

Survey of Air/Ground and Human/Automation Functional Allocation for Separation Assurance

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Separation assurance is a fundamental requirement for safe operations of air traffic. New paradigms of separation assurance will be required to accommodate the anticipated increase of air traffic in the future. This paper defines a taxonomy for the allocation of separation assurance functions along the air/ground and human/automation axes, and then builds a knowledge base from a comprehensive survey of separation assurance studies conducted over the past 12 years with an emphasis on high-fidelity human-in-the-loop simulations and operational evaluations. The goal of this effort is to identify trends and gaps in the current knowledge base of functional allocation for separation assurance, so that it may serve as a guide for planning future work. One finding is that limited delegation for arrival merging/spacing has been developed to a relatively high level of maturity. Another finding is that various aspects of automated concepts for ground-based and airborne separation assurance have been well studied; the key challenge going forward is system level integration and evaluation.

I. Introduction

SEPARATION assurance is a key component of air traffic management (ATM); its purpose is to ensure safe operations. One aspect of separation assurance is to meet specified requirements for distance-based separation between aircraft pairs; for example, a typical requirement in en route airspace is a horizontal separation of at least 5 nmi or a vertical separation of at least 1,000 ft. Another aspect of separation assurance is to keep aircraft away from a region of airspace that is unavailable due to weather or special use (e.g., military operations). In some situations, the separation assurance requirements must be satisfied while also conforming to traffic flow management constraints such as time-based metering where merging flows are metered in time across a reference point in order to facilitate efficient minimum-delay flows into capacity-constrained airports.

The primary separation assurance functions are: predict/detect the conflict; determine a trajectory modification that resolves the conflict safely and efficiently; and, execute the selected trajectory modification to resolve the conflict. Functional allocation pertains to where these separation assurance functions are performed (e.g., air, ground, or distributed between air and ground) and what entity performs these functions (e.g., human alone, human assisted by automation, or automation alone).

Currently, separation assurance functions are human-workload-intensive because they are performed with a limited set of tools. In order to safely accommodate significantly higher traffic densities in the future, a new separation assurance paradigm will be required. Concepts of future airspace operations, such as the Next Generation Air Transportation System (NextGen) [JPDO, 2010] and the Single European Sky ATM Research (SESAR) [Eurocontrol, 2009], generally feature a higher level of automation. However, some separation assurance concepts propose a centralized ground-based control authority [Erzberger and Paielli, 2002], while others envision limited and/or full delegation of control functions to the cockpit [Green et al, 2001], [FAA/Eurocontrol, 2008]. There is a large body of literature reporting investigations of such future concepts; they cover various aspects of separation assurance, e.g., conflict detection and resolution algorithms, information displays, integrated decision support tools, datalink communications, and the roles and responsibilities of humans and automation tools.

The goal of this paper is to identify trends and gaps in the current knowledge base of functional allocation for separation assurance, so that it may serve as a guide for planning future work in this area. Section II defines a taxonomy for the allocation of separation assurance functions along the air/ground and human/automation axes. Section III summarizes the knowledge base assembled from a comprehensive survey of separation assurance studies,

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with an emphasis on high-fidelity human-in-the-loop (HITL) laboratory simulations and operational evaluations. The focus areas of these studies are categorized by a mapping to the functional allocation space established by the taxonomy. Section IV presents some insights in the form of trends and gaps gleaned from a qualitative analysis of the knowledge base.

II. Taxonomy of Separation Assurance Functions

In this work, separation assurance functions are allocated along two axes: Locus of Control and Level of Automation. Some points of interest along these axes are defined below; Fig. 1 provides an overview. Each cell aggregates other relevant factors such as: time horizon (strategic/tactical), incorporation of flow constraints such as metering, level and frequency of information exchanged between system elements, airspace domain, and aircraft flight phase (climb, cruise, descent).

A. Locus of Control

This refers to the location(s) of control authority and responsibility for separation assurance. Three points are identified along this axis, as defined below. Note that each category can have various levels of automation (described in subsection II-B) for separation assurance.

Ground-based Control: Air Navigation Service Provider (ANSP) predicts conflicts and sends resolution clearances to cockpit crew for execution.

Air-Ground Control: There are two types of air-ground control, as described below.

Type 1: ANSP delegates specific conflict resolution functions to cockpit crew on a limited (per-event) basis. For en route operations, this generally means a climbing/descending, passing, crossing, or turn-behind maneuver relative to a designated reference aircraft; for terminal area operations, this generally means merging into an arrival stream and establishing/maintaining a specified time/distance spacing from a designated lead aircraft.

Type 2: In the same airspace, some aircraft are under ground-based control while others are under limited-delegation (Type 1) control and/or airborne control.

Airborne Control: Full delegation of separation assurance functions from ANSP to the cockpit crew, which predicts and resolves all of their conflicts without any ANSP involvement.

B. Level of Automation

This refers to the scope and role of the human and/or automation for performing separation assurance functions. Comprehensive taxonomies for human-machine interaction have been published, e.g., [Parasuraman, 2000], but this work simply uses three levels of automation as defined below. Note that each category can have various configurations along the locus of control (described in subsection II-A) for separation assurance.

