Separation Assurance and Collision Avoidance Concepts for the Next Generation Air Transportation System

John P. Dwyer[1] and Steven Landry[2]

[1] Boeing Research & Technology
[2] School of Industrial Engineering, Purdue University
John.p.dwyer@boeing.com

Abstract. A review was conducted of separation assurance and collision avoidance operational concepts for the next generation air transportation system. The concepts can be distributed along two axes: the degree to which responsibility for separation assurance and collision avoidance is assigned to the controller verses the pilot(s), and the degree to which automation augments or replaces controller and pilot functions. Based on an analysis of the implications of these concepts from a human factors standpoint, as well as the technological readiness of the concepts, it appears that some form of supervisory control of separation by controllers is the most viable concept.

Keywords: Air traffic control, separation assurance, automation, roles and responsibilities.

1 Introduction

To accommodate 2 to 3 times air traffic demand, significant changes to the roles and responsibilities of air traffic controllers and pilots must occur. Cursory observation of the system, discussions with controllers, and experimental studies confirm this statement. Specifically, experimental work done by NASA Airspace Operations Lab (AOL) has demonstrated that beyond about 1.5 times the current day's traffic density, air traffic controller performance at the primary function of assuring proper separation declines precipitously [19]. Under higher capacity scenarios, therefore, allocation of the roles and responsibilities for separation assurance must change.

An analysis of options for separation assurance roles and responsibilities has been conducted. Implications of these different concepts, including the likely impact on separation assurance situation awareness, the likely impact on workload, and feasibility impacts are discussed in this document. In addition, several specific, existing concepts are examined in detail. Experimental work is underway to provide empirical evidence to support the impact estimates.

2 Separation Assurance Concepts

There are a number of plausible changes to separation assurance roles and responsibilities. First, the separation assurance function may be shared between pilots

M.J. Smith and G. Salvendy (Eds.): Human Interface, Part II, HCII 2009, LNCS 5618, pp. 748–757, 2009.

and controllers, without support from new automation. Second, some form of automation may aid or replace the controller's function. Third, on-board aircraft automation may carry out a separation assurance function or aid the pilot in doing so. Finally, some combination of these options may be used. Each of these general concepts will be outlined in the next section. After this discussion, a review of several tested concepts will be presented.

2.1 Pilot/Controller Shared Separation Assurance (No New Automation)

In one sense, the current air traffic control system shares responsibility for safe operation between controllers and pilots. Air traffic controllers provide separation, keeping aircraft apart by a procedurally mandated distance. Collision avoidance is provided by an Automated Collision Avoidance System (ACAS) on board the aircraft, supplemented by "see-and-avoid" – pilots visually scanning for potential collisions. The two systems work independently from one another, with no required coordination between them, although pilots may indicate to controllers when they are following ACAS avoidance maneuvers.

However, while providing additional safety, ACAS is not sufficient to increase the capacity of the air traffic management system since it has no direct impact on the controller's function. ACAS is a backup system, and provides no contribution to procedurally mandated separation. It instead aids in the prevention of collisions, typically after proper separation has already been lost. To improve capacity, pilots must share in the separation responsibility currently allocated solely to controllers.

The most aggressive form of this strategy is "free flight," in which pilots assume primary separation assurance responsibility [1]. However, no free flight concept has been advanced that does not also require new on-board automation, such as a cockpit display of traffic information (CDTI) or an advanced ACAS [3, 23]. For this approach, CDTI would display all traffic within the selected range of the instrument, and would likely be integrated with an advanced ACAS. Current ACASs work well as tactical collision avoidance backups, but lack capabilities required to perform separation assurance. ACASs work by interrogating the transponders of nearby aircraft and calculating relative positions and closure rates. If the system detects an excessive closure rate, it alerts the pilot. The most severe level of alert also includes a resolution maneuver, which can be coordinated with the intruding aircraft (if that aircraft is properly equipped). However, current ACAS has no capability to resolve multiple aircraft intrusion problems, does not consider strategic needs (such as the requirement to return to course), and does not work well in high-density airspace (e.g., the terminal area). For these reasons (among others), it would have to be radically modified to perform well as a primary separation assurance tool.

