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Shayne Loft

Scott Bolland

Michael S. Humphreys

Andrew Neal

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Loft, S., Bolland, S., Humphreys, M. S., & Neal, A. (2007). Modelling the Human Air Traffic Controller, Part 1: Expert-Trainee Differences in Conflict Detection. *2007 International Symposium on Aviation Psychology*, 409-414.
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MODELLING THE HUMAN AIR TRAFFIC CONTROLLER, PART 1: EXPERT-TRAINEE DIFFERENCES IN CONFLICT DETECTION

Shayne Loft, Scott Bolland, Michael S. Humphreys, and Andrew Neal
University of Queensland
Brisbane, Australia

The provision of air traffic management services is highly dependent on the ability of controllers to ascertain whether or not aircraft will lose separation (known as conflict detection). Due to flight environmental factors there is an inherent uncertainty involved in predicting aircraft trajectory. A model of conflict detection is presented that assumes that controllers predict aircraft progress between a minimum and maximum speed and climb/descent rate, depending on error bounds placed on nominal values. An initial study is reported to calibrate this model. Controllers indicated whether they would intervene to assure separation between pairs of converging aircraft at cruising altitude. A 5nm lateral separation standard was used. Based on nominal speeds, minimum lateral distance of separation varied from 0nm to 20nm. Experts were more likely to intervene than trainees. The effects of expertise are captured by assuming that experts are sensitive to greater uncertainty in the minimum and maximum speed of aircraft than trainees. Directions for future research are outlined.

Introduction

The capacity of en route airspace systems to deal with increases in traffic is constrained by the levels of mental workload experienced by air traffic controllers (ATCos). In order to predict workload and thus improve airspace capacity planning, research efforts have focused on quantifying characteristics of air traffic that create task demand (Manning, Mills, Fox, & Pfleiderer, 2001), identifying strategies that ATCos use to minimize the amount of control activity required to meet their objectives (Loft, Sanderson, Neal, & Mooji, in press), and building performance models to simulate how ATCos carry out control tasks (Leiden, Korpardekar & Green, 2003). The parallel development of these approaches requires understanding of the information that ATCos use to perform control tasks. The control task focused on in the current paper is that of conflict detection.

A core skill of ATCo's is the ability to project the trajectories of aircraft from their current position to a future point, in order to determine the distance of their closest point of approach with other aircraft. Aircraft pairs are considered to be in conflict if they will violate both lateral and vertical separation standards simultaneously. While prior research has identified strategies that ATCos use to detect conflicts, it has not considered carefully enough the context in which ATCos make decisions. The current paper focuses on identifying the domain-specific knowledge and processes that underlie conflict detection, with the intent of building a model of conflict detection that is compatible with the strategies and objectives of the ATCo. In particular, we focus on the inherent uncertainty involved in predicting aircraft trajectory that arise due to flight environmental factors (e.g., wind shift, aircraft load etc). A conflict detection model is presented where ATCos assume that aircraft progress between a minimum and maximum speed and climb rate. The predictive validity of the model is tested by examining how the probability of ATCo intervention varies (a) with the minimum distance of lateral separation between aircraft and (b) experience levels. Before introducing the model and initial study, we provide a brief review of prior research.

Prior Research

The study reported in this paper presented scenarios to ATCos where aircraft were flying at the same altitude on converging courses. In these circumstances, the ATCo needs to predict the distance or time between the aircraft at the intersection point, based on their expected trajectory. This process is often referred to as relative judgment (Xu & Rantanen, 2003; Rantanen & Nunes, 2005). A substantial body of research has focused on identifying the perceptual (Tresilian, 1991) and cognitive (Law, Pellegrino, Mitchell, Fischer, McDonald, & Hunt, 1993) mechanisms underlying relative judgment, including identification of memory mechanisms that drive how cues come to be associated with responses (Loft, Humphreys, & Neal, 2004; Loft, Neal, & Humphreys, in press).

