equation (1) and the former formula reflect the accurate duration of having a conflict in 3D.

4. Visualiser Design Evolution

The design process underlying the final version of the HTA-Viz presented in this paper has spanned design activities and iterative prototyping over 18 months. The prototype has been implemented in python by the first author. An ATCo supported development by providing domain specific feedback on required information for the CD&R task, tool functionalities, and interaction design requirements. In addition, the design process consisted of two major activities: an initial work domain analysis and an evaluation with ATCos.

4.1. Initial design process and prototype development

The design work started with conducting a work domain analysis [Nai16] on the CD&R decision-making task. The goal of this task is to ensure safety and maintain efficiency, while promoting ATCos' performance. To achieve this goal, the analysis revealed a need for visualising three core sets of information about conflicts: (a) the aircraft pairs currently in conflict; (b) time to conflict; and (c) horizontal and vertical separation information.

The initial HTA-Viz prototype was developed with two main design concepts: the heading solution space (HSS) and the time-based altitude (TA) solution space. Figure 2 depicts an initial schematic representation of the first prototype, which consists of two windows showing a linked and coordinated view of the airspace. (Figure 2(a) shows the HSS concept, and Figure 2(b) shows the TA concept). The figure shows an example situation with five aircraft, of which four are in conflict. In Figure 2(a), the circles' centre represent aircraft position (latitude-longitude) and the diameter represents lateral separation criteria (5nm). Direction and length of the green line represents aircraft current heading and lateral speed, respectively.

HSS information is calculated by the analyser (see Section 3) and conveyed by the coloured and dark-shaded circle sectors in aircraft symbols (Figure 2(a)).Coloured triangle sectors (e.g. blue sector for aircraft F and G) represent heading conflict zones. If the aircraft's speed vector (green line) is within this coloured sector, they are in conflict. The non-coloured areas represent the available solution space for resolving the conflict. This can be achieved by adjusting the heading (of any aircraft) to be outside the coloured area. The dark-shaded sectors represent heading zones for potential conflicts. Colours are used as a visual channel to encode linked aircraft pair (those that are in conflict with each other).

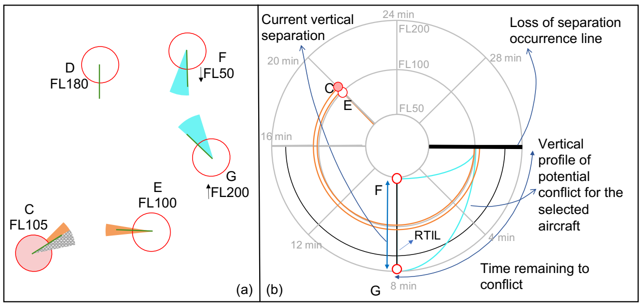

Figure 2: *Schematic representation of initial HTA-Viz prototype. (a) HSS concept, where the text next to each aircraft represents a flight label that contains aircraft call sign (e.g. D) and flight level information (e.g. FL180). (b) TA concept, which only displays aircraft (in (a)) that are in conflict.*

TA information (Figure 2(b)) is a novel concept that only visualises aircraft pairs in conflict. TA aims to direct focus on the temporal (urgency) and vertical aspects (solution space) of conflicts. Mapping temporal dimensions to a radial chart can be an intuitive representation [Bra05, BW14, KFM11], such as using a clock metaphor for monitoring temporal patterns [FFM*13]. The TA visualisation uses the clock metaphor in terms of the well-known polar graph technique to highlight conflict urgency. In the polar grid depicted in Figure 2(b), angles (in degrees) represent time remaining (up to 30 minutes prior) to a loss of separation, while circles with increasing radius represent increasing flight levels.