We know of no concept that, in the absence of advanced automation, would augment the controller's separation assurance function by shifting some responsibility to the flight deck. Moreover, it seems unlikely that, given current air crew workload, they could shoulder more of this burden without automation assistance. In short, this change in responsibility would likely transfer situation awareness from the controller to air crews at the cost of significantly increasing their workload. In addition, under future demand scenarios, this concept would not seemingly reduce the controllers' workload to an acceptable level. For future discussion in this document, this concept will be referred to as "Shared Responsibility – No Automation."

2.2 Air Traffic Control Automation

Since automation appears to be the only solution to expanding the capacity of controlled airspace to the extent desired, one option is to augment or replace the controller's separation assurance function with automation. Such a concept is being considered and developed by NASA under the Advanced Airspace Concept (AAC) [8]. (Other concepts are being developed but are further behind in terms of technology readiness.) One possible implementation of AAC uses only a centralized, air traffic control-based automation system. Such an implementation involves little change to pilot roles, so it would have minimal to no direct impact on their situation awareness and workload.

Under this implementation [9], an automated system would detect likely future losses of separation up to 15 minutes prior to the event. Another part of the automated system (the "autoresolver") would then identify a trajectory that would resolve the (primary) conflict. This system would look strategically at conflicts, incorporating intent (via the flight plan) and ensuring that secondary conflicts do not occur when resolving a primary conflict. A shorter separation-horizon tactical system would provide an independent backup for unresolved short-range conflicts using only projected current states and not considering secondary conflicts. The concept then diverges into several possibilities regarding the alerting and resolution functions.

One possibility is that the system only identifies the possible separation problem to the controller, who would then be responsible for resolving it. Considerable work has been done on automation that can identify conflicts [2, 22], although no system is sufficiently ready that it could be fielded in the near term. Such a system essentially replaces (or augments) the conflict detection role of the controller but leaves the controller's conflict resolution role unchanged. However, given that it is both detection and resolution that proved difficult for controllers under high capacity scenarios [1], such a concept seems to be insufficient due to excessive workload for controllers. This concept will be referred to as "Conflict ID Only."

A second possibility is that the system identifies the conflict, and the controller uses an automated tool to manually identify a resolution. This concept replaces/augments the conflict detection role and augments the conflict resolution role of the controller. Such a concept is being investigated empirically, as will be discussed toward the end of the paper. This additional conflict resolution automation used by the controller, while utilizing the same conflict detection system described above, would pose a currently unresolved human factors challenge regarding the display of this function. It also seems that the workload associated with using the tool would quickly exceed the capability of the controller should multiple, short-term conflicts arise simultaneously or in very high-density situations. Nonetheless, the system, via the highly integrated controller role, would seem to retain a great degree of controller situation awareness whereas more completely automated concepts would begin to reduce it. This concept will be referred to as "Conflict ID with Resolution Tools."

A third possibility is that the system identifies the conflict and at least one resolution to the controller, who would have the option of accepting or modifying the resolution. This concept is similar to the previous one, except that the controller is under no obligation to develop a resolution (i.e. the controller can simply accept the automation's resolution). Given its possibly low impact on controller situation awareness, along with its reduction in workload compared to the less-automated approaches described above, this option is being pursued as the current primary candidate for an operational concept, and will be referred to as "Conflict ID and Resolution Option." This concept includes relieving the controller of responsibility for losses of separation, and instead places that responsibility on the automation.

A fourth possibility is that the system identifies the conflict and computes a resolution that is automatically implemented, without controller intervention. Such a system would significantly reduce controller workload. This concept is also being seriously pursued, although the significant impact on the situation awareness of the controller is problematic. In addition, it is expected that such a concept is impractical unless the automation can be demonstrated to be 100% reliable, which at the current time seems unlikely. This concept will be referred to as "Conflict ID and Automatic Resolution."

This "Conflict ID and Automatic Resolution" option can be modified in a number of ways. For example, the responsibility for separation can be shared with the flight deck (to be discussed in the next section). Alternately, the controller can be made responsible for some of the aircraft in the sector (including any of the other air traffic automation options), while automation handles the remaining aircraft. This "segmentation" can be on the basis of a number of factors, including equipage, time to conflict, and "nominal" versus "off-nominal" groupings. Some means for distinguishing those under the control of the automation from those under the control of the air traffic controller (such as dimming the datatags of those handled by automation) would need to be defined. This idea is particularly appealing for the more highly automated concepts, as it holds the possibility of recapturing some of the controller situation awareness lost under those concepts.