A conflict detection model also needs to account for situations where aircraft are climbing through the flight levels of other aircraft. If aircraft are changing level, the ATCo must assess when the aircraft will violate and regain lateral separation, and also when aircraft will violate and regain vertical separation. For example, if one aircraft passes through the level of another, and re-establishes vertical separation before losing lateral separation, then the aircraft are not in conflict. Boag, Neal, Loft, & Halford (2006) developed a 'transitions metric' for assessing the difficulty of such judgments. They assumed that the transitions into and out of conflict in each dimension are variables that may be represented in working memory. The transitions metric accounted for a significant portion of the variance in the perceived complexity of conflict detection problems, and response time. Boag et al. concluded that ATCo's mentally project the trajectories of aircraft to determine changes in vertical separation and lateral separation, and in so doing, identify transitions into and out of conflict in lateral and vertical dimensions.

Other research has focused on factors that influence the difficulty of visual search. Conflict detection performance has been shown to be affected by a variety of variables that include level of control (Metzger & Parasuranman, 2001), number of aircraft (Nunes & Scholl, 2004) convergence angle (Remington et al., 2000), time to conflict (Remington et al., 2000), and the altitude distribution of surrounding aircraft (Nunes & Scholl, 2004). As traffic load increases, more aircraft need to be assessed, increasing the difficulty of searching for conflicts. Increased time to conflict and convergence angle both increase the likelihood that distracter aircraft will be interspersed between conflict pairs, especially under high traffic load. In the current study, aircraft pairs were presented in isolation and in a generic en route sector. Thus, the visual search requirements of conflict problems were controlled, allowing for systematic test of the conflict detection model.

We argue that a significant limitation of conflict detection research conducted to date is that it too heavily focuses on the final product of conflict detection (accuracy and timeliness), and does not provide enough consideration of the constraints imposed by the ATC system. The two significant constraints placed on conflict detection are (a) the uncertainty regarding the trajectory of aircraft (Nunes & Kirlik, 2005), and (b) the time pressure the ATCo is under (Loft, Sanderson et al. in press). The current paper focuses on the former constraint.

Uncertainty and Separation Assurance

ATCos use flight plan information (altitude, speed, heading) and trajectory data derived from prediction tools to detect conflicts. However, due to variations in flight environmental factors, there is an inherent uncertainty in estimates of aircraft trajectory derived from these sources. Aircraft ground speed and climb/descent rates can be altered by a variety of factors. These factors include aircraft performance, flight level, wind shift, aircraft load, engine parameters, temperature, and airline operating rules. Thus, ATCos can not be certain exactly where aircraft will be in the future relative to other aircraft. For example, in order to calculate the minimum separation between two converging aircraft in altitude transition, ATCos need to consider relative ground speed and relative climb/descent rate. ATCos can use prediction tools to determine the relative arrival-time of aircraft at the intersection point, and estimate vertical separation based on the average climb and descent rate profiles of aircraft. However, a conflict prediction derived from these sources is limited because it is based on current state information, without consideration of uncertainty in flight progress.

Bisseret (1981) reported that only 30% of the aircraft pairs that experts intervened too in his study would have actually gone on to violate minimum separation. He concluded that ATCos make their decisions from a rough processing of the aircraft, preferring to be cautious and intervene than spend valuable time making precise trajectory calculations. There is a growing body of converging evidence that ATCos attend to cues that that provide them with smallest amount of information necessary to assure separation between aircraft (for a review see Loft, Sanderson, et al. in press). ATCos set appropriate extra margins for predicting conflicts in order to *assure separation* between aircraft, using approximating mechanisms for determining conflict status with modest amount of computation.

Findings that highly trained ATCos missed so many conflicts in prior studies seem counterintuitive to such notions. For example, Metzger & Parasuranman (2001) reported a miss rate of 65%. Boag et al. (2006) reported a miss rate of 10%, despite the fact that ATCos were not required to perform concurrent control tasks. This level of error is unlikely to occur in the field due to serious safety consequences. However, a significant limitation of these studies is that ATCos were instructed that aircraft were only in conflict if they would literally violate minimum separation, and more often than not ATCos made trajectory calculations without prediction tools. This is not the manner in which ATCo routinely detect conflicts in the field.