Low Automation: Corresponds to current air traffic operations. Most of the information processing for separation assurance is done by the human controller and/or pilot who generates solutions using a basic set of tools. ANSP has a radar traffic display, flight plan strips (paper/electronic), and possibly a basic conflict probe/solver. Cockpit crew has an out-the-window view, basic flight displays, and the Traffic Alert and Collision Avoidance System (TCAS). This level of automation features voice clearances for route/altitude/speed-based control. Responsibility for separation assurance lies with the human.

Moderate Automation: Corresponds to a point on the evolutionary path to mature NextGen/SESAR operations. This level of automation features decision support tools (DSTs) that offer trajectory-based advisories which the human controller and/or pilot can accept as proposed or with appropriate modifications. Basic trajectory clearance information is sent to the cockpit flight management system (FMS) from the DST (via datalink if the DST is ground based). These trajectory clearances may incorporate new waypoints and/or a required time of arrival at an arrival fix or en route flow control point. Responsibility for separation assurance lies with the human.

High Automation: Corresponds to mature NextGen or SESAR operations. Most of the information processing, including the generation of resolution advisories, is done by advanced trajectory-based automation. The automation computes full 4D trajectory-based solutions which are sent to the cockpit FMS (via datalink if the automation is ground based). The human controller and/or pilot has a high-level supervision or intervention role. In some operational concepts, responsibility for separation assurance may lie with the automation rather than the human.

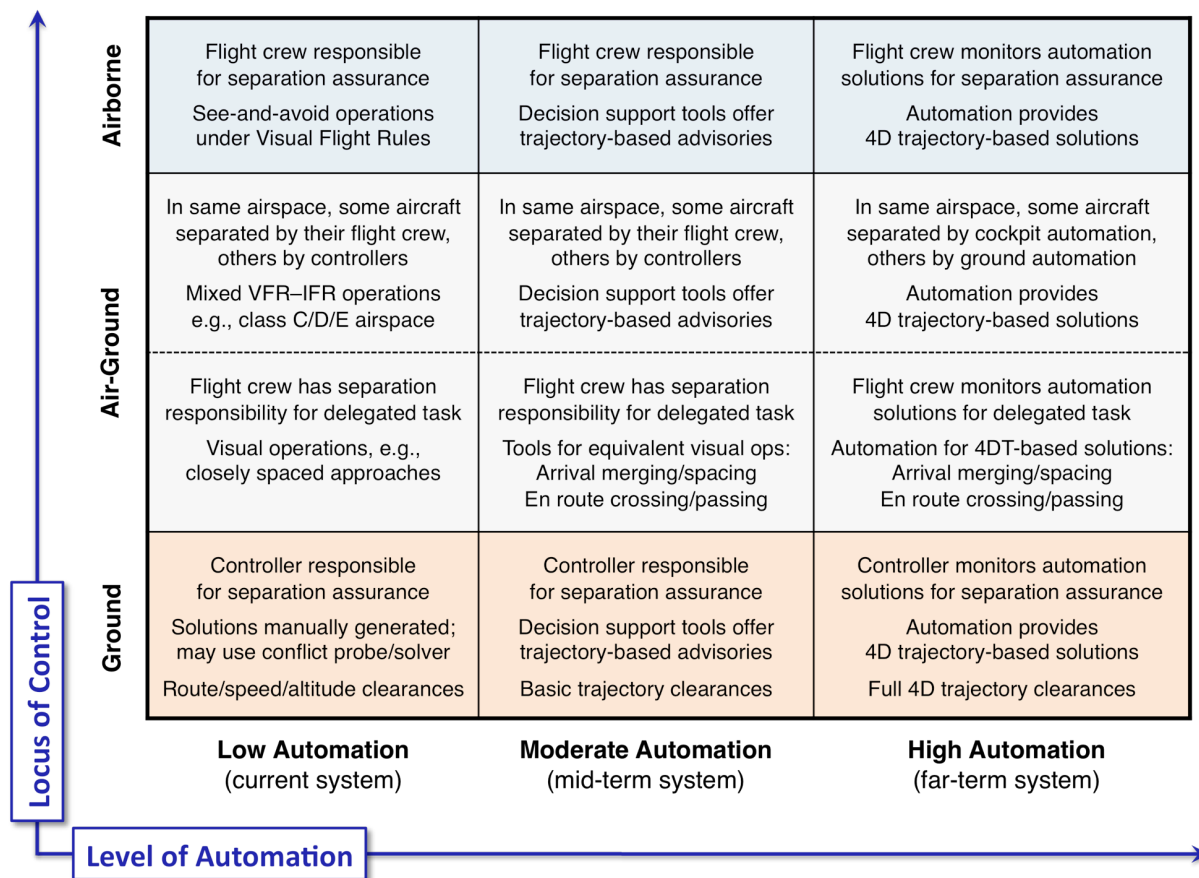


Figure 1. Functional allocation space for separation assurance

III. Literature Survey Results

A comprehensive literature survey was conducted, covering air/ground separation assurance research in the U.S. and Europe, with emphasis on results of human-in-the-loop (HITL) simulations and operational evaluations. The survey covered the period from 1998 to 2010. The primary sources used for the survey were peer-reviewed papers from the *Air Traffic Control Quarterly* journal and the proceedings of the FAA/Eurocontrol USA/Europe ATM R&D Seminars (mostly from the Air/Ground Integration track and Separation track). Other sources included proceedings of American Institute of Aeronautics and Astronautics (AIAA) conferences and the International Congress of Aeronautical Sciences (ICAS). About 50 relevant publications were identified, and they are listed alphabetically by author at the end of this paper.