In the near term, many aircraft in the airspace system will not be equipped with technologies required for the automation schemes discussed above to be effective [18]. In a basic implementation of any of the above concepts, all aircraft currently controlled under radar can be tracked and resolved. However, it is likely that additional technologies, such as a satellite-based positioning system, a position and intent broadcast system (such as Mode S or ADS-B), data communications, and advanced Flight Management System (FMS) computers would be helpful for increasing the capacity of the system under high-density scenarios. One option is therefore that automation would resolve conflicts for equipped aircraft, while controllers handled unequipped aircraft.

Another proposal is to segment aircraft on the basis of time to loss of separation (LOS). At present, it seems likely that AAC will not be able to resolve 100% of conflicts. In particular, controllers may be required to resolve conflicts either a short time to LOS (inside of a few minutes so as not to rely on tactical backups) or a LOS time longer than that handled by the strategic autoresolver. Such aircraft would be the responsibility of the controller, who may use automation tools to assist with resolutions.

Another concept is that responsibility for "off-nominal" aircraft, such as emergencies or other high-priority aircraft, may be shifted to the controller. Such a concept was investigated, but controllers found substantial difficulty in accomplishing this task without resolution automation assistance. Even so, comments by the participant controllers in the experiment seemed to suggest that they were not capable of understanding whether computer-based resolutions were accurate or not, making their role in such a control loop of questionable benefit.

2.3 Flight Deck Automation

A large number of flight deck automation concepts have been proposed [3, 11, 10], although the distinction between these concepts is mainly captured by the algorithms used by an airborne separation assurance system (ASAS). These concepts are typically referred to as "Distributed Control" concepts. These concepts have the desirable feature of reducing controller workload, although this reduction is at the expense of much lower controller situation awareness.

Unfortunately, no mature concept has been proposed. However, one can speculate that aircraft with ASAS could handle separation from each other (and possibly from unequipped aircraft as well). The ASAS would identify conflicts to the pilot, who would handle them in a manner similar to the controller options outlined above (ID only, resolution tools, resolution option, and automatic resolution).

For such concepts, the mix of aircraft is particularly problematic. Currently conceived algorithms often require (at least) an ASAS to be on board both aircraft, and often work best when the aircraft are ADS-B equipped. This is similar to the current situation with ACAS, which works best when both aircraft are equipped.

2.4 Combination of Centralized and Distributed Separation Assurance Systems

What seems more likely is that centralized and distributed systems will act in concert to provide both separation assurance and collision avoidance. Certainly some form of collision avoidance will be on board all commercial aircraft, as it is in today's system. It is unclear as yet, however, what form such distributed systems would take and what function they would serve in a "Mixed Concept."

One possibility arises from the idea that a future system concept will need to demonstrate that it is at least as safe as today's system. One way of accomplishing this is to ensure that, in the event of failures, the worst-case mode of the system is today's system. In other words, the system would need to be able to gracefully degrade from an automated system to a fully manual (i.e. today's) system. One method of accomplishing this is to ensure that ASASs can "pick up" the separation function should the centralized system fail. ASASs could run in parallel with the centralized system, perhaps deferring to it in normal operation. In case the centralized system fails (e.g., as indicated by the loss of a "heartbeat" signal), the ASAS would resolve separation issues. Under conditions of more general failures of the centralized system, the ASASs could be designed to migrate the system from high-capacity (i.e. 3x) to current-level capacity (i.e. 1x), which could then be managed manually by an air traffic controller.

2.5 Pilot and Controller Roles and Responsibilities under Automation Schemes

Under the automation schemes presented, the roles and responsibilities of the controllers and pilots would clearly change. The evolution path to these new concepts from today's system is undefined, as is the effect that the various schemes would have on the performance of pilots and controllers. Empirical research is underway to answer these questions. As of now, two options appear to be most likely: automation monitoring, and supervisory control (airspace management). These functions are in addition to the assumption that some responsibility for separation assurance and collision avoidance would remain with the pilot and controller.