The Conflict Detection Model

In capturing the inherent uncertainty involved in detecting conflicts we have used the algorithms described in Granger, Durand & Alliot (2001), as they provide a simple means of capturing the noise of the environment. In this approach (illustrated in

Figure 1), the position of an aircraft projected into the future can be modeled as the region bounded by an aircraft flying at the minimum possible speed (and climb/descent rate) and a second aircraft flying at the maximum possible speed (and climb/descent rate). In the horizontal plane, at a given point in time, the possible set of positions can be modeled as a set of line segments along the current flight path, whereas in the vertical plane, it will simply be captured by a minimum and maximum set of altitudes. Thus, as illustrated in Figure 1, depending on the magnitude of these error bounds, the position of aircraft at specific points in the future will be a certain distance closer of further than the values predicted by the aircrafts nominal values (and that indicated by prediction tools). A conflict between two aircraft is deemed to exist if the bounded regions partially violate separation standards (i.e. if the minimum distance between potential positions in the horizontal plane are within 5nm, and the range of heights are closer than 1000ft).

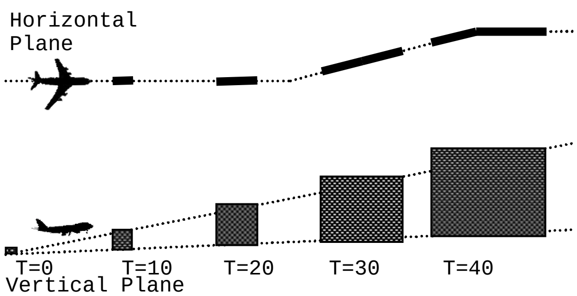

Figure 1. Modeling position uncertainties (adapted from Granger et al, 2001, figure 3). The location of an aircraft projected into the future is bounded by its best and worst case flight performance, with a potential conflict being detected if the regions of two aircraft violate separation standards.

In an initial test of the conflict detection model, we manipulated the minimum lateral separation of aircraft pairs, and examined the performance of two groups of ATCos with different experience levels. For experts, the minimum and maximum speeds were calculated as 2% deviation away from the current speed in the horizontal plane. To capture within and between rater variability in decision making, random Gaussian noise was added to these speeds for each separate judgment (10% variance). In contrast to experts, trainees (1 year training) will have less experience dealing with variability in the distribution of aircraft performance (Seamster, Redding, Cannon, Ryder, & Purcell, 1993), leading them to place greater emphasis on the predictive validity of prediction tools. For trainees, the minimum and maximum speeds were calculated as 1% deviation away from the current speed in the horizontal plane, with 5% random Gaussian noise. According to these parameters, the probability of ATCo intervention will vary according to the minimum lateral distance of separation between aircraft, and experts will be more likely to intervene than trainees.

The Study

Each trial presented a single pair of aircraft traversing an en route sector. ATCos made conflict status judgments by indicating whether they would (now or in the future) intervene to assure separation. Controllers had access to prediction tools. A 5nm lateral and 1000ft vertical separation standard was used. Both aircraft were cruising. Based on nominal speeds, minimum distance of lateral separation varied from 0nm to 20nm.

Participants. Thirteen ATCos participated. All currently worked at Brisbane ATC Centre in Australia. They had been ATCos for an average of 15.2 years, and had average age of 39.4 years (12 males, 1 female). Seven trainees participated, with average age of 26 years (6 males, 1 female). These trainees had 1 year training. This training included both theory (aircraft performance, navigation aids, scanning, meteorology, separation standards), and practice (aircraft coordination and separation assurance in fictitious sectors under both procedural and radar control).

