

A Review of Function Allocation and En Route Separation Assurance

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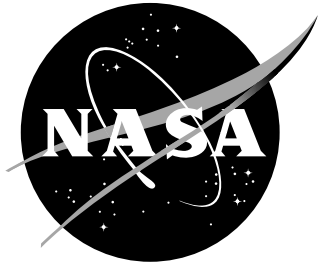
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Abstract

Today's air traffic control system has reached a limit to the number of aircraft that can be safely managed at the same time. This air traffic capacity bottleneck is a critical problem along the path to modernization for air transportation. The design of the next separation assurance system to address this problem is a cornerstone of air traffic management research today. This report reviews recent work by NASA and others in the areas of function allocation and en route separation assurance. This includes: separation assurance algorithms and technology prototypes; concepts of operations and designs for advanced separation assurance systems; and specific investigations into air-ground and human-automation function allocation.

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Nomenclature

AAC	Advanced Airspace Concept
ADS-B	Automatic Dependent Surveillance–Broadcast
AFR	Autonomous Flight Rules
ANSP	air navigation service provider
AOC	airline operations center
ATC	air traffic control
ATM	air traffic management
CD	conflict detection
CD&R	conflict detection and resolution
CDTI	cockpit display of traffic information
CP	conflict prevention
CR	conflict resolution
CTAS	Center-TRACON Automation System
FAA	Federal Aviation Administration
HITL	human in the loop
IFR	Instrument Flight Rules
LOS	loss of separation
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NLR	Netherlands Aerospace Centre
RTA	required time of arrival
TFM	traffic flow management
TRACON	Terminal Radar Approach Control
UAS	unmanned aircraft system
URET	User Request Evaluation Tool
WDA	Work Domain Analysis

1 Introduction

Separation assurance is one of the original air navigation services since the early days of air transportation. Today, this service is provided to aircraft operating under Instrument Flight Rules (IFR) by an international network of air traffic controllers who use a variety of procedures and technology to monitor aircraft and relay critical instructions to pilots during flight. These actions ensure that aircraft remain separated at safe distances in order to mitigate the risk of mid-air collision.

This system provides separation assurance and other services necessary to maintain the safe, orderly, and expeditious flow of air traffic today. However, this system is reaching a limit to the number of aircraft that can be safely managed simultaneously, presenting a bottleneck for international plans to modernize and accommodate future growth in demand for air travel [1].

A new paradigm for providing separation assurance is needed in order to enable significant advances in air traffic capacity and efficiency while preserving the hard-won safety record of today's system. The question of this new paradigm is important now more than ever to ongoing efforts such as the FAA's Next Generation Air Transportation System (NextGen) [2] and the Single European Sky ATM Research project [3]. The next evolution (or revolution) in separation assurance remains an unsolved problem, and its solution will shape the course of air transportation and its impact on the global economy in the coming decades.

Although there are a number of approaches to the design of the next separation assurance system, this report is motivated from the perspective of function allocation. Function allocation, for the purposes of this report, is concerned with all of the necessary functions comprising a separation assurance system, as well as how those functions should be allocated to the various human operators and automation systems participating in air traffic operations on the ground and in the air.

This separation assurance system design problem and its formulation in terms of function allocation is one of the core problems in air traffic management (ATM) research. All paths to modernization must somehow address this problem and resolve the air traffic control capacity bottleneck of today's operations. This question has been the subject of much research at NASA and elsewhere, and although much has been learned to date, it is still unclear what the future of separation assurance should look like.

The purpose of this report is twofold. First, this report will give an introduction to separation assurance and function allocation in order to define the problem and its key research issues. Second, the report will summarize the history of research and development into separation assurance and function allocation by NASA and others over the last 20 years, including: separation assurance algorithms and technology prototypes; concepts of operations and designs for advanced separation assurance systems; and specific investigations into function allocation in particular. This review and discussion is intended to inform decisions about future R&D investment in separation assurance and related technologies.

1.1 Background

In today's air traffic operations, the aircrew are generally not responsible for separation under IFR. This limitation is driven by a number of practical and technological constraints on the flight deck. The first constraint is the lack of adequate surveillance of other aircraft. Under instrument meteorological conditions and at transonic speeds, the aircrew cannot be relied upon to visually see other aircraft at the distances necessary to detect and respond to upcoming conflicts. Also, until recent advances such as Automatic Dependent Surveillance–Broadcast (ADS-B) in the last decade, civilian aircraft have not been equipped to reliably observe other aircraft electronically. Second, even when surveillance is available on the flight deck, pilots are generally not trained to solve complex traffic problems in high-density airspace without assistance.

