23 The invariant that drives conflict detection

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Abstract

The detection and avoidance of collisions in a congested space is a problem that all independently mobile agents must solve quickly and efficiently. A powerful method for solving the problem of conflict detection is to base navigation decisions on estimates of time to contact (T_C). We conducted a series of experimental investigations to determine if professional pilots flying a modern commercial airliner use Tc when given the authority to make decisions regarding routing and separation. Such authority would exist under current designs for the National Airspace System (NAS), namely the continuum of distributed control structures referred to as free flight. Ten currently certified commercial airline pilots, with 6000-24000 hours of flight time (average 9177 hours), flew 12 simulated en-route air traffic scenarios in our Boeing 757 glass-cockpit experimental platform. The pilots had the authority to make all decisions regarding routing and separation. The CRT displays were their only source of traffic information. From analysis of the pilots' concurrent verbal reports and manoeuvres, we determined the separation (from the subject's ownship) and relative velocity of each aircraft at the moment the subject identified the aircraft as a potential conflict. The data were plotted in a phase plane representation of the airspace which we call the risk space. The slope of a line in the risk space has units of time. Any line passing through the origin of the risk space (x=y=0) represents Tc. A least-squares linear regression analysis of the data resulted in a line with a slope of 3.0 minutes and an intercept of 3.6 nautical miles (r^2=0.48, n=61). The intercept is statistically equivalent to the five-mile FAA criterion for minimum separation. The pilots detected conflicts when they were 3 minutes away from violating the FAA's constraint on their behaviour. The least-squares fit to the data represents an invariant in the pilot-airspace interaction that triggers a consistent and task-relevant change in behaviour. The line defines the conditions that guide skilled detection of an impending en-route conflict. The risk space and its invariant elucidate the

knowledge pilots invoke to identify impending conflicts, and could form the basis of a new decision aid tailored to free flight.

Introduction

The United States Federal Aviation Administration (FAA) is currently evaluating options for modifying the National airspace system (NAS). One of the initiatives receiving widespread attention is free flight. Free flight is defined as any move away from the current system of centralized, ground-based control toward a more distributed system for the allocation of navigation authority (RTCA, 1995). In a fully decentralized free-flight environment, aircrews would make navigation (routing and separation) decisions without intervention from ground-based control, except during emergencies.

Under a grant from the FAA, the University of Minnesota Human Factors Research Laboratory (HFRL) is evaluating constraints on the distribution of control in the NAS. Central among these constraints are the navigation strategies used by commercial pilots and airline dispatchers. Since estimating time to contact (T_C) is a powerful method for detecting obstacles when navigating congested space, one of our research objectives has been to determine if commercial pilots use T_C when given the opportunity to navigate freely, e.g., in simulated free flight. We assume that pilots base navigation decisions on T_C, and have designed experiments to test whether an invariant relationship based on T_C describes skilled pilot behaviour.

Systems and organizations can be divided into two categories: those that demand error-free performance and those that stress efficiency (Weick & Roberts, 1993). The NAS is an exemplar of the former category. None of the partners in the NAS can tolerate error because the alternative is, all too often, catastrophic. Indeed, U.S. Secretary of Transportation Frederico Peña and Federal Aviation Administrator David R. Hinton urged conference attendees at the Aviation Safety Initiative Review in New Orleans 'to stay focussed on meeting the goals of *zero accidents* and *shared responsibility* that were adopted last January at the nationwide Aviation Safety Summit in Washington D.C.' (USDOT News Release, December 6, 1995). These goals demand continuous operational reliability.

The transition to free flight in en-route airspace will not change the demand for continuous operational reliability. It transfers the responsibility for ensuring reliability from a centralized decision-making system (ATC) to a distributed decision-making system composed of dispatch, aircrews and air-traffic managers. For example, when two aircraft converge to a point, each aircrew must take the other's actions into account when making decisions about separation and routing. For free flight to succeed, the crews must communicate strategically, represent each other's patterns of behaviour, and exercise heed when they modify their own behaviour (e.g. execute a manoeuver). Aircrews can act with heed only when they take account of others and communicate in a manner that enables others do the same. Estimating T_C is a powerful method for taking account of others.

