An Integrated Air Traffic Control Display Concept for Conveying Temporal and Probabilistic Conflict Information

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In this paper, we introduce an innovative conflict detection and resolution display for air traffic control. Our display explicitly incorporates uncertainties in velocity, heading, and position of each airplane in a given air space. Probabilistic, temporal, and spatial information of potential conflicts is provided through integrated graphical patterns.

INTRODUCTION

The central role of air traffic control encompasses: 1) minimizing the probability of loss-of-separation conflicts between aircraft, and 2) facilitating the flow of air traffic by providing such services as traffic and weather information and navigational assistance to pilots. In spite of an increasing number of near misses, there have been almost no midair collisions in the past 35 years between aircraft under radar control (McFarland, 1999). Nevertheless, if the current air control system is not redesigned to accommodate increasing traffic, it is anticipated that by the year 2015 a major aviation incident could occur as frequently as every 7-10 days (Perry, 1997). Some of the factors underlying this forecast include inadequacy of hardware due to the fact that many control towers still use equipment that was installed in the early 1970s, as well as recognised deficiencies in current aviation rules.

In response to the forecast of increasing air traffic, the concept of *free flight,* involving the relaxation of many of today's flight constraints, has been introduced. The economic benefit of increased traffic flow expected from free flight may come at the expense of more potential conflicts, however. In particular, it remains to be shown that this concept will not hinder controllers' ability to manage air traffic at anticipated increased loads (Wickens, 1998). For example, an analysis of a one day sample of current Eurocontrol traffic, comprising 1000 intersections, showed that with free flight this number would likely increase to at least 62,000 intersections (Ratcliffe, 2001).

Exacerbating the challenge of detecting and resolving conflicts is the fact that positions, velocities, and headings of airplanes may vary randomly. In the aviation community some have even argued that the role of controllers and pilots is one of reducing uncertainty (Leroux, 1998).

In response to this situation, we present in this paper our design of an innovative air traffic control display concept, incorporating information about not only predicted *times to potential conflicts*, but also explicit information about the *uncertainty of those predictions*. It is our aim that this display be useful for facilitating both *detection* of potential conflicts and *planning* for conflict resolution.

Although earlier research has revealed consistent human biases during probability estimation tasks (Wright, 1982), few studies have been based on human capabilities in dealing explicitly with computation of probability of conflict between airplanes (Yang & Kuchar, 1997; Paielli & Erzberger, 1997). In light of this, our proposed display makes the predicted consequences of uncertainties in velocity, heading, and position of each airplane in a given air space as apparent to the user as possible. Furthermore, the display is also unique in the sense that it conveys the probabilistic, temporal, and spatial aspects of potential conflicts within a single integrated visual pattern.

NEW DISPLAY CONCEPT

Definition of Conflict

First, we must define what a conflict is. In current air traffic management systems, each aircraft is surrounded by a virtual cylinder, called the *protected region* (PR). A conflict, or loss of separation, between two aircraft occurs whenever the PRs of the aircraft overlap (Yang & Kuchar, 1997). Currently, over US airspace for example, the lateral radius and vertical height of each PR are 2.5 nautical miles and 2000 ft respectively. (The latter changes to 1000 ft below 29000 ft and 4000 ft over oceanic airspace.) Note that this definition encompasses both spatial and temporal elements, in the sense that the protected region effectively extends the concept of "simultaneity". That is, by defining a loss of separation in spatial units, we are equivalently saying that two aircraft are permitted to arrive at the same point in space, but must do so with a minimal amount of time separating the two arrivals at that point.

Probability and Time Interference Patterns

Our new display is an integrated graphical representation that visually conveys probabilistic, spatial, *and* temporal information about potential conflicts between aircraft, using a distinctive pattern and relying on human pattern recognition ability for its interpretation. As an analogy to help understand the underlying concept, consider a magnet placed under a sheet of paper upon which iron filings have been scattered. One can clearly infer the location of the magnet below simply by observing the pattern of how the filings are aligned to the field of the magnet below. Our design model is based on the assumption that a human observer will be able to view an "interference pattern" generated by our display and, similarly to the magnet example, infer meaning from it about the temporal, spatial and probabilistic nature of the causes of that pattern.

The pattern generated by our display is a combination of the following three types of information:

1. *Time to conflict (TTC):* the time remaining until a loss of separation occurs;
2. *Spatial probability*: given any point in space, the probability, due to heading uncertainties, that an intersection will occur at that point;
3. *Temporal uncertainty*: given any point in space, the probability, due to velocity uncertainties, that any two aircraft will conflict at that point in space.

Our hypothesis is that presenting these three types of information (explained in detail in the following sections), using an integrated display format, will facilitate the air traffic controllers' task of detecting and then dealing with potential conflicts, while effectively lowering their mental load.