The limitations that have historically prevented pilots from assuming responsibility for separation have at the same time driven the development of air traffic control (ATC). Today, air traffic controllers provide separation services using traffic displays and a variety of procedures to monitor aircraft and relay critical

instructions to pilots via radio voice communication. Although this arrangement is responsible in part for the remote risk of mid-air collision today, it is a mentally demanding and notoriously stressful task for the controller [4]. The existing controller workforce has been pushed to its practical limits, leading to a “workload bottleneck” impeding significant growth in commercial air traffic as well as the burgeoning demand to operate unmanned aircraft systems (UAS) in the same airspace.

This bottleneck is a core problem of ATM research, and all plans to modernize the airspace must address this problem in some way. Many solutions have been proposed, each involving some combination of new technology and procedures, with varying impact on the current operational paradigm.

One approach to the workload bottleneck problem recognizes the air traffic controller’s workload saturation and proposes to alleviate it by introducing a variety of automation tools to perform or assist with part of the work. If the controller’s efficiency can be improved through automated support of some of the separation assurance functions, then presumably the entire airspace system can accommodate more air traffic without compromising safety. For instance, perhaps the lower-level task of monitoring traffic for conflicts could be automated, freeing the controller’s attention to higher-level decision making and strategic planning tasks. Eventually, as automation technology becomes more and more sophisticated, consider the possibility of a fully automated air traffic control system accommodating great numbers of aircraft, where humans no longer routinely participate in the inner control loops but instead act on the outer loops as automation system managers.

A parallel approach seeks to reduce the controller’s workload by transferring some of the separation functions to the flight deck under certain circumstances. If each aircraft can share some of the overall separation assurance workload, then this may lend to the scalability of the overall airspace system in response to growing air traffic. For example, a controller may delegate a certain conflict to be resolved by the aircrew of a specific aircraft using the surveillance equipment and automation tools on board, thereby offloading some of the controller’s workload for that encounter. In the limit, aircrews operating under new procedures with sufficiently advanced technology on board might take full responsibility for their own separation and manage traffic conflicts autonomously without assistance from ATC. This concept is known as airborne self separation.

There are many alternatives between the span of these two approaches. A number of concepts involve the dynamic allocation of functions that shift between agents depending on the situation. In others, decisions are made through an iterative process of negotiation between agents, and thus not made by any single agent alone. In such a system, it becomes more difficult (and perhaps less important) to a priori define exactly who will perform what function at a given time. Regardless, it is clear that there are a multitude of paths to consider in the evolution of separation assurance in the future.

Many of these approaches have been investigated by NASA and others through the development and evaluation of specific technology prototypes and concepts of operation at varying levels of detail. These “point designs” have offered a great deal of knowledge and experience regarding the feasibility and promise of many advanced separation assurance concepts. At the same time, there is a need to understand the trade space between the points in order to skillfully distinguish between them, and to make broader recommendations for R&D investment. Hence, the motivation for the function allocation approach.

In this context, the purpose of function allocation is to determine how the functions comprising a separation assurance system should be performed and who should be responsible for performing them. Specifically, the “how” intends to answer which functions should be performed on board the aircraft vs. in a ground-based facility. The “who” refers to what agent should be responsible for performing these functions, whether a human operator or an automation system.

Each question has wide-ranging implications across the domains of airspace design; communication, navigation, and surveillance infrastructure; decision support automation and human-systems integration; and economic cost and benefit. The potential impacts go beyond the number of aircraft that can be safely accommodated in the sky at any one time; they extend to other potential benefits to the global economy

realized by changing the way aircraft are operated in the airspace. The far-ranging, multidisciplinary nature of the problem makes it challenging to study and presents difficulty in the search for a simple, single answer to the question.

There is a sense that despite the tremendous amount of research behind future separation assurance systems and other ATM areas, the progress towards real-world implementation of any advanced solution has stalled in recent years. In 2014, a report from the FAA Inspector General [5] found that key requirements for NextGen had yet to be defined, among them the “division of air-ground responsibility” and the “level of automation” for separation assurance. Hence, this is an appropriate time to examine the research that has been done to date and attempt to identify critical work moving forward that might address the barriers to growth and change in the current system.