Collision detection and time to contact

Time to contact (T_C) is a quantity often encountered in the research literature on navigation, sport and cognitive ethology. From an evolutionary perspective, the facility to extract from the environment knowledge of T_C is a highly useful adaptation. We can use it to dodge a spear, to navigate through a cluttered environment, or to intercept a ball. Though technology has removed us more than a few steps from nature, the mathematical relationships which describe adaptive motor behaviour remain appropriate.

A lingering debate over T_C revolves around two questions: *What* information is extracted from the environment to estimate T_C, and *how* is the estimate of T_C generated from this information? An information processing analysis of T_C assumes *conscious* calculation of T_C based on separation and velocity, information readily abstracted from the environment. The calculation would take the form $T_C = x/[dx/dt]$ where x is separation and [dx/dt] its time derivative, velocity. For example, air traffic controllers without radar must rely on numerical data from flight strips, and clearly derive T_C consciously using position and velocity data.

In contrast, ecological psychologists argue for 'direct perception', *pre-conscious* knowledge of T_C (McLeod & Ross, 1983). Support for direct perception comes mainly from studies of infants, who presumably are incapable of higher cognitive processes, and from examples from fast-motion tasks, such as hitting a cricket or tennis ball, in which time does not permit conscious processing of visual information. The measure of T_C resulting from direct visual perception is tau (τ), and was defined by Lee (1976) as $\tau = \phi/[d\phi/dt]$ where t is visual time to contact, ϕ is the angle subtended by the object as is approaches the observer, and $[d\phi/dt]$ its rate of closure.

Hypothesis: T_C drives collision detection by commercial pilots

Given the limited space allotted, we take a neutral position in this paper in the debate between information processing psychology and ecological psychology. We note that the two approaches produce an identical result - an estimate of the time to collision with another physical object. Our purpose is to raise important and interesting academic issue and to demonstrate the existence of an invariant relationship based on T_C that describes skilled pilot behaviour. Given the structure of T_C equations based on both the conscious and pre-conscious models, it is clear that a meaningful representation of any space to be navigated can be derived from separation and relative velocity. These parameters are made explicit in the representation we call the 'risk space'.

The risk space is a phase plane (Phatak & Bekey, 1969). The defining characteristic of a phase plane is that one of its axes is the time derivative of the other. Figure 1 is the risk space we proposed for en-route traffic dynamics (Smith & Hancock, 1995). The vertical axis is the separation between two aircraft; the horizontal axis is the rate of change of separation, or relative velocity. The axes capture information readily extracted from most glass-cockpit navigation displays (CDTIs). We propose that the phase plane of figure 1 captures and explains assessments of risk in the airspace made by commercial pilots, hence the name risk space.

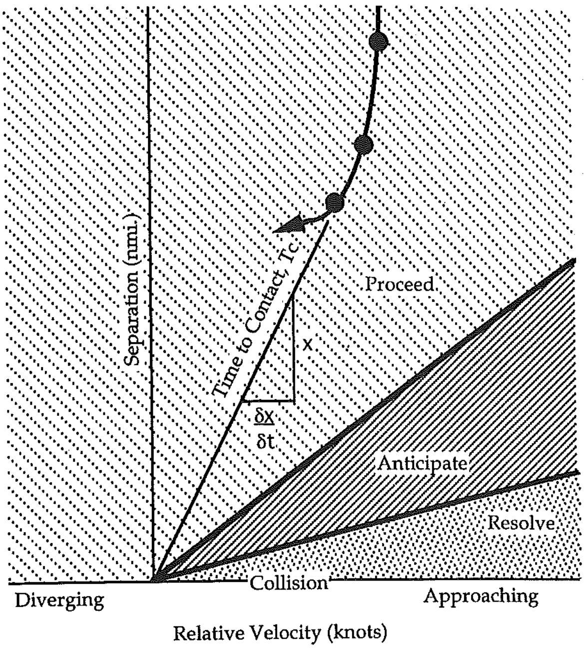

Figure 1 The risk space, a phase plane representation pilot decision making about separation between aircraft in en-route airspace

The separation and relative velocity of any two aircraft at an instant in time define a unique point in the risk space. As time passes and the aircraft traverse the airspace, the point traces a path through the risk space. While aircraft are converging, the path lies to the right of the vertical axis; while aircraft diverge, the path lies to the left of the axis. The path sweeps across the axis as the aircraft pass the point of minimum separation. Conflicts occur whenever the path approaches the horizontal axis, that is, as separation approaches zero. The slope of any straight line in the risk space has units of time. If the line passes through the origin of the risk space (x=y=0), the slope equals T_C.