Based upon earlier related work by Telner & Milgram (2004), the new display reported here was programmed (in C++) to include temporal and spatial uncertainties due to changes in altitude (that is, a migration from 2D to 3D), velocity uncertainties in the probability computations, a migration from a static to a dynamic, interactive simulation, including an ability to change display parameters in real time, interactively examine the predicted consequences of potential interventions, plus a wide variety of other features.

Parameter 1: Time to Conflict (TTC)

The TTC is defined as an estimate of the potential arrival time of any pair of aircraft, given a point in space. This measure is based purely on the nominal velocities, independent of the headings of the aircraft. Consider Figure 1, where the two black dots, A and B, represent two planes with arbitrary headings. The arrows represent the ensemble of all directions in which the planes can travel, with their respective velocities shown by the arrow lengths. The circles around the planes represent all the possible locations at which the planes can possibly arrive after a fixed amount of time – in this case one minute. The two radii are different since they are moving at different velocities.

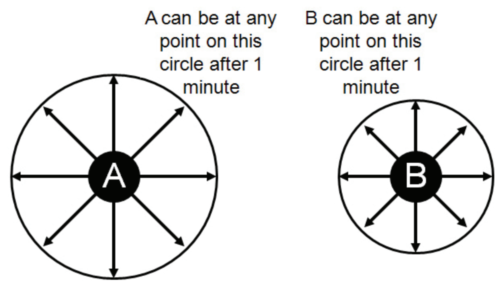

Figure 1. Circles representing all possible arrival locations for aircraft A and B after 1 minute.

We can now extend this same idea to include increments of 1 minute, to generate a set of *iso-time circles*, as depicted in Figure 2. In other words, the intersection points, or *time to conflict (TTC) points*, in the figure represent the locations where the planes can both arrive at the same time, to potentially cause a conflict.

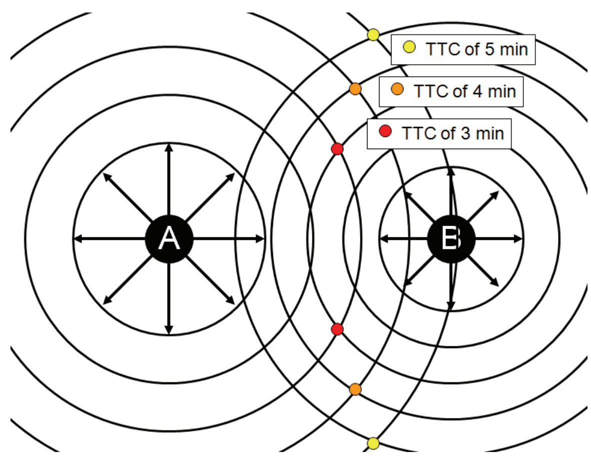

Figure 2. Two planes with their iso-time circles and time to conflict (TTC) points of 3, 4, and 5 minutes.

This idea can be taken further to create a *continuous* pattern, by decreasing the radii, that is, the time intervals between each iso-time circle. Doing so will generate a single line, or locus of potential intersection points (not shown). If we then relax our definition of "simultaneity", to include the concept introduced earlier of a *protected region* (PR), this is equivalent to defining a conflict as any crossing of aircraft which occurs within a specified time window. This has the net effect of broadening the one dimensional locus of TTC points into a two dimensional area, as illustrated in Figure 3, where the brightness of the pattern depicts the estimated TTC of both planes at that point. According to our initial design, the brighter the colour (red in this case), the more imminent the potential conflict.

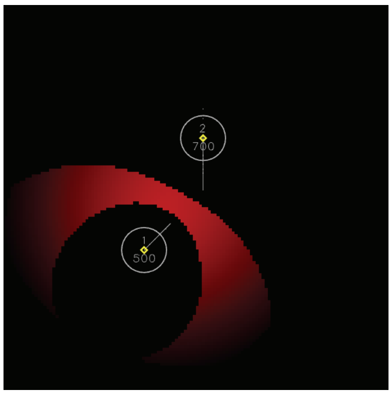

Figure 3. Sample pattern of TTC information about potential conflicts for two planes, indicated by circles, with smaller TTC (conflict more imminent) encoded by colour brightness.

Parameter 2: Spatial Probability

Rather than assuming that a plane's heading is known with certainty – that is, that it never varies from its nominal value – we assume instead that each heading can take on some value whose probability is determined by a normal distribution about its nominal (mean) heading, h_N. For example, a plane travelling with nominal heading $h_N = 45°$ is more likely to be travelling at 45º than it is at 20º, which is also a possibility however.