The thick black line (at three o'clock) is a fixed reference line representing the time when separation between two (or more) aircraft is lost. The black line between the red aircraft symbols F and G is called the radial time indicator line (RTIL). This line is always drawn for the most imminent conflict and moves counterclockwise towards the loss of separation line (time for when loss of separation is predicted to occur). The angle in the polar grid between the above two lines (8 minutes in Figure 2(b)) informs the viewer of the time available for solving the conflict before separation is lost. Vertical profiles of conflicting pairs are visualised on the TA with the same colour as on the HSS. The TA information in Figure 2(b) reveal two conflicts (F and G, and C and E). The most imminent is a conflict between a (mixed) climbing-descending aircraft pair (F and G) where separation loss is predicted to occur at a flight level between the current flight levels of both aircraft. The temporal axis (i.e. angles in polar grid) shows that the conflict between aircraft E and C will occur after the conflict between F and G. Aircraft D is not visualised as the TA only visualises in-conflict pairs.

4.2. Evaluation

Eight ATCos (four men and four women) with an average of 22.6 years experience (*SD*=11.7) participated in a quantitative experiment that evaluated the extent to which HTA-Viz affected their time to detect and solve conflicts. Following a fifteen-minute training session, during which the prototype interface was introduced, ATCos were asked to work with the tool. Their task was to report detected conflicts and then resolve them. Interaction with the tool was done by means of keyboard and mouse. The two main independent variables were traffic situation (conflicts geometry) and display condition. Four display conditions were used: a control condition consisting of a conventional situation display (without any visualisation support for conflict solution spaces) and three treatment conditions depending on whether the HSS and TA visualisation was enabled or disabled (HSS alone; TA alone; or HSS and TA). Eight different conflict geometries were designed with the assistance of an expert ATCo. Analysing number of detected conflicts applying Friedman's test indicated an effect of display conditions ($X2$ = 18.2 , $p < .001$). Analysing time for solving conflicts indicated an effect for the urgent (time to loss of separation < 3 minutes) climb-descend conflict ($X2 = 8.864$, $p = 0.031$) and a marginal effect for the non-urgent (12< time to loss of separation <30 minutes) conflicts ($X2 = 7.267$, $p = .064$). A semi-structured debriefing was conducted to explore design improvements for HTA-Viz. Several ATCos requested a representation depicting how aircraft rate of climb/descend options affect the vertical solution space. ATCos also claimed that collecting information from two displays were time consuming, especially during urgent conflicts. They found colour coding very useful in detecting conflicting pairs. Some ATCos found the TA visualisation more useful for detecting urgent conflicts consisting of a mixed climb-descend aircraft pair.

4.3. Visual Design of HTA-Viz

Based on the outcome of the evaluation study, two modifications to HTA-Viz were made: (a) visualising conflict zones for rate of climb/descend (ROCD) range and (b) the HSS and ROCD visualisations were merged and integrated into a composite glyph.

Figure 3 depicts the designed composite glyph. The glyph replaces the red circle symbol for aircraft used in the initial prototype in Figure 2(b). The glyph consists of two concentric circles (Figure 3(a)). The red-filled sector in the outer circle (5nm radius) illustrates the HSS conflict zone. In the initial prototype, colour-coding was used for HSS and vertical profiles to discriminate between different conflict pairs. However, based on the TA concept in HTA-Viz, aircraft-in-a-conflict pair are located on the same RTIL and can easily be picked out by the ATCo; thus, eliminating the need for colour-coding. The inner circle area of the glyph is divided in half by the RTIL (Figure 3(b)). The RTIL intersects with the glyphs of the two aircraft that are closest in time to losing separation. In the half of the glyph facing the conflict occurrence line, lies a no-fill black sector, which represents the ROCD range that a particular aircraft has based on its performance characteristics. The black line inside the ROCD, which always is perpendicular to RTIL, represents level flight (zero rate of climb/descend) and is aligned with the aircraft's current flight level. The sector to the right of the level flight line represents the rate of climb (ROC) range while the other represents the rate of descend (ROD) range. Filled sectors inside ROCD, which have the same colour as conflicting vertical profile, represent conflict zones for ROCD. To make the current ROC line distinguishable, the ROCD conflict zone is visualised with lower transparency. The area "behind" the RTIL in the glyph represents passed time and is used to show if an aircraft is selected (indicated by a green colour).