Under a typical automation monitoring concept, the controller would track the automation, intervening when it failed to detect or resolve a conflict, and would take over in case the system failed [21]. However, in the present case this seems highly implausible since the system has been automated *because* the controller is unable to accomplish the task. Removing the controller from the control loop (radically lowering the controller's situation awareness) with re-insertion under conditions of automation failure, would simply not work. Humans are (in general) poor monitors of reliable automation [20], and the abrupt and unanticipated shift in workload from near zero to extremely high is conducive to very poor performance. Moreover, the controller would most likely be unable to detect system failures for the same reasons. Therefore, a typical automation monitoring concept seems ill-advised.

One variation of the automation monitoring concept attempts to keep the controller "in the loop." Using "conflict ID and resolution option" and "segment by equipage," controllers would be shown only those aircraft that are expected to conflict. (Other aircraft would be "grayed out" to reduce clutter.) Automation would identify the conflict and a resolution to the controller, who can choose to implement the resolution, or not address the conflict immediately. If the conflict is left unresolved, the automation would transmit the resolution to a properly equipped flight deck once a certain time to loss of separation was reached. Controllers would not be responsible for losses of separation; that responsibility would remain with the automation. However, controllers would be responsible for communicating resolutions to unequipped aircraft. This concept has been tested at NASA with substantial success.

Under one supervisory control concept, controllers would "manage" the airspace by setting global flow factors for the sector, such as separation minima and acceptance rates along sector routes. The automation would control the traffic subject to these constraints. When off-nominal events (such as adverse weather) were likely (or currently) impacting the sector, the controller would "throttle back" the traffic using these settings. Such a concept would keep the controller aware of the conditions in the sector, and keep workload at a reasonable level. However controller situation awareness of the actual traffic could be severely reduced, making it impossible to detect automation errors or taking over in case of system failure.

Another supervisory control concept arises out of the observation that controllers currently mitigate many conflicts, whereas proposed automation merely detects and intervenes. Controllers intervene not only to resolve projected conflicts (or near conflicts), but also intervene to ensure that there is sufficient time to intervene should some off-nominal event occur. For example, controllers might place an aircraft that is climbing to one thousand feet below a second aircraft's altitude on a parallel, rather than intersecting, course, just to be sure that, should the aircraft fail to level off at the assigned altitude, it will not rapidly pose a LOS or even collision danger.

Such strategies are extremely common for controllers, and suggest a possible supervisory control role. Controllers might monitor near, but not actual, LOS aircraft pairs (which would be resolved by the automation), and could instruct the automation to resolve such pairs if the controller felt that there was sufficient likelihood that an adverse situation could arise quickly in the event of an unfortunately timed off-nominal event. The controller could even be kept apprised of the number of such pairs, and could intervene to "lessen the pressure" on the sector by (for example) reducing capacity, or by creating contingency plans.

2.6 Summary of General Classes of Concepts

Based on the above analysis, a summary of currently proposed automation schemes, along with their technological readiness (with "low" readiness equating to "needing much more development"), impact on controller and pilot situation awareness and workload, and an assessment of their viability, are shown in Table 1. Viable concepts include those that utilize ATC automation, with or without flight deck automation.

Table 1. Taxonomy of separation assurance concepts and projected impact on situation awareness and workload

			Expected impact comparing NextGen environment to current environment				
	Concept	**Expected technological readiness**	**Controller situation awareness**	**Controller workload**	**Pilot situation awareness**	**Pilot workload**	**Concept appears viable?**
	Shared responsibility - no automation	High	Small reduction	Excessive	Moderate increase	Excessive	No
ATC automation	Conflict ID only	Medium-High	Neutral	Excessive	Neutral	Neutral	No
	Conflict ID with resolution tools	Medium	Neutral	Very large increase	Neutral	Neutral	Yes
	Conflict ID with resolution options	Medium	Small reduction	Moderate increase	Neutral	Neutral	Yes
	Conflict ID with autoresolver	Medium	Large reduction	Moderate reduction	Neutral	Neutral	Yes
	Distributed control	Low	Very large reduction	Large reduction	Large increase	Large increase	No
	Mixed concepts	Medium-Low	Moderate reduction	Moderate increase	Moderate increase	Moderate increase	Yes

3 Concept Implementations Currently Under Study

Several versions of the concepts described above are under investigation by researchers at NASA. These candidate schemes are versions of the air traffic automation discussed herein. In the three concepts outlined in this section, automation detects aircraft-pair LOS conflicts, calculates candidate conflict resolutions, and can (depending on extent of air traffic controller involvement) deliver the resulting resolution clearances to flight decks for pilot or FMS implementation.