If pilots do base navigation decisions on T_C, an invariant relationship based on T_C should divide the risk space into regions characterized by different decision alternatives and behaviour patterns. The thresholds shown in figure 1 divide the risk space into three such regions. The upper region represents wide separation and/or slow convergence (or divergence). Risk in the upper region is low; continuing on course is a safe decision. The lower region represents a near-conflict situation where risk is high; at least one of the converging aircraft must make a manoeuver to resolve the impending conflict. The middle region was proposed to represent a situation where decision makers anticipate the possibility of an impending conflict, seek resolution alternatives, and may or may not decide to initiate a manoeuver to avoid conflict.

If an invariant relationship based on time to contact, T_C, does indeed drive pilot decision making regarding conflicts, then the times when they decide to move from one course of action to another, e.g., from proceed to anticipate or directly to resolve, will form linear thresholds between decision regions in the risk space. Our experiments tested and failed to reject this hypothesis.

Experimental method

Subjects were currently certified commercial airline pilots (n = 10). Average flight hours was 9,177 (range 6,000 to 24,000). Aircraft types included A320, DC9/10, MD80/90, B747-400, B757, and B767. Ages ranged from 38 to 63 with a mean of 51.9 years.

HFRL designed and constructed the glass-cockpit experimental platform to evaluate pilot decision-making in alternative control schemes (ATC control, pilot control/free flight, and distributed control). The glass-cockpit simulates Boeing 757 instrumentation, and includes a primary flight display (PFD), a cockpit display of traffic information (CDTI), and a flight management system (FMS) with MCDU keypad. Simulations run via a network of Pentium based computer workstations running Linux OS. Software developed in-house enables the pilot to navigate a simulated airspace and to maintain or deviate from a preprogrammed flight plan using instrument flight rules and procedures. The CDTI and FMS were the pilots' only source of traffic information.

Subjects were presented twelve different en-route air traffic scenarios and were instructed to maintain standard FAA aircraft separation (five nautical miles horizontal/ 1,000 ft. vertical) between their ownship and six to sixteen other aircraft. In the free flight condition presented here, pilots were free to make all decisions about routing and separation without ATC support. In eleven of the twelve scenarios, pilots encountered realistic but challenging traffic conditions including crossing or merging traffic and non-conflicting traffic. The eleven conflict scenarios developed violations of minimum separation rules within six minutes if the pilot followed the preprogrammed flight plan.

Subjects were instructed to think aloud as they navigated through traffic in the en-route scenarios. This verbal protocol was recorded on a Dictaphone recorder with a Telex hands-free headset. Computer workstations recorded the pilot's MCDU keystrokes, FMS button-pushes, and CDTI settings. Separation and relative velocity and for each aircraft with respect to the pilot's ownship were calculated and recorded at approximately 5 Hz throughout the scenario. A Sony 8mm camcorder with audio input from the Telex system was also used to record trials and add a time stamp for correlation of the verbal protocol and other data.

The protocols were scored to determine when a pilot first indicated detection of an impending violation (the detection time). Protocol analysis was augmented by computer 'playback' of the subject's session to identify the aircraft that motivated the pilot's decisions (the target aircraft). The separation and relative velocity were plotted in the risk space for each target aircraft at its detection time.

Results

Grouping across subjects and scenarios, the analysis identified 148 target aircraft and their detection times. Of these 148, the pilots were able to resolve 61 of the conflicts,