1.2 Scope

The scope of this report mirrors the scope of NASA’s recent research activity into function allocation for separation assurance. This report is focused on separation assurance systems that are realizable in a notional 2025–2035 time period. This will be referred to as the mid-term period. The mid-term encompasses separation assurance systems that rely on more advanced automation and automatic exchange of information between the aircrew, operators, and the air navigation service provider than is possible with the air traffic operations and infrastructure of today. In this period, humans generally remain in the decision-making loop, although they may be supported by a significant amount of automation in performing lower-level tasks. At the end of the mid-term period, automation systems may be allocated control of some critical decision-making tasks under certain conditions, e.g., in low-density, en route airspace.

The mid-term period is contrasted with the near-term period (2015–2025), which is characterized by incremental and more-limited advancements to today’s air traffic management systems. The mid-term is also contrasted with the far-term period (2035+), which may be characterized by much more advanced and pervasive automation technology and increasingly autonomous systems. The mid-term does not extend to the fully-autonomous concepts of the far-term period, where human operators may only be peripherally involved in the operation or not at all.

This report is focused on the evolution of commercial, scheduled IFR operations, which comprise the majority of passenger and cargo traffic today. However, also of interest is the flexibility of mid-term separation assurance systems to accommodate a variety of other airspace users, including general aviation, military operations, and emerging unmanned applications. In particular, any proposed separation assurance system architecture must be designed to operate with full functionality in the presence of potentially high numbers of unmanned vehicles.

This report is focused on en route operations outside of the terminal area. This includes the climb, cruise, and descent phases of flight that occur during normal transport operations. However, many interfaces between this phase and the rest of the flight are also relevant, e.g., the importance of coordination between en route separation assurance with arrival management functions [6].

This report is focused on separation from air traffic rather than the avoidance of severe weather, terrain, etc. While not the primary focus, these additional hazard avoidance functions will be discussed where they have a significant interaction with air traffic separation. Short-term traffic collision avoidance, while sharing similarities with separation assurance, is not in scope.

2 Problem Definition

2.1 High-Level Agents in Air Traffic Operations

The term *agent* is used in this report to loosely denote any person or socio-technical system capable of taking an active role in air traffic operations and carrying out one or more functions associated with separation assurance. In this context, we are concerned with those agents who could be said to bear the responsibility for performing the given function. This notion of responsibility serves to distinguish between people or technology with whom the responsibility, authority, and accountability for performing the function actually lie, versus agents that merely provide assistance or support in the performance of the function.

Today, the air navigation service provider (ANSP) is a complex network of ground-based agents responsible for the overall management of air traffic in a given geographic region. The ANSP typically provides separation assurance and other navigation services to aircraft while also performing other large-scale traffic management functions necessary for the operation of the entire airspace. Included under the umbrella of the ANSP are the air traffic controllers who are responsible for providing separation assurance to IFR aircraft. The ANSP also plays a primary role in managing contingency situations arising in a local or system-wide scenario. The ANSP as a whole has good information about the overall state of operations throughout the airspace system. However, it has comparatively poor information about the detailed state of any given aircraft and has limited knowledge of the business objectives of any given flight operator.

The flight deck system is comprised of the aircrew and the supporting technology on board a given aircraft. Today, the aircrew are responsible for reviewing and complying with instructions from the ANSP whenever possible, but are generally not responsible for separation. However, the aircrew are ultimately responsible for the safety of flight and have the final authority regarding trajectory of their own aircraft. They have high-quality knowledge about the state of their own aircraft and their operational intentions. They also have fair information about the immediate environment (e.g., nearby weather, terrain). Although the aircrew may have some surveillance on surrounding traffic, they usually have very limited knowledge about the intentions of this traffic. The aircrew have comparatively poor information about the regional and airspace-wide state of air traffic operations, the ANSP's traffic management objectives, and the activity throughout the rest of the flight operator's fleet.

The flight deck and the ANSP are the two principal agents of separation assurance today. However, there is growing interest in the role of the airline operations center (AOC) (or flight operations center) in the separation assurance domain. The AOC is responsible for managing daily flight operations of a given airline or aircraft operator. In today's system, the AOC is concerned with the conformance of flights to a variety of federal regulatory and safety requirements, the optimization of business operations and logistics, as well as recovery from off-nominal events such as severe weather or security issues. Although the AOC plays a significant role in the trajectory management of a given flight, this report will focus on the primary separation assurance relationship between the ANSP and the flight deck.