Based on the literature survey, studies that are best associated with the relevant functional allocation configurations in Fig. 1 are summarized. Although results from some computer-based (no participation by human controllers/pilots) analyses are included when appropriate, the emphasis is on HITL laboratory simulations and operational evaluations (field tests at air traffic control facilities and/or flight tests). Unless noted otherwise, the HITL simulations involved participation by professional air traffic controllers and airline pilots. Simulated traffic was at current levels (1X) unless noted otherwise. Key results from these studies are drawn directly from the referenced publications with minimal editing. The quotation of results and conclusions from these journal/conference papers should not be construed as an endorsement or independent confirmation.

Many of the studies were evaluations performed while the concepts, enabling technology, and even the supporting infrastructure (i.e., simulation capabilities and analysis methodologies) were being developed. Often the research itself highlighted issues that were then resolved in subsequent developments of procedures and

technologies during the iterative cycle that is characteristic of research and development work. Therefore, conclusions drawn from any specific reference must be evaluated in the context of its sequence in the entire body of literature. There are also some cases where research was not continued beyond the initial studies. In those cases, the reader should keep in mind that issues identified may be resolvable with additional research and development. Many initial studies were by necessity performed with simplifying assumptions. Because of them, the reader should keep in mind that positive assessments of feasibility reported in the literature are only initial indications of feasibility.

A. Ground-based Control with Low Automation

Controllers in today's air traffic control system can separate traffic using only flight plan strips and a radar display with flight data blocks. Additionally, conflict probe and trial planning (what-if evaluations) functionality may be available.

The User Request Evaluation Tool (URET) is a conflict-detection tool that automatically detects and advises air traffic controllers of predicted conflicts between aircraft or between aircraft and special use airspace, and gives controllers the capability to create alternative conflict-free flight routings in en route air traffic control centers. [Arthur and McLaughlin, 1998] reports on a quantitative evaluation of conflict probe performance; [Kerns and McFarland, 1998] reports on an operational evaluation and benefits assessment. Full deployment of URET in the U.S. national airspace system was completed in 2006.

[McNally et al, 2001] reports an operational evaluation of the Direct-To (D2) controller tool in Fort Worth Center. D2 is a prototype tool for en route radar controllers that provides clearance advisories for wind-favorable direct routes, traffic conflict detection information, and a rapid-feedback "what-if" trial planning function. Controller feedback during testing was consistently very positive and the controller team reported that all D2 functionality would be beneficial if integrated into their R-Side traffic situation displays.

B. Ground-based Control with Moderate Automation

There is a set of studies assessing a separation assurance concept featuring trajectory-based operations with air/ground datalink. Ground-based automation computes integrated solutions to problems like metering, weather avoidance, traffic conflicts and the desire to find and fly more time/fuel efficient flight trajectories in en route and transition airspace. Clearances, in terms of altitude, route, and speed changes, are delivered using currently available integrated FMS/datalink with Controller-Pilot Data Link Communications (CPDLC).

In a HITL evaluation of trajectory-based automation, a conflict probe detected and displayed conflicts to a human controller who generated resolutions using an interactive trial planner [McNally and Gong, 2007]. The traffic scenario covered five high-altitude sectors at 1X and 2X traffic densities. Under laboratory conditions, a single controller (simulation engineer) performed the separation functions normally performed by 4 – 10 people in today's operations with no separation violations for 1X traffic and only one violation for 2X traffic. Direct wind-favorable routing improved flying time efficiency of non-conflicted aircraft by 5% for 1X traffic.

A study was conducted using the avionics of a Boeing 747 Level-D simulator [Mueller, 2007] to establish the datalink protocols needed for a significant majority of the trajectory change types required to solve a traffic conflict or deviate around weather. Engineers on the "ground side" of the datalink generated lateral and vertical trajectory clearances and transmitted them to the FMS of the aircraft simulator; the airborne automation then flew the new trajectory without human intervention, requiring the flight crew only to review and to accept the trajectory.

An operational evaluation of Boeing 777 trans-Pacific arrivals to San Francisco International airport demonstrated datalink-enabled conflict-free continuous descent approaches that conform to metering constraints and provide fuel savings [Coppensbarger et al, 2009]. Upon sharing wind and descent-speed-intent data, ground-based and airborne automation were found to predict meter-fix arrival times to within a mean accuracy of 3 sec over a 25 min prediction horizon.

A computer-based analysis covering 100+ hrs of simulated en route traffic is reported in [McNally et al, 2010]. Key results are that integrated strategic-tactical automation maintained separation above 17,000 ft, and wind-favorable direct routings during a busy 4-hour period saved 269 min flying time for traffic above FL240.