ATC-lab. ATC-lab is a laboratory suite that presents simulations of ATC (Loft, Hill, Neal, Humphreys, & Yeo, 2004). However, note that this simulator needed to be significantly upgraded for the purposes of the current study. Each trial presented a single pair of aircraft traversing a fictitious en route sector that has full radar coverage. The area airspace was 260nm by 195nm. Each aircraft had a data block that displays the call sign, the type of aircraft, the current and cleared flight level, and the speed in nm. On each trial, the aircraft pair converged to a common intersection point. The positions of aircraft updated once per five seconds. Aircraft were in conflict if they would, given their respective nominal respective flight levels, speeds, and headings, simultaneously violate vertical and lateral separation standards in the future. The ATCos had no control over the flight levels, speeds or headings. Their task was to make judgments regarding the conflict status of each aircraft pair. The response panel required indication of whether they would intervene now (or in the future) to assure separation (definitely, likely, unlikely, definitely not). A number of prediction tools were provided, including (a) a 20nm X 10nm scale maker, (b) history dots, (c) range and bearing lines, and (d) velocity vectors.

Aircraft Scenarios. Ten aircraft types were presented (each with a specific speed and altitude range). Aircraft types were randomly allocated to problems, with speed and altitude randomly selected from the appropriate range. All aircraft pairs were cruising at the same flight level, and thus needed to be assessed for lateral separation. Group (expert, trainees) was the between-subject factor, while distance of minimum lateral separation (0nm, 1nm, 2nm, 4nm, 6nm, 8nm, 10nm, 12nm, 14nm, 16nm, 18nm, 20nm) was factorially manipulated within subjects. Thus, a total of 36 lateral problems were presented, 12 of which were in conflict (minimum lateral separation <5nm). Three type of convergence angles (45, 90, 135 degrees) were counterbalanced across problems. Time to minimum lateral separation (the time between the start of the trial to when the aircraft pair reach minimum separation) ranged from 5 to 15 minutes, and was counterbalanced across problems.

Procedure. Printed instructions informed ATCos the separation standards were 5nm (lateral) and 1000ft (vertical), and then outlined how to use the response boxes and prediction tools. Next, ATCos were given several task assumptions. First, they were to assume that they were under moderate workload conditions. Specifically, they we asked to imagine they were busy and under some time pressure. However, this time pressure was not excessive and they had enough time to accomplish their tasks. Second, they were to assume that aircraft presented were on their optimal (preferred) flight paths, and that there were no other considerations like flow. Third, ATCos were reminded that there were a number of conditions that affect aircraft performance, such as aircraft weight, air density, thunderstorms, winds etc. When making their judgments, they were to assume that there was no reason to expect any drastic change in environmental conditions. However, they were also asked to take into account the inherent uncertainty of the typical en route control environment. ATCos completed 4 practice trials before the main task.

Results. The primary dependent measure was the probability that ATCos would intervene to assure separation. Cases where ATCos indicated they would definitely intervene or would be likely to intervene were coded 1 (intervene). Cases were ATCos indicated they would unlikely to intervene or would definitely not intervene were coded 0 (no intervene). Figure 2 presents the probability that expert ATCos would intervene to assure separation, and the corresponding estimations of intervention probability predicted by the model. Figure 3 presents the same data for trainees.

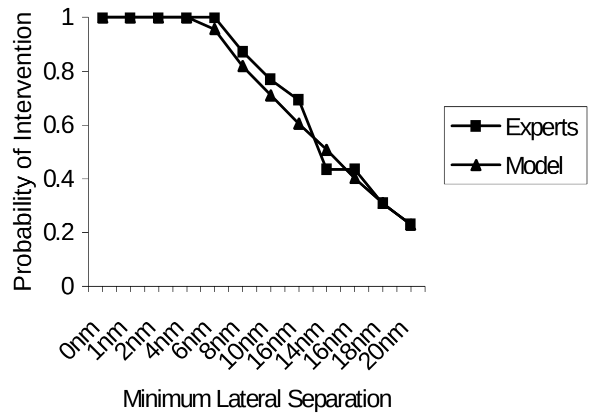

Figure 2. The probability of intervention by experts and the predictions of model.