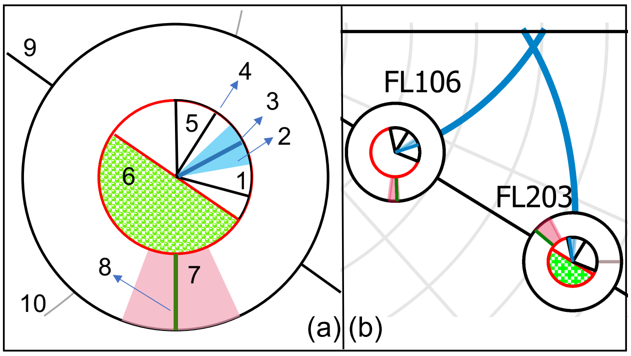

Figure 3: *Schematic explanation of the designed composite glyph (a), and two glyphs along the RTIL depicting two aircraft in conflict (b). Numbers in (a) represent: 1) ROC range; 2) ROCD conflict zone; 3) current ROC; 4) level flight line; 5) ROD range; 6) selection indicator; 7) HSS conflict zone; 8) current heading; 9) RTIL; 10) altitude contours.*

Figure 4 depicts the final HTA-Viz design. HTA-Viz visualises four conflicts, of which two are on the same RTIL that need to be resolved in less than two minutes. Both conflicts consist of a climbing and descending aircraft pair. The conflict "behind" consist of two aircraft flying at similar flight levels (thus infringing 1000ft vertical conflict criteria), but with sufficient horizontal separation (more than 5nm). In order to enable the ATCo to distinguish each aircraft, a plain circle will be shown instead of the glyphs. By double-clicking anywhere on the screen, the ATCo can toggle between a view with overlapping simple circles (Figure 4) and a view where all composite glyphs are shown (not depicted in figure).

Unlike previous designs that provide information about vertical solution spaces on-demand (i.e. [LCVPM11, BBE*15]), HTA-Viz visualise the information about conflict zones in real-time without a need to click on individual aircraft. This is expected to reduce working memory load in terms of collecting and storing information in memory. Moreover, HTA-Viz allows for exploring "what-if" situations for vertical solution spaces. For instance, HTA-Viz shows that if the selected aircraft (aircraft with green half circle and cyan-coloured line in Figure 4) remains at its current flight level (FL334) it will have a conflict with another aircraft which is cruising at FL340. With this information available, an alternative solution can be chosen that does not introduce a secondary (knock-on) conflict.

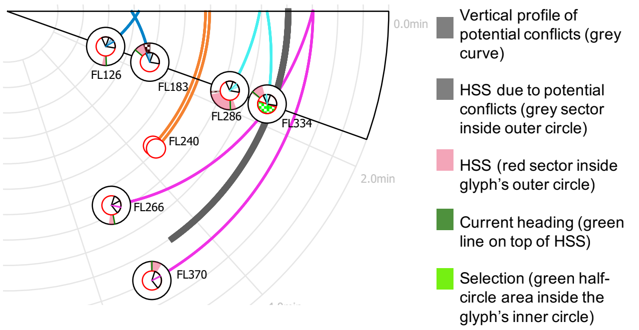

Figure 4: *HTA-Viz finalised design visualising solution spaces for four conflict pairs. The black curve indicates the vertical profile of the potential conflict for the selected aircraft (indicated in green).*

5. Discussion and Conclusion

This paper has presented the design process of a novel visualisation tool (HTA-Viz) for real-time analysis of solution spaces in ATC CD&R. In particular, the tool provides a holistic view of conflicts by visualising the corresponding horizontal and vertical solution space simultaneously. Based on the outcome of an evaluation study conducted on the initial prototype, it proved to be useful for ATCos, especially in urgent and difficult-to-detect conflict situations.

While the tool eliminates the need for creating a mental model of vertical relationship between aircraft and estimation of when in time they will lose separation, it requires the user to create a mental model of the horizontal traffic situation. This is a possible limitation of the design as it may increase the cognitive load. This should be evaluated in future experiments. We devise three lines of future work. First, we aim to conduct a full evaluation study to explore the extent to which HTA-Viz affects ATCos' way of problem solving and performance. Second, new versions for HTA-Viz will be explored where flight levels are shown with angles and time shown with circles on polar graph, and time and flight levels are visualised linearly. Implementing such changes make it possible to evaluate how the toroidal structure of the polar graph affects cognitive information processes. Third, we aim to explore possibilities of visualising situations relative to other time references, in addition to time to separation loss, such as: time to reach sector border, planned time to change the route or current time.