C. Ground-based Control with High Automation

The Automated Airspace Concept (AAC) is described in [Erzberger and Paielli, 2002]. A ground-based component, the Advanced Airspace Computer System (AACS), generates efficient and conflict-free route, altitude, and speed clearances and associated trajectories, and sends them directly to the aircraft via datalink. Another ground-based component, the Tactical Separation Assisted Flight Environment (TSAFE), would provide a safety net to ensure that safe separations are maintained in the event of failures in the AACS or in certain on-board systems.

A computer-based analysis of simulated traffic in two en route sectors was conducted [Andrews et al, 2006]. Key results reported in this paper are that fault-tree analysis simulations indicated that AAC had a high (> 99%) rate of success for providing separation assurance in en route airspace at up to 3X traffic density while incurring a ~30 sec delay per conflict. The authors state that if AAC automation were to fail, the collision rate during the subsequent airspace evacuation would be under 1 per 10 million hours.

A computer-based analysis [Farley and Erzberger, 2007] covering 24 hrs of (1X, 2X, 3X) simulated traffic with no trajectory uncertainty found that for en route conflicts, the resolution success rate was 100% for 1X traffic and better than 99% for 3X traffic. Average delay incurred per conflict was 21 sec for 1X and 25 sec for 3X.

[Prevot et al, 2009] reports a HITL piloted simulation in which ground-based separation automation managed the trajectories for all aircraft at 2X and 3X traffic densities in en route airspace without controller involvement. Off-nominal events were carefully scripted to cause short-term conflicts, simulate emergency situations, or require trajectory negotiations. For nominal operations, the medium-term conflict detection and resolution automation coupled with data link was able to solve conflicts with a success rate of 99.9% at 2X and 98.1% at 3X. More than 95% of uplinked trajectories were acceptable to the flight crews. While controller workload was low in general and they were able to resolve over 75% of scripted off-nominal short-term conflicts, many issues were identified that need to be further addressed in the area of short-term conflict detection and resolution.

D. Air-Ground Control with Moderate Automation

(1) Limited Delegation of Separation Responsibility

There is a substantial body of work on equivalent visual operations for: merging/sequencing/spacing in terminal and en route airspace; crossing/passing in en route airspace; and climbing/descending in oceanic airspace. The flight deck equipage generally consists of a Cockpit Display of Traffic Information (CDTI) with an ADS-B data feed of local traffic.

[Hoffman et al, 2000] reports a HITL simulation to explore the concept of limited delegation of separation assurance to the aircraft for: crossing and passing in en-route airspace, and sequencing in terminal areas. The task delegated to the pilot was limited to the monitoring and implementation of solutions, using a CDTI. Situation analysis, identification of problems (e.g. conflict detection), definition of solutions, and decision of delegation remained with the ANSP. The feedback from this initial qualitative evaluation was: “promising with a great potential.”

A performance assessment of airborne spacing for arrival traffic is reported in [Prevot et al, 2003]. A HITL simulation combined airborne self-spacing and merging functions with trajectory-oriented time-based arrival operations. Results showed that, compared to tactical air traffic control, 4D trajectory-based operations yield a significant reduction in the variance of inter-arrival spacing at the metering fix.

CDTI assisted visual separation (CAVS) for arrival spacing has been evaluated [Bone, 2005]. The CDTI is used to maintain situational awareness when out-the-window visual contact with a target aircraft is temporarily lost. The ANSP designates “Traffic To Follow” in a single-stream approach under visual meteorological conditions (VMC); the cockpit crew use the CDTI and their own judgments to achieve self-determined spacing. This VMC CAVS concept was found to be technically and operationally possible based on subjective feedback from pilots and objective simulation data, both collected during a series of HITL simulations. A study on extending the CAVS concept into instrument meteorological conditions (IMC) is reported in [Mundra et al, 2009]. A HITL simulation evaluating the CAVS concept for single-runway operations found that approach spacing performance achieved under IMC with CAVS was roughly equivalent to the baseline performance achieved under visual conditions with no CDTI.

An evaluation of some benefits of airborne spacing for arrival traffic is reported in [Grimaud et al, 2005]. A series of HITL simulations was conducted in terminal airspace, with low, medium-high, and high arrival rates. Flight crews were tasked by the controller to maintain a given spacing with respect to a designated aircraft. Analysis of instructions and eye-fixations showed a positive impact on controller activity (relief from late vectoring and earlier flow integration). Analysis of inter-aircraft spacing on final approach showed more regular spacing than current-day operations.

Time-based airborne merging/spacing operations on FMS arrival routes has been evaluated [Callantine et al, 2006]. There were trials with: (1) ground tools for sequencing/spacing; (2) airborne spacing tools at 75% equipage; (3) both air and ground tools. Clearances were issued by voice. Results from a HITL simulation indicate that airborne spacing improves spacing accuracy and is feasible for FMS operations and mixed spacing equipage.

An assessment of Flight Deck-based en route Merging and Spacing (FDMS) from a ground controller’s perspective is reported in [Penhallegon and Bone, 2007]. Results from a HITL simulation indicate that relative to

current-day operations, FDMS reduces the number of controller-issued maneuvers, the number of communications, and workload. No reduction of controller situation awareness was observed.