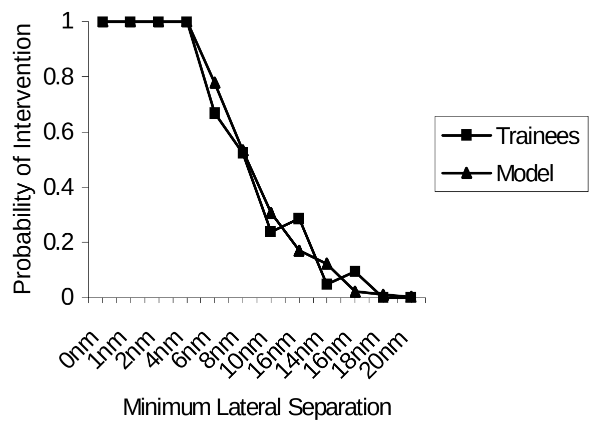

Figure 3. The probability of intervention by trainees and the predictions of model.

As can be seen in Figures 2 and 3, the predictions of the model closely matched both the expert and trainee intervention decisions. When minimum lateral separation was less than 5nm (i.e., conflict), both experts and trainees would always intervene. However, at larger distances of minimum separation (>5nm), experts were more likely to intervene than trainees.

General Discussion

The current paper presented a model of ATCo conflict detection and an initial study. The model assumes that invention probability will vary as function of the uncertainty ATCos set regarding the trajectory of aircraft. ATCos expect that aircraft trajectory will progress between a minimum and maximum speed and climb/descent rate, depending on the error bounds they place on nominal values. If ATCo intervention decisions are tuned to the statistics of their environment, they will reflect this inherent noise. The model correctly predicted that the probability of ATCo intervention would vary according to the minimum lateral distance of separation between aircraft, and that experts would be more likely to intervene than trainees. The results indicate that ATCos set extra margins for predicting conflicts in order to assure separation between aircraft.

Bisseret (1981) found that trainees discriminated between conflicts and non-conflicts more accurately than experts, indicating that the predictions that they were making were more precise. He concluded that experts were being more cautious than trainees, by making rougher calculations and choosing to intervene too many non-conflicts in order to assure separation. Bisseret argued that while the cost of missing a conflict and subsequently causing a mid air collision was no doubt as important an issue to a trainee as it was a expert, this risk was not yet integrated into their operative decisions. In the current paper, we specify a cognitive mechanism for this. The current model and data suggest that trainees are less likely to intervene than experts because they place smaller uncertainty bounds on the speed and climb/descent rate of aircraft. Performance by novice controllers may thus partly reflect an overestimation regarding the accuracy of prediction tools.

In the current study, ATCos needed only estimate relative arrival-time in the horizontal plane. If aircraft were climbing or descending, the ATCos would have needed to estimate whether the aircraft would be at some point occupy the same (<1000ft) altitude at the same time that lateral separation (<5nm) was violated (Boag et al., 2006). The ATCo generally considers the vertical evolution of flight to be more unpredictable than aircraft movement in the horizontal plane, because of extra random factors such as aircraft loads, wind speeds, descent throttle settings etc. In addition, ATC prediction tools provide little assistance for calculations of rate of climb and descent. Consistent with this, Bisseret (1981) found that a margin of about 10nm (two times the minimum) seemed to be the average for ATCos to deliver a non-conflict judgment, compared to 3000ft (3 times the minimum) in the vertical plane. The conflict detection model will also need to be calibrated to account for the probability of intervention when aircraft are passing through the levels of other aircraft.

In summary, the results here provide the initial information that is needed to develop a separation assurance component of an ATCo human performance model. Task demand alone is insufficient basis for modeling mental workload because of the need to predict mental workload ahead of time (Loft, Sanderson, et al. in press). The problem is that task demands change dynamically - ATCos change the trajectories of aircraft when they intervene to assure separation and establish arrival sequences. Human performance models provide a way of addressing these important issues. By building a human performance model that simulates how the ATCo carries out control tasks, we may be able to generate more accurate predictions of aircraft trajectories and hence of future task demands. The human performance model would perform basic tasks, such as accepting hand-offs, resolving conflicts, and handing off aircraft. We now have a basic understanding of the some of the factors that influence whether controllers intervene to assure separation.

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