2.2 Separation Assurance Functions

2.2.1 Primary functions

A separation assurance system performs the functions necessary to ensure that aircraft remain at safe distances from other traffic during flight. In today's system, this safe distance is referred to as a separation standard. An event in which two aircraft pass closer than the separation standard distance (unless operating under special conditions, e.g., visual separation) is referred to as a loss of separation (LOS). A conflict occurs when a loss of separation is predicted to occur in the future with some degree of certainty. While a conflict can also exist between three or more aircraft simultaneously, this report will focus on two-aircraft conflicts in discussion.

An agent performing conflict detection (CD) uses the available air traffic surveillance data, flight plans and trajectory intent information, vehicle performance models, and winds aloft in order to detect conflicts within a given airspace and time frame. CD relies on the function of trajectory prediction in order to accurately detect conflicts. Given that such a system will always operate in the presence of uncertain information, the CD function must deal with the fundamental sensitivity trade-off between false and missed detections. There may be other related sub-functions included as a part of CD, i.e., the prioritization of conflicts by urgency, and the decision to alert another agent to take an action in response to a conflict.

In response to a given conflict, some agent must perform conflict resolution (CR) in order to resolve the conflict and maintain separation. This is an optimization and decision-making problem, posed as follows. Choose a lateral, vertical, or speed change maneuver, or a combination of those, to be taken by the aircrew of one or both aircraft, such that the two aircraft will no longer be in conflict after the maneuvers have been executed. The chosen maneuvers should be within the nominal performance envelope of the aircrew and the aircraft and should minimize the operational impact of the change to each flight. The resolution should not create any new conflicts with additional aircraft or otherwise worsen the situation. The CR function to generate the resolution maneuver is distinct from the function that executes the maneuver and physically changes the aircraft's trajectory, although they may be performed by the same agent.

Conflict detection and resolution, commonly styled together as CD&R, form the foundation for separation assurance. Closely related to CD&R is conflict prevention (CP). Whereas CD&R is a reactive function performed in response to conflicts that occur ("pop up") during flight, CP is a proactive function that encompasses a variety of actions taken to prevent conflicts from occurring in the first place. For example, if the aircrew intends to execute a climb maneuver in order to reach a more fuel optimal cruise altitude, this maneuver should be checked ("probed") for conflicts before it is executed. If the proposed climb has a conflict, then an alternative maneuver should be taken in order to achieve a similar objective without creating a new conflict.

Separation assurance forms one safety layer in an overall system intended to mitigate the risk of mid-air collision. Collision avoidance is another layer of this system. Whereas separation assurance operates on distances and times on the orders of miles and minutes, collision avoidance is measured in feet and seconds. Whereas a loss of separation is a significant but nonetheless routine event during everyday operations, a collision avoidance event is a serious and potentially life-threatening occurrence. It is the purpose of a separation assurance system to maintain separation and provide a comfortable margin such that aircraft never enter the realm of collision avoidance. While similar in principle to separation assurance, collision avoidance is a separate area of research and is outside the scope of this report.

2.2.2 Relationship to other ATM functions

While this report is concerned with separation assurance, the interface between separation assurance and the rest of the ATM system is complex, and it is not always clear where the boundary should be drawn. The agent performing the functions to maintain separation from traffic is typically also concerned with a number of other ATM functions to be considered simultaneously. The following related functions fall under the broad umbrella of trajectory management.

Separation assurance is closely related to a set of analogous functions for separation from other hazards and restrictions, such as severe weather, terrain, and special use airspace. These hazards must be detected and avoided in the same manner as the CD&R functions for traffic, and it is often the case that all of these factors should be taken into account simultaneously. For instance, when making trajectory decisions about an aircraft in response to a traffic conflict, the presence of severe weather in the area will restrict the space of safe maneuvers available for conflict resolution. Thus the weather problem must be taken into consideration when solving the traffic problem, and vice-versa.

There may be other trajectory constraints that should be considered when performing separation assur-

ance, such as those imposed by a traffic flow management (TFM) system. For example, if the aircrew has a required time of arrival (RTA) to achieve at a given location, then trajectory changes made to resolve traffic conflicts may affect the ability of the aircraft to meet this constraint. Other examples of TFM constraints that may impact separation assurance functions are miles-in-trail and sector capacity restrictions. Thus, an agent performing separation assurance may be concerned with meeting multiple constraints at the same time.

In addition to the satisfaction of operational constraints, separation assurance also has an impact on the overall optimization and efficiency of a given flight. Any given maneuver, whether it is lateral, vertical, or speed change, will have some affect on the fuel economy of the flight, be it positive or negative, large or small. An efficiency-minded aircraft operator will be interested in making the most optimal trajectory changes during flight, and thus the metrics of efficiency and the performance of separation assurance functions are tied to one another.