The Mediterranean Free Flight (MFF) Programme was a series of HITL simulations and operational evaluations [Barff, 2007]. Results of the MFF studies confirmed the feasibility of applying airborne spacing, sequencing, and merging techniques to arrival streams of aircraft under optimum conditions, which include the segregation of inbound and outbound flows. On the other hand, serious safety concerns were identified with en route crossing and passing; controllers were extremely uncomfortable retaining responsibility for separation while delegating the crossing maneuver to the flight crew.

A study based on a set of HITL simulations and computer-based Monte Carlo simulations has demonstrated the ability of an aircraft to space itself precisely relative to another aircraft during continuous descent arrivals (CDA) [Barmore et al, 2009]. The study evaluated the use of flight deck speed control to achieve pair-wise spacing. Results indicate that FDMS is viable and that expected benefits should be realized. A limited implementation of FDMS is currently certified and in use for United Parcel Service (UPS) revenue flights.

An operational evaluation in oceanic airspace (north Atlantic tracks) supports the feasibility of the in-trail procedure for altitude changes through flight levels that contain other traffic [Martensson and Rekkas, 2009]. The procedure uses advanced technologies to increase the possibility of flight level changes in procedural airspace, thus enabling fuel burn savings as well as environmental benefits through reduced carbon dioxide emissions. The flight crew continues to be responsible for the operation of the aircraft and conformance to its clearance, and the controller continues to be responsible for separation and the issuance of clearances. They conducted an operational evaluation (flight test of an A340 in Reykjavik ATC south sector), a HITL for operational acceptability and technical feasibility, and a computer-based benefits assessment in North Atlantic tracks airspace. Qualitative results indicate operational acceptability of the procedure. Preliminary results also indicate technical feasibility. Finally, the results show benefits in the form of reduced fuel burn and emissions.

(2) *Mixed Air-Ground Separation Responsibility*

A concept feasibility study of shared air-ground separation responsibility is reported in [DiMeo et al, 2001] and [Lozito et al, 2001]. ANSP had a conflict probe, while cockpit crew had CDTI with alerting logic and state-based trajectory predictors. Results from a HITL simulation indicated that while safety was not compromised, pilots and controllers had differing opinions regarding the application of these new tools and the feasibility of the operational concept.

An evaluation of integrated air and ground operations is reported in [Callantine et al, 2001]. Air traffic controllers managed simulated arrival traffic using Center-TRACON Automation System (CTAS) tools. Flight crews in FMS- and datalink-equipped aircraft simulators were included in the arrival flows. Results from a HITL simulation indicate that procedures developed for FMS and datalink operations can work in concert with ground-based tools. In general pilots found the concept favorable, and the concept appears especially promising with some modifications and additional pilot familiarity. Controllers appear capable of using automation tools; other advanced technologies can improve efficiency as required to support anticipated air traffic demands. The role of a proposed multi-sector arrival planner deserves further examination.

E. Air-Ground Control with High Automation

(1) *Limited Delegation of Separation Responsibility*

A feasibility evaluation of the airborne self-spacing concept is reported in [Lee et al, 2003]. A HITL simulation in terminal airspace was conducted, and the key result is that the pilots and controller liked the self-spacing concept but had some difficulties implementing an effective strategy to maintain time-based spacing.

[Krishnamurthy et al, 2005] reports a computer-based analysis of simulated precision spacing operations across multiple arrival routes to a common runway. Flight crews were cleared by the ANSP to follow speed cues from onboard automation to achieve precision spacing (time- or distance-based) at the runway threshold, relative to a designated lead aircraft. Results from a computer-based analysis indicate that inter-arrival spacing was achieved to well within 10 seconds even with a diverse fleet of aircraft types having dissimilar final approach speeds and unequal spacing assignments.

An operational evaluation of a time-based airborne inter-arrival spacing tool is reported in [Lohr et al, 2005]. A cockpit tool computed speed commands for appropriately equipped aircraft to maintain a required time interval behind another aircraft. Results from a flight test in Chicago terminal airspace, using three different types of aircraft, support the feasibility of using cockpit tools to maintain time-based spacing behind another aircraft. For a target in-trail spacing of 90 sec, the results over all scenarios showed a mean of 90.8 sec with a standard deviation of 7.7 sec.

An operational evaluation of airborne self-spacing in Mediterranean airspace is reported in [Henley and Pywell, 2005]. The ANSP issued clearances for pass-behind or merge-behind maneuvers. The FMS automatically generated an optimal maneuver in accordance with the instruction, and then guided the aircraft through the maneuver. Over four days of trial flights, pass-behind and merge-behind maneuvers were successfully repeated, causing pilots and controllers to remark that it had become routine.

An evaluation of a highly automated concept for arrival management is reported in [Prevot et al, 2007]. ANSP had scheduling and spacing tools; cockpit crew had spacing tools and datalink. Results from a HITL simulation indicate that it is possible to conduct continuous descent arrivals in high density airspace. Airborne spacing had a positive effect on runway throughput and no negative impact on on-time arrivals.

(2) *Mixed Air-Ground Separation Responsibility*

[Prevot et al, 2005] advocates an integrated air/ground system combining trajectory negotiation, data link communication, and airborne separation assistance as complementary components of a modernized airspace system. The paper describes procedures and technologies for an integrated air/ground system, and provides an overview of several HITL simulations previously conducted to evaluate key components of this system.