Finding solutions to complex traffic situations can impose huge cognitive workload on ATCos, which can jeopardise safety. This paper presents one alternative solution for better managing such complexity through visualisation design.

References

[AAB*13] ANDRIENKO G., ANDRIENKO N., BAK P., KEIM D., WROBEL S.: *Visual analytics of movement*. Springer Science & Business Media, 2013. 1

[AAGS18] ANDRIENKO N., ANDRIENKO G., GARCIA J. M. C., SCARLATTI D.: Analysis of flight variability: a systematic approach. *IEEE transactions on visualization and computer graphics 25*, 1 (2018), 54–64. 1

[ALP12] ALBRECHT G., LEE H.-T., PANG A.: Visual analysis of air traffic data using aircraft density and conflict probability. In *Infotech@ Aerospace 2012*. 2012, p. 2540. 2

[BBE*15] BEERNINK B., BORST C., ELLERBROEK J., VAN PAASSEN R., MULDER M.: Toward an integrated ecological plan view display for air traffic controllers. In *18th International Symposium on Aviation Psychology* (2015), p. 55. 2, 4

[BDCP10] BAGASSI S., DE CRESCENZIO F., PERSIANI F.: Design and evaluation of a four-dimensional interface for air traffic control. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 224*, 8 (2010), 937–947. 2

[Bra05] BRASSEUR L.: Florence nightingale's visual rhetoric in the rose diagrams. *Technical Communication Quarterly 14*, 2 (2005), 161–182. 3

[BTD16] BUSCHMANN S., TRAPP M., DÖLLNER J.: Animated visualization of spatial–temporal trajectory data for air-traffic analysis. *The Visual Computer 32*, 3 (2016), 371–381. 1

[BW14] BURCH M., WEISKOPF D.: On the benefits and drawbacks of radial diagrams. In *Handbook of human centric visualization*. Springer, 2014, pp. 429–451. 3

[FFM*13] FUCHS J., FISCHER F., MANSMANN F., BERTINI E., ISENBERG P.: Evaluation of alternative glyph designs for time series data in a small multiple setting. In *Proceedings of the SIGCHI conference on human factors in computing systems* (2013), pp. 3237–3246. 3

[HTC09] HURTER C., TISSOIRES B., CONVERSY S.: Fromdady: Spreading aircraft trajectories across views to support iterative queries. *IEEE transactions on visualization and computer graphics 15*, 6 (2009), 1017–1024. 1

[KFM11] KINTZEL C., FUCHS J., MANSMANN F.: Monitoring large ip spaces with clockview. In *Proceedings of the 8th international symposium on visualization for cyber security* (2011), pp. 1–10. 3

[LCVPM11] LODDER J., COMANS J., VAN PAASSEN M., MULDER M.: Altitude-extended solution space diagram for air traffic controllers. In *16th International Symposium on Aviation Psychology* (2011), p. 345. 2, 4

[LDC06] LANGE M., DANG T., COOPER M.: Interactive resolution of conflicts in a 3d stereoscopic environment for air traffic control. In *2006 International Conference onResearch, Innovation and Vision for the Future* (2006), IEEE, pp. 32–39. 2

[Nai16] NAIKAR N.: *Work domain analysis: Concepts, guidelines, and cases*. CRC Press, 2016. 2

[RN05] RANTANEN E., NUNES A.: Hierarchical conflict detection in air traffic control. *International Journal of Aviation Psychology - INT J AVIAT PSYCHOL 15* (10 2005), 339–362. 1

[VDMVP08] VAN DAM S. B., MULDER M., VAN PAASSEN M.: Ecological interface design of a tactical airborne separation assistance tool. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans 38*, 6 (2008), 1221–1233. 2