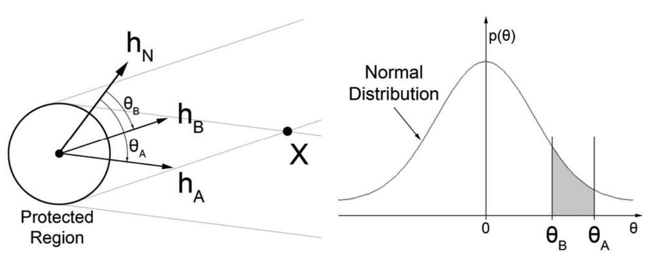

Figure 4. The method of computing the probability that X will be in the path of the plane's protected region.

In Figure 4, we illustrate the case of a plane with nominal heading, h_N, as well as an arbitrary point X in space. At first glance, it would appear that, if the plane were to proceed with heading h_N, it would clearly never arrive at point X. However, according to our assumption of a normal distribution of headings, there is in fact some finite probability that the plane will arrive at X, as shown in the right side of Figure 4. The two other headings in the figure, h_B and h_A, indicate the limits of directions of travel that the plane could take in order for its PR, indicated by the circle, to just touch the point X. (This concept is illustrated by the two pairs of lines parallel to each heading, showing the area which would be swept out by movement of the PR in either of those two directions.) It follows that, for any direction between these two vectors, the point X will fall within the path of its PR.

As shown in Figure 4, the probability of having the point X fall within the path of the moving PR corresponds to the probability of the aircraft following any one of the possible headings between h_B and h_A. This can be calculated by:

$$P = \int_{\theta_B}^{\theta_A} p(\theta) d\theta \qquad (1)$$

where the two limits of integration correspond to the respective deviations from the nominal heading.

Extending this concept to two aircraft, we can now define the *probability of an intersection* at a particular point, X, as the probability that the PRs of both planes will pass over X at some time (but not necessarily at the same time). Since the probability density functions are mutually exclusive, the joint probability, JP, is simply the product of the two probabilities from Equation 1:

$$JP = \int_{\theta_{1,B}}^{\theta_{1,A}} p_1(\theta) d\theta \int_{\theta_{2,B}}^{\theta_{2,A}} p_2(\theta) d\theta \qquad (2)$$

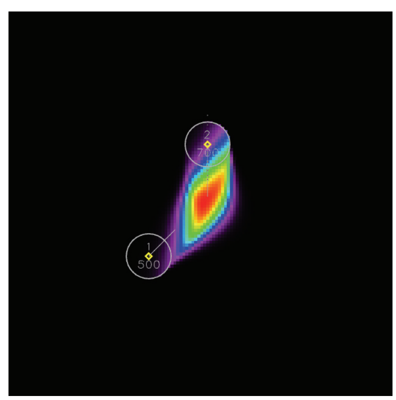

Figure 5. Pattern of spatial probabilities of potential intersections of two planes shown in circles, travelling at nominal headings of 45º and 180º respectively.

Given joint probabilities for each pair of aircraft for all points within a particular sector, we can generate a *pattern* to convey that information. In Figure 5 the hue at any particular point depicts the probability of both planes arriving at that point: the longer the wavelength (the redder the colour), the higher the probability of an intersection; and, conversely, the shorter the wavelength (the bluer the colour), the lower the probability of an intersection.

Parameter 3: Temporal Uncertainty

Consider another situation, as depicted by Figure 6, where the paths of two planes, A and B, cross at point X. In contrast to our consideration of spatial probability above, where we compute the probability of two PRs crossing at any time – i.e. an *intersection* – here we are interested in the probability of two PRs crossing within a defined time window – i.e. a *conflict*. In Figure 6, even though the PR of A at time t_1 may have already passed X before the PR of B, at time t_2 we see that their PRs have in fact overlapped, thus causing a conflict.

To accommodate the fact that to be considered a conflict the two planes need not necessarily be at the same point *at exactly the same time*, we introduce the notion of a *time window*. In particular, for any point in space, we say that a conflict will occur if the following inequality is met:

$$\left| t_A - t_B \right| < \textbf{\textit{Time Window}} \qquad (3)$$

where t_A and t_B are the times of arrival at that particular point in space by planes A and B respectively, each travelling at its own velocity.

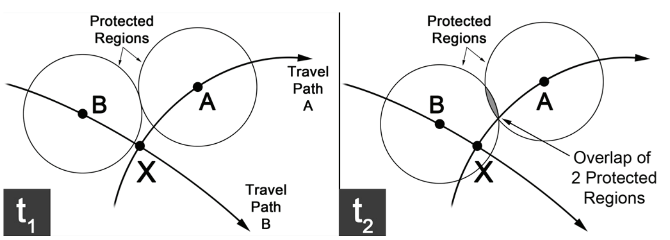

Figure 6. Planes A and B with their respective travel paths crossing at the point X at two different times ($t_1 < t_2$). Note the overlap, or intersection, of the protected regions at time t_2 .