A HITL simulation of integrated air/ground operations in arrival sectors and terminal airspace is reported in [Barhydt and Kopardekar, 2005]. Pilots of autonomous aircraft met controller-assigned meter fix constraints with high success, with few separation violations. Controller workload was lower for mixed flight conditions, even at higher traffic levels. Pilot workload was deemed acceptable under all conditions. Controllers raised several safety concerns, most of which pertained to the occurrence of near-term conflicts between autonomous and managed aircraft.

A HITL simulation of integrated air/ground operations in en route airspace is reported in [Kopardekar et al, 2009]. Centralized groundside automation detected and resolved conflicts involving datalink-equipped aircraft on four-dimensional (4D) trajectories. Datalink-equipped aircraft were managed by automation that resolved conflicts between equipped aircraft without controller involvement by issuing FMS-loadable datalink clearances, thus maintaining common trajectory intent between air and ground. Controllers managed unequipped (no datalink) aircraft using manually created resolutions, or resolution maneuvers generated by ground-based automation. There were four scenarios with different percentages of equipped aircraft. Participants rated the mixed operations concept as acceptable, with some qualifications about procedures and information displays. These results showed that mixed operations might be feasible in the same airspace if the unequipped aircraft count is held to a workable level; this level will decrease with increasing complexity. The results imply that an integrated airspace configuration is feasible up to a limit. The results also indicate that the conflict detection and resolution automation, equipage, and traffic density are important factors that must be considered in airspace configuration.

F. Airborne Control with Moderate Automation

Air and ground perspectives on self-separation, compiled from two separate HITL simulations conducted in the U.S. and Europe, are presented in [Mackintosh et al, 1998]. There were flight crew performance differences between high and low traffic density conditions. Acute angle conflicts were easier for controllers to detect, but were not as easy for the crews to resolve. Obtuse angle conflicts were detected later by controllers, but flight crews were able to adequately self-separate. There were some air-air and air-ground communication issues. Subjective data showed a pilot acceptability rating of 80%. Seventy-five percent of the runs were perceived by the pilots to be as safe as, or safer than, conventional air traffic control. In the majority of the runs, the amount of maneuvering was more than in today's ATM environment, in the opinion of the pilot participants. The resolution maneuver data show a clear preference for heading changes, although altitude changes are far more economic and less disruptive to the intended route than horizontal maneuvers. The overall conclusion is that the feasibility of the given Airborne Separation Assurance concept for a future free flight environment could not be refuted. The primary challenge is to prevent short-notice conflicts arising from sudden maneuvers.

As part of the U.S. government/industry Safe Flight 21 program, an operational evaluation (OpEval) was conducted in 1999 in the Ohio Valley [Cieplak et al, 2000]. Twenty-four aircraft participated in the OpEval, with the objective of evaluating enhanced visual acquisition and enhanced visual approaches, using ADS-B traffic data displayed on a CDTI. Both pilots and controllers felt that the CDTI augmented the visual acquisition task and improved pilot awareness of surrounding traffic. Results from the enhanced visual approaches revealed significant performance benefits in the form of enhanced spacing awareness and a reduction in the misidentification of traffic callouts.

[Hoekstra et al, 2003] reports a HITL simulation designed to study the interactions between a large number (10 to 24) of pilots using ASAS in high-density en route airspace. The pilot tools included a state-based conflict

detection system as well as a predictive-ASAS system that displayed no-go zones for conflict prevention. Results showed that pilot workload was relatively low even at high traffic densities. For conflict resolution, pilots preferred horizontal maneuvers during level flight and vertical maneuvers during climbing/descending flight.

An operational evaluation with three general aviation aircraft in VFR airspace in the vicinity of Frankfurt International airport is reported in [Reitenbach, 2005]. The goal was to study the feasibility and possible safety benefits of performing the “Enhanced Visual Acquisition for See and Avoid” application using TIS-B data displayed on a CDTI. The results showed on one hand that a significant increase of the overall detection probability was achieved during the flight trials by the use of the onboard traffic presentation. On the other hand, it was also seen that the onboard installation of a traffic presentation introduces new risks. The author concludes that for a flight under visual flight rules it is not possible to replace the visual scan of the surrounding airspace by the use of a traffic presentation onboard – an electronic presentation can be used only as an aid to support the pilot.

The Mediterranean Free Flight (MFF) Programme was a series of series of HITL simulations and operational evaluations [Barff, 2007]. Large-scale real-time simulations indicate that Free Routing applications appear feasible in much of the airspace over the Mediterranean, except near the northern coastline. It was found that the vertical transition from/to Free Route airspace poses its own particular problems. Results from Airborne Separation Assurance System (ASAS) flight trials show that pilot workload remained well within tolerable limits and pilots positively accepted ASAS Self-Separation due to the lack of need for radio communication, more flight efficiency, and low workload. The author states that, overall, no showstoppers were discovered even in a challenging environment featuring transitions between managed and free flight airspace, significant weather, military operations, and system failures.