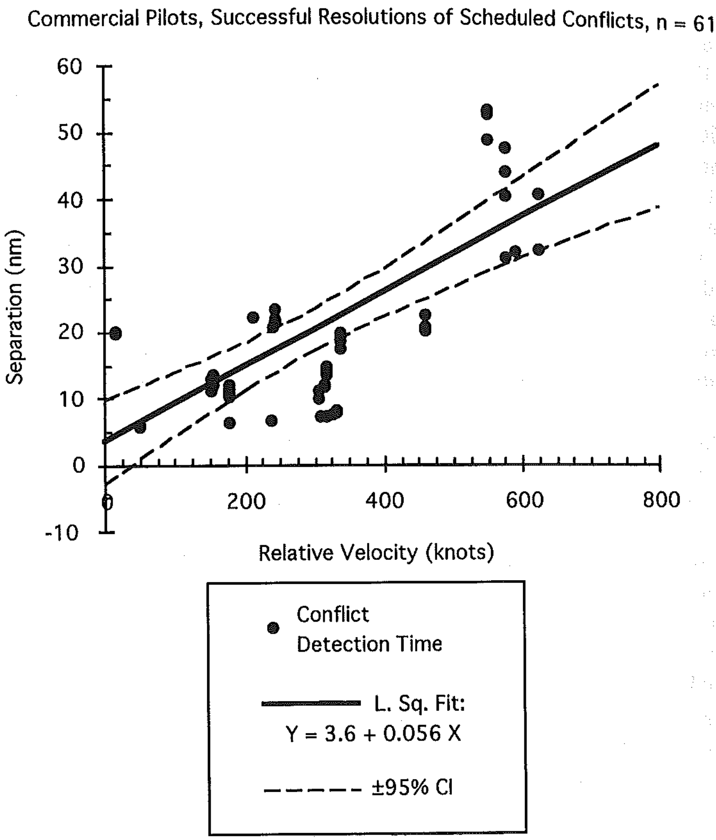

Figure 2 **Risk space showing pilot conflict detection times and least-squares linear regression analysis. Curves represent ±95% confidence interval for the regression line. Plotted points may overlap**

e.g., they made decisions that maintained the FAA's criterion for minimum separation. Each point in figure 2 represents the separation and relative velocity between the pilot's aircraft and a target aircraft at its detection time for the 61 conflicts that were successfully resolved. The data near the vertical axis represent conflicts in overtaking scenarios that unfolded slowly. The data at the far right represent conflicts with aircraft approaching nearly head-on. In several scenarios, when more than one subject detected a conflict at essentially the same time; their data may overlap.

The data shown in figure 2 collapse across subjects and scenarios. The data represent the full diversity of complexity factors: conflict type, density and bearing. In spite of this diversity, the data exhibit a strong linear trend. A least-squares linear regression analysis of the data defined a line with an intercept of 3.6 nm. and a slope of 0.056 hr. = 3.0 minutes ($r^2 = 0.48$, $n = 61$). The 95% confidence interval for the least-squares regression line, shown with dashed curves in figure 2, indicates that the Y-intercept is statistically equivalent to the five-mile FAA criterion for minimum separation. This result suggests that the behaviour of experienced pilots reflects a thorough adaptation to the central organizational constraint on how to take account of others in the airspace.

Discussion

Threshold for detection = $F(T_C)$, an explanation of pilot adaptation

The slope of the regression line indicates that commercial pilots detect conflicts when approximately three minutes from violating the FAA's minimum separation criterion. This result indicates that experienced pilots detect impending conflicts with sufficient lead-time take actions that maintain minimum separation. We interpret the regression line to define a threshold that differentiates between two classes of pilot behaviour. Above the threshold, pilots stay on their flight plan. Below the threshold, pilots begin to seek, select, and execute manoeuvres designed to resolve an impending conflict.

The single threshold divides the risk space into two regions, rather than the hypothesized three. Our experienced subject pool spent no discernible time 'anticipating'. Instead, they responded with action. Thinking in action is a hallmark of adapted individuals. The threshold represents an invariant in pilot-airspace interaction that triggers a task-relevant action across participants and situations. The invariant has units to time - time to an impending violation of the FAA's criterion for minimum separation. We argue that this 'time to contact' IS the knowledge that pilots extract from cockpit displays of traffic information (CDTI) that enables them to resolve impending conflicts safely and efficiently. By elucidating the knowledge pilots invoke to identify conflicts, the risk space and its invariant T_C document pilots' adaptation to the central organizational constraints on their behaviour. Pilots act heedfully by extracting knowledge of Tc.

We are convinced that free flight will fly if, and only if, it is implemented in a manner that fits the adaptation of its participants. To this end, regulators must heed how pilots interact with the airspace. The threshold in the risk space defines a critical element of that interaction and suggests itself as the natural model for the 'conflict probe' sought by the engineers of free flight. The conflict probe is meant to ensure heedful interaction. The threshold explains how pilots come to act heedfully. Our threshold for heed is what the NAS needs.

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Acknowledgments

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