Predicting a conflict according to Equation 3 would be straightforward were it not for our assumption that velocities are also not deterministic, but rather can take on any of a range of values according to some distribution about a nominal value. With this in mind, the probability of a conflict occurring between planes A and B, given point X, is then:

$$P_c(t_A, t_B \mid X) = \int_S p_t(t_A, t_B)\,dt \qquad (4)$$

where S is the time region defined in Equation 3.

The challenge in evaluating Equation 4 is that the probability distribution $p_t(t_A,t_B)$ is difficult to model in the time domain. On the other hand, using our assumption that velocities may follow a normal distribution, we can evaluate Equation 4 by rewriting Equation 3 in the velocity domain, using the relationship $t = d/v$:

$$\left| \frac{d_A}{v_A} - \frac{d_B}{v_B} \right| < \textbf{\textit{Time Window}} \qquad (5)$$

where

d_A is the distance from plane A to point X
d_B is the distance from plane B to point X
v_A is the velocity vector of plane A
v_B is the velocity vector of plane B

Using the substitution rule, Equation 4 can now be rewritten as:

$$P_c(v_A, v_B \mid X) = \int_{S'} p_v(v_A, v_B)\,dv \qquad (6)$$

where $p(v_A,v_B)$ is the probability distribution function in the velocity domain and S' represents the time region defined by Equation 5.

Finally, with probabilities computed for each pair of planes and for each point in space, we can generate another pattern to convey that information, an example of which is shown in Figure 7. Using the same encoding rule as in Figure 5, the hue here represents the probabilities caused by the velocity uncertainties.

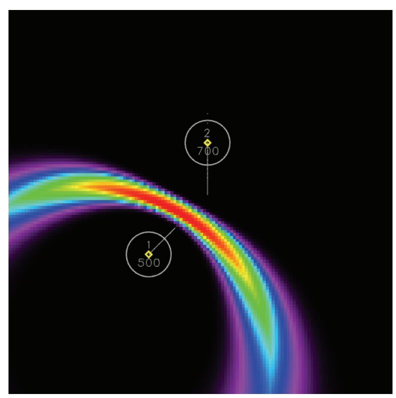

Figure 7. Example of probability pattern generated by two planes (within circles) caused by uncertainty in velocity.

Colour Map

As indicated above, in response to the challenge of conveying information about two independent, continuously varying parameters within a single display in a distinguishable manner, we have elected to use *hue* and *brightness*, in the form of a Colour Map. Figure 8 shows the encoding scheme used in the display. Along the vertical axis is the brightness, which depicts the estimated time of arrival of both planes at a particular point. The brighter the colour, the more imminent the potential conflict, and vice versa. Along the horizontal axis is the hue, which depicts probability, where "cooler" hues at the left indicate lower probability of potential conflict, while "hotter" hues to the right denote higher probability.

Figure 8. Colour Map represents the colour space of the pattern used to convey the temporal and probabilistic information in the display.

Display Integration

When the three types of information described above are combined, as in the example shown in Figure 9, the resulting visual pattern conveys, through hue and brightness, an integrated representation of temporal and probabilistic information about potential conflicts. Due to the expected uncertainty in the positions, velocities, and headings of all the planes, the computed patterns represent predictions of future potential conflicts, together with an estimated measure of the likelihood of those conflicts.

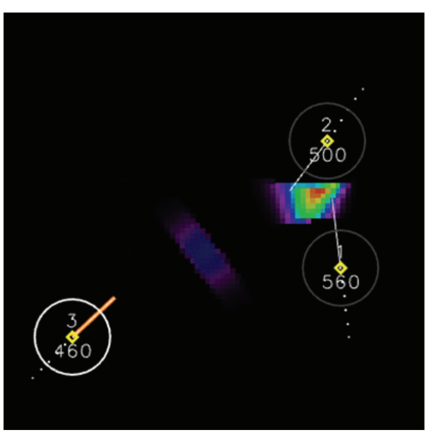

Figure 9. Example of patterns created by time to conflict, temporal, and probabilistic information of potential conflicts.

CONCLUSION

Conflict detection and resolution is one of many tasks for which air traffic controllers are responsible, in addition to traffic management, weather forecasting, handoffs, takeoff and landing clearances, etc. If alerted too soon about the need for a potential intervention, controllers might make unnecessary decisions at the expense of attending to other tasks. If alerted too late on the other hand, there might not be enough time to react. Furthermore, if actions are taken unnecessarily in response to perceived conflicts which are in fact relatively unlikely, further costs may ensue.

Our hypothesis is that for (future) complex air traffic flows, where aircraft will not be counted upon to consistently maintain either their nominal headings or nominal velocities, the two integrated parameters presented in our display will be of use not only for the detection of imminent potential conflicts, but also to assist in the knowledge-based problem solving that will be needed to evaluate and, if necessary, resolve those potential conflicts.

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