3.1 Candidate Concept 1: Conflict ID with Resolution Tools

Simulations at NASA have been conducted using an operational concept that provides controllers with automated conflict identification and conflict resolution tools [17]. The simulations included arrival spacing tasks, and controllers used the conflict resolution tools to help manage spacing and resolve conflicts.

Under this concept, controllers had available to them decision support tools for scheduling and trajectory planning. Aircraft were equipped with an FMS and data communications system, an airborne separation assistance system, and a flight deck display of traffic information. Controllers used substantively the same procedures as today, augmented by the above mentioned decision support tools and communications system. In one version of the concept, voice communication was still necessary to hand off aircraft to the next sector controller, and some of the data communication information was not used by the ground automation. In a subsequent version, these shortcomings were removed.

The results of this simulation indicated that without the ability to uplink trajectories electronically to flight decks, the concept, while manageable, did not provide capacity improvements. With more tightly integrated tools, the system was able to manage a 50% increase in traffic capacity with little workload increase over current day operations. A subsequent simulation (with no arrival task) of this concept found that operations with 200% traffic was "somewhat manageable," and 300% traffic was unmanageable [19]. However, these simulations were conducted using 100% equipage with the improved automation. In conditions of less than complete equipage, it would be expected that this increased traffic capacity would be correspondingly lessened.

3.2 Candidate Concept 2: Conflict ID with Resolution Options

Recent simulations at NASA have been using an operational concept that provides controllers with automated conflict identification and a resolution option [19]. The resolution option was displayed when requested by the controller, and could be accepted and uplinked or modified. This concept was implemented in en-route airspace (no arrival task), but otherwise was similar to the configuration for candidate concept 1. A slightly updated controller display was used.

Controller workload was reduced using this concept, and appeared feasible at even the 300% traffic level. Controller acceptance of the automated resolutions was high. However, situation awareness was not tested, nor was system disruption (e.g., system failures). Moreover, there was no operational concept for handling system disruptions.

Additional simulations were run using this concept at different levels of equipage. The basic finding is that controller workload is driven by the number of unequipped aircraft, and initial results suggest that some unequipped aircraft could be handled under these conditions, but more data analysis is needed to confirm this.

3.3 Candidate Concept 3: Conflict ID with Auto Resolution (with segmentation)

One last scheme evaluated at NASA is a fully automated concept in which automation closes the loop by electronically transmitting a conflict resolution to the appropriate aircraft [19]. That resolution is then implemented by the pilot or FMS. In such a case, controllers are "out of the loop," and are only responsible for unequipped aircraft.

The results for this concept are virtually the same as for candidate concept 2 (again, situation awareness was not measured). Resolutions have been found to be acceptable to controllers, and workload at 300% traffic levels is acceptable. Tests are underway to evaluate the effect of disruptions on this (and other) concept(s).

Acknowledgments. This research was supported by NASA Ames Research Center under cooperative agreement NNA06CN30A (Walter Johnson, Technical Monitor).