Given the number of different agents involved in separation assurance and other air traffic management functions associated with a given flight, coordination is important for ensuring that all of these agents work well together. Coordination itself can be considered a function. For instance, a controller may coordinate with controllers in downstream sectors regarding changes to a given aircraft's flight plan in response to a traffic conflict; or, the aircrew may coordinate a re-route with both the AOC and the ANSP in response to emerging weather detected by onboard radar. The degree to which the various agents act in a coordinated way and the manner in which this coordination is accomplished is important for separation assurance.

2.3 Function Allocation

The term *function allocation* originated in the human-machine systems research discipline. In that context, function allocation is a core activity concerned with the assignment of functions and tasks between the human operators and machine elements of a given system. While it has been applied across virtually the entire spectrum of human-machine systems, perhaps the earliest application of function allocation was by coincidence to the problem of air traffic control [7].

For the purposes of this report and the NASA research referenced here, the definition of function allocation is somewhat augmented from its traditional sense. First, the reference to machines is taken to mean automated or autonomous functions executed by computer software. Second, this human-automation axis is complemented by the air-ground axis, wherein special attention is paid not only to whether a function is assigned to a human or automation agent, but also to whether that agent resides on the flight deck or in a ground-based facility. Thus, the interest is not only in changes brought about by increasing the level of automation of today's separation assurance system, but also those that result from the changes in the roles and responsibilities of the air and the ground in separation assurance operations.

In the abstract, the function allocation for separation assurance problem can be posed as follows. Consider all of the necessary functions comprising a separation assurance system as well as all of the potential ground-based/airborne/human/automation agents that could perform them. The combination of these functions with all of their possible assignments to agents forms a space of alternative separation assurance system architectures. It is then desirable to understand the trade-offs between these alternatives and to form recommendations about which architectures are superior on the basis of metrics such as performance, safety, efficiency, cost, etc. This may be viewed as an analytical trade space exploration problem, with multiple design factors, external constraints, and objective functions.

2.3.1 Air-ground axis

The air-ground axis refers to whether a function is performed by an agent on board the aircraft or in a ground-based facility. This implies a question of locus of control or responsibility, i.e., whether the function is performed in a centralized manner on the ground by few (or one) agents vs. distributed to a larger number

of agents on board many aircraft. This in turn relates to a question of coordination: are the centrally-made decisions of the one agent better coordinated and more optimal than the decisions of many distributed agents each acting individually?

Further, is the locus of control static and unchanging throughout the operation? Or could it change dynamically depending on the situation? What is the relationship between the responsibility of the air and the ground during normal operations compared with off-nominal and emergency conditions? Is the one agent suited to be the backup for the other?

The air-ground axis and its questions of locus of control and coordination capture the dichotomy between the two most significant paradigms in separation assurance that have been proposed: i) ground-based separation and ii) airborne self separation. While there are a plethora of variations on these themes, these two represent the primary competing philosophies behind the majority of separation assurance research to date.

2.3.2 Human-automation axis

The human-automation axis refers to whether a function is performed by a human operator or by an automation system. This is the traditional sense of function allocation in the human factors discipline. The axis represents a range of human-automation team configurations. On one end, a human operator performs the function with minimal or no automated support. In the middle, the human performs the function with varying degrees of automation assistance. At the other end, a shift occurs where an automation system performs the function with diminishing human involvement or oversight. This description by levels of automation is broadly used in many fields [8].

Along this axis lie all of the traditional problems of human-systems integration. Which level of automation is appropriate to a given function? What is the most appropriate allocation given the natural strengths and weaknesses of human beings and computer algorithms? How does one design a team in which humans and automation work well together to jointly solve a problem? How can the interface and procedures be designed in order to establish trust between the human operator and the automation system? In what configurations are humans and automation systems more effective together than either alone?

Further, there is an issue of automation system reliability and the human response to automation failures. If there is an intent to introduce automation in order to increase the number of aircraft in the airspace, what happens when the automation fails? Can the human managers take over in a crisis situation, particularly if they no longer exercise those skills in daily operations? Can an automation system be designed to perform the complex functions of separation assurance in a highly robust, reliable, and certifiable way, to prevent such a disaster from occurring?

Both the advanced ground-based and airborne separation assurance approaches will require some form of automation support for the human operator, and thus all of the traditional questions along the human-automation axis are of great importance to the problem at hand.