G. Airborne Control with High Automation

Several studies have been conducted to investigate some of the complex challenges associated with airborne self-separation in en route airspace: short-notice (pop-up) conflicts, highly constrained operations (convective weather, Special Use Airspace (SUA), metering), transitions to/from free-flight airspace, lack of trajectory coordination and/or intent information (strategic vs. tactical ASAS), uncertainty/errors in data (surveillance signal, wind forecast), pilot delay during interaction with ASAS tools, and equipage for 4D trajectory-based operations.

Transitioning between Managed Airspace (MAS) into Free Flight Airspace (FFAS) features a shift of separation responsibility between ANSP and cockpit crew. [Beers and Huisman, 2001] reports a study on the feasibility and controller acceptability of procedures for horizontal and vertical transitions between FFAS and MAS, using the concept of transition zones that act as safety buffers. They found that the transition should be made more flexible in entry/exit position (provide multiple points) and time.

[Wing et al, 2001] describes a study of intent information exchange in constrained en route operations, and its effect on pilot decision-making and flight performance. The experiment scenario featured a single autonomous aircraft in en route cruise flight with variable airspace complexity: 1X and 3X traffic density, weather cells, and SUA. They conducted a HITL simulation of autonomous operations in tactical (state only) and strategic (state plus intent) modes. Preliminary results indicated that pilots in both modes were generally able to meet the operational constraints. Subjective data indicated a consistent pilot preference for the strategic mode of operations over the tactical mode.

While ASAS tools would normally allow pilots to resolve conflicts well before they become hazardous, an evaluation of system performance in sudden, near-term conflicts is needed in order to determine concept feasibility. Results from a HITL simulation [Barhydt et al, 2003] indicate that pilots performed better in resolving close-range (pop-up) conflicts when they followed tactical conflict resolution guidance cues provided by ASAS than when they didn’t follow the guidance.

[Barmore et al, 2003] describes a HITL simulation with traffic scenarios where the pilot had to maneuver through a narrow corridor between two SUAs, avoid other traffic, and meet flow management constraints. Strategic and tactical resolutions were provided by an autonomous operations planning tool. Nearly all of the pilots were able to meet their flow constraints while maintaining adequate separation from other traffic. In only 3 out of 59 runs were the pilots unable to meet their required time of arrival. Two loss of separation cases were studied and it was found that the pilots need conflict prevention information presented in a clearer manner. No degradation of performance or safety was seen between wide and narrow corridors.

[Wing et al, 2003] studied the feasibility and safety of autonomous aircraft operations in a multi-piloted HITL simulation of over-constrained traffic conflicts to determine the need for, and utility of, priority flight rules to maintain safety in extraordinary and potentially hazardous situations. The over-constrained conflict scenario studied here consisted of two piloted aircraft, maneuvering through SUAs, that were assigned an identical en-route waypoint arrival time and altitude crossing restriction. Results indicated that the pilots safely resolved the conflict without the

need for a priority flight rule system. The use of priority flight rules, although effective as implemented by staggering the alerting time, had no effect on the percentage of the aircraft population meeting all assigned constraints.

[Ruigrok et al, 2005] addresses procedures for transitions between Managed and Free Flight airspace, as well as the effects of weather, military activities, and failures. Based on the results of a HITL simulation, they reported that no showstoppers were found for ASAS Self-Separation in challenging environments. The human-machine interface as well as the conflict detection and resolution algorithms appeared to be well-accepted by participating subject pilots.

[Consiglio et al, 2007] describes computer-based Monte Carlo simulation experiments to analyze and quantify safety behavior of airborne separation. The study explored four factors: broadcast surveillance signal interference, extent of intent sharing, pilot delay, and wind prediction error. Early results at 5X traffic density indicate that a distributed approach to maintaining separation of aircraft can be safely achieved, even after introducing several sources of error and uncertainty.

[Consiglio et al, 2008] addresses the potential impact of operator delay when interacting with separation support systems. This computer-based simulation utilized 3X – 8X traffic at a single flight level in an en route sector to evaluate an airborne separation capability operated by a simulated pilot. Pilot actions required by the airborne separation automation to resolve traffic conflicts were delayed within a wide range, varying from 5 to 240 seconds while a percentage of randomly selected pilots were programmed to completely miss the conflict alerts and therefore take no action. It was found that the strategic ASAS functions exercised in the experiment can sustain pilot response delays of up to 90 seconds and more, depending on the traffic density. However, when pilots or operators fail to respond to conflict alerts the safety effects are substantial, particularly at higher traffic densities.

A computer-based Monte Carlo simulation was conducted to study airborne self-separation without any coordination or negotiation of trajectory intent between aircraft [Blom et al, 2009]. It was found that uncoordinated airborne self separation can be very effective in safely handling low density en route airspace. However, events of multiple conflict clusters may grow in size more rapidly than an uncoordinated airborne self separation scheme may be able to solve.

IV. Summary and Recommendations

Some high-level observations and recommendations are made here, based on insights gained from the various studies presented above. It is evident that the functional allocation space of Fig. 1 has a different state of the art in each cell, and the goal here is to draw some conclusions about trends and gaps to help guide future studies on separation assurance.