References

1. Andreatta, G., Brunetta, L., Guastalla, G.: From ground holding to free flight: An exact approach. Transportation Science 34, 394–401 (2000)
2. Barhydt, R., Eischeid, T.M., Palmer, M.T., Wing, D.J.: Use of a prototype airborne separation assurance system for resolving near-term conflicts during autonomous aircraft operations. In: Proceedings of the AIAA Guidance, Navigation and Control Conference, Austin, TX, USA, AIAA (2003)
3. Bilimoria, K.D., Sheth, K.S., Lee, H.Q., Grabbe, S.R.: Performance evaluation of airborne separation assurance for free flight. Air Traffic Control Quarterly 11, 85–102 (2003)
4. Consiglio, M.C., Carreno, V., Williams, D.M., Munoz, C.: Conflict prevention and separation assurance in small aircraft transportation systems. Journal of Aircraft 45, 353 (2008)
5. Consiglio, M.C., Hoadley, S., Wing, D., Baxley, B.: Safety performance of airborne separation: Preliminary baseline testing. In: Proceedings of the 7th AIAA Aviation Technology, Integration and Operations Conference, Belfast, Ireland (2007)
6. Dowek, G., Munoz, C., Carreno, V.: Provably safe coordinated strategy for distributed conflict resolution. In: Proceedings of the AIAA Guidance Navigation, and Control Conference and Exhibit, San Francisco, California (2005)
7. Eby, M.S., Kelly III, W.E.: Free flight separation assurance using distributed algorithms. In: Proceedings of the 1999 IEEE Aerospace Conference (1999)
8. Erzberger, H.: The automated airspace concept. In: 4th USA/Europe Air Traffic Management R&D Seminar, Santa Fe, NM (2001)
9. Erzberger, H.: Transforming the NAS: The Next Generation Air Traffic Control System. In: 24th International Congress of the Aeronautical Sciences, Yokohama, Japan (2004)
10. Galdino, A.L., Munoz, C., Ayala-Rincon, M.: Formal verification of an optimal air traffic conflict resolution and Rrecovery algorithm. In: Leivant, D., de Queiroz, R. (eds.) WoLLIC 2007. LNCS, vol. 4576, pp. 177–188. Springer, Heidelberg (2007)
11. Hill, J.C., Archibald, J.K., Stirling, W.C., Frost, R.L.: A multi-agent system architecture for distributed air traffic control. In: AIAA Guidance, Navigation, and Control Conference AIAA 2005-6049, San Francisco, CA, pp. 1–11 (2005)
12. Hwang, I., Kim, J., Tomlin, C., McNally, D., Gong, C., Rantanen, E.M., Naseri, A., Neogi, N.: Protocol-Based Conflict Resolution for Air Traffic Control. Air Traffic Control Quarterly 15, 1–34 (2007)
13. Jackson, M.R.C., Sharma, V., Haissig, C.M., Elgersma, M.: Airborne technology for distributed air traffic management. In: Proceedings of the 44th IEEE Conference on Decision and Control, Seville, Spain, pp. 3947–3954 (2005)
14. Johnson, W.W., Battiste, V., Delzell, S., Holland, S., Belcher, S., Jordan, K.: Development and demonstration of a prototype free flight cockpit display of traffic information. In: Proceedings of the 1997 SAE/AIAA World Aviation Conference (1997)
15. Kuchar, J.K., Yang, L.C., Mit, C.: A review of conflict detection and resolution modeling methods. IEEE Transactions on Intelligent Transportation Systems 1, 179–189 (2000)
16. McNally, D., Gong, C.: Concept and Laboratory Analysis of Trajectory-Based Automation for Separation Assurance. Air Traffic Control Quarterly 15, 35–63 (2007)

17. Prevot, T., Battiste, V., Callantine, T., Kopardekar, P., Lee, P., Mercer, J., Palmer, E., Smith, N.: Integrated air/ground system: Trajectory-oriented air traffic operations, data link communication, and airborne separation assistance. Air Traffic Control Quarterly 13, 201–229 (2005)
18. Prevot, T., Callantine, T., Lee, P., Mercer, J., Battiste, V., Johnson, W., Palmer, E., Smith, N.: Cooperative air traffic management: A technology enabled concept for the Next Generation Air Transportation System. In: 5th USA/Europe Air Traffic management Research and Development Seminar, Baltimore, MD (2005)
19. Prevot, T., Homola, J., Mercer, J.: Human-in-the-loop evaluation of ground-based automated separation assurance for NEXTGEN. In: 8th AIAA Aircraft Technology, Integration, and Operations Conference, Anchorage, Alaska (2008)
20. Senders, J.W.: The human operator as a monitor and controller of multidegree of freedom systems. Ergonomics: Major Writings (2005)
21. Sheridan, T.B.: Telerobotics, Automation, and Human Supervisory Control. The MIT Press, Cambridge (1992)
22. Tomlin, C., Mitchell, I., Ghosh, R.: Safety verification of conflict resolution manoeuvres. IEEE Transactions Intelligent Transportation Systems on 2 2, 110–120 (2001)
23. Yang, L.C., Kuchar, J.K.: Prototype conflict alerting system for free flight. Journal of Guidance, Control, and Dynamics 20, 768–773 (1997)