Among the future (moderate and high automation) configurations of functional allocation studied here, the one at the highest level of maturity is shared air-ground control where ANSP delegates specific conflict resolution functions to cockpit crew on a limited (per-event) basis. The applications fall under the general category of equivalent/enhanced visual operations. Multiple teams from diverse organizations have independently conducted many evaluations of operational feasibility and benefits, by means of computer-based simulations, HITL simulations, and operational evaluations (flight tests). The application of arrival merging/spacing has been particularly well studied and the airborne technology is at a relatively high level of maturity, although its integration with the ground side needs further development. Three independent operational evaluations of flight deck based merging and spacing (FDMS) have been successfully conducted, and it has been reported that a limited implementation of FDMS is currently certified and in use for revenue flights of a major cargo carrier (United Parcel Service). It is recommended that future work in this area be directed at off-nominal operating conditions and feasibility/benefits at higher traffic densities, as well as ground-side integration. Flight deck based in-trail climb/descent procedures have been successfully flight tested in oceanic airspace, and it is recommended that the applicability to high-altitude en route airspace be studied. Some evaluations of en route crossing and passing, including flight testing, have been conducted but the results so far are mixed and hence more work is recommended to assess operational feasibility and benefits.

In comparison to the above, only a limited amount of resources have been devoted to studying the shared air-ground control concept where in the same airspace some aircraft are under ground-based control while others are under limited-delegation control and/or airborne control. The literature survey found four HITL simulation studies (no operational evaluations) on mixed air-ground separation responsibility. Evaluation results were mixed: they indicate that even when safety was not compromised, pilots and controllers tended to have different opinions about the operational suitability of this separation assurance concept with pilots generally giving a higher acceptability rating than controllers. It is recommended that future efforts be directed at a sharper definition of controller/pilot

roles and responsibilities, and determining the combinations of aircraft equipage mix and airspace complexity that may yield tangible benefits.

A key feature of future (moderate and high automation) concepts for ground-based separation assurance is trajectory exchange via datalink. Procedures for sending automation-generated trajectories to the cockpit FMS for execution have been demonstrated on Level-D flight simulator hardware. Datalink transfer of wind and descent-speed-intent information has been successfully accomplished on revenue flights as part of an evaluation of continuous descent approaches. Results of computer-based and HITL simulations show that even a moderate level of automation can accommodate high-altitude en route traffic levels of up to 3X with a very high rate of successful conflict resolution. Failure modes are particularly important at a high level of automation. It has been reported that: a fault-tree analysis indicates a success rate of over 99% for providing separation assurance in en route airspace at up to 3X traffic density; if the automation were to fail, the collision rate during the subsequent airspace evacuation would be under 1 per 10 million hours. A HITL simulation in en route airspace at up to 3X traffic density found significant robustness to off-nominal events such as short-term conflicts. It is recommended that some future resources be devoted to developing procedures for operations under equipment degradation/failure conditions as well as highly constrained scenarios. There is also a need for evaluations of high-density traffic in arrival sectors of en route airspace, with and without metering constraints. Finally, a limited-scope field evaluation with a medium to high level of automation would help establish proof of concept.

Airborne separation assurance with moderate automation has been flight tested in low density airspace, and pilot acceptance was found to be good. Although it is reported that no showstoppers were found in the MFF Programme flight tests, there were some issues associated with transitions to/from free flight airspace. HITL simulations have found very high rates of successful conflict resolution for en route traffic densities up to 3X. Paired experiments indicate that while there were some differences between controller and pilot perspectives on airborne self-separation, the overall validity of the concept was not refuted. Two independent studies examining the issue of transitions to/from free flight airspace found some issues as well as workable solutions. Other experiments determined that highly constrained situations (narrow corridors between SUAs, metering constraints, etc.) can be handled even without priority rules. Studies have also found that a distributed approach to maintaining aircraft separation can be safely achieved, even with several sources of error/uncertainty (e.g., surveillance data errors, wind forecast uncertainty, pilot response delay). Other experiments have investigated the need for exchanging intent information. They found that it was possible to perform airborne self-separation functions tactically without intent knowledge (especially at lower traffic complexity), but pilots consistently preferred a strategic mode of operations that utilized intent data. It is recommended that some future resources be devoted to further develop/refine procedures for operations under equipment degradation/failure. Resources permitting, it would be desirable to conduct flight tests, featuring higher levels of cockpit automation, in high density en route airspace as well as arrival sectors.

The survey found only one study specifically designed to formally compare traffic operations with ground-based and airborne separation assurance. A pair of coordinated HITL simulations [Wing et al, 2010] were conducted to gain insight on comparability of different functional allocations (ground-based and airborne) for separation assurance. The simulation modeled 1.5X and 2X traffic in high-altitude (above FL290) en route sectors. Where comparisons were possible, no substantial differences in performance or operator acceptability were observed. Mean schedule conformance and flight path deviation were considered adequate for both methods of separation assurance. Conflict detection warning times and resolution times were mostly adequate, but certain conflict situations were detected too late to be resolved in a timely manner. This led to some situations in which safety was compromised and/or workload was rated as being unacceptable in both experiments. Operators acknowledged these issues in their responses and ratings but gave generally positive assessments of the respective concept and operations they experienced. More such studies are recommended to objectively evaluate the relative strengths and weaknesses of ground-based and airborne separation assurance, and identify a domain of operational conditions under which they can provide benefits to the airspace system.

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