2.3.3 System metrics

The comparison between candidate architectures requires a set of metrics on which to make an evaluation. This section discusses the major categories of metrics for consideration.

As the purpose of a separation assurance system is to ensure that aircraft remain at safe distances in order to mitigate the risk of mid-air collision, safety is a critical metric. Here, safety can be described in terms of the reliability of the system and its effectiveness in maintaining separation of traffic during normal operations and during disturbances. In general, advancements to aviation systems have the requirement to maintain or increase the safety of operations while meeting other performance goals.

At a simplified level, a measure such as the probability of loss of separation (e.g., per flight hour) can be used here. Other safety-related metrics include conflict detection accuracy (in terms of the rates of missed alerts and false alarms) and the amount of warning time necessary to detect and resolve a given conflict. Additionally, for some airborne distributed separation assurance architectures, there is concern over issues such as the “domino effect,” wherein the uncoordinated resolution of one conflict may lead to the repeated creation of additional conflicts with other aircraft. If such an effect propagates without bound, it could lead to widespread disruptions to air traffic operations, which is a highly undesirable outcome. Thus, the stability of the system and its ability to resist and recover from disturbances, internal and external, are also important safety metrics.

There are also a number of other human factors metrics that are essential to the safety and feasibility of an architecture. The most basic one relates to workload, in that the frequency and difficulty of tasks assigned to human operators must be within the operator’s functional capability. As the separation assurance problem is motivated by the existing workload pressure on today’s controller workforce, it is important to ensure that the workload induced by a candidate separation assurance architecture on any human operator, pilot or controller, is reasonable and ideally no greater than today. There are a number of other human factors concerns that relate to the nature of the functions being performed as well as the human-human and human-automation interactions required by the architecture, which must be considered.

After safety, the next purpose of a separation assurance system is to provide air traffic capacity to the airspace. The most basic measure of en route capacity is the number of aircraft that can safely be accommodated in a given airspace at a given time. Increases in capacity can be achieved by reducing the standard separation distance between aircraft as well as changes to the workload of the human operators to allow them to manage more aircraft at any given time. En route capacity is also related to other ATM capacity restrictions, such as the spacing between aircraft in the terminal area, as well as the safe arrival rate of aircraft at the airport runway. Related to capacity is the scalability of the system to meet projected demand for future air traffic.

While the number of aircraft is an important metric of system performance, the operational efficiency of those flights is also significant. For any given aircraft flight, there is an idealized, optimal trajectory that would be flown if there were no other aircraft in the sky, and it is a separation assurance system goal to minimize the deviation of each flight from this optimum. This trajectory efficiency can be measured in terms of the difference in fuel consumption or flying time of the actual flight compared with the ideal. In other terms, the system should maximize the flexibility of each aircraft operator to realize its business objectives through minimal impact to the user-preferred trajectory for each flight.

The metrics of trajectory efficiency are directly related to a set of economic metrics described in terms of costs and benefits. Costs include the cost of developing, implementing, and operating a given separation assurance architecture, e.g.: research, development, and certification; one-time and recurring costs associated with fixed infrastructure and aircraft equipage; operational costs associated with fuel consumption, flying time, and schedule delays; and workforce-related costs associated with training and daily operations. Benefits include the value of the system derived by various stakeholders, such as: taxpayers; regulators; service providers; aircraft and equipment manufacturers; and passengers and other users.

The goal of the separation assurance system is then to maximize the net economic value compared to today’s operations. Another part of this value is in the accommodation of new and increasingly autonomous uses of the airspace, e.g., UAS of all types, on demand air travel and personal air vehicles, as well as civil supersonic flight and commercial space access.

Finally, there are a number of social, political, and institutional challenges or barriers to realizing any significant change to today’s separation assurance system. Thus, an important metric is in the acceptability of a given architecture to all stakeholders, which is a slow and difficult thing to achieve in practice. Beyond the technical merit and theoretical value of a given architecture, these other concerns can be grouped under the umbrella of “implementability.”

3 Separation Assurance Automation

Much research into the problem of separation assurance has focused on the development of software algorithms for conflict detection and resolution as a key enabler for automated separation assurance. This includes algorithms intended for both ground-based and airborne separation applications. Reference [9] is a comprehensive survey of algorithms and modeling methods, highlighting many of the design and implementation issues to be encountered in a practical CD&R system.

3.1 Conflict Detection

A conflict detection system relies on trajectory prediction (a.k.a. state propagation) to predict an aircraft's future path and detect future losses of separation. A CD system can be classified by the nature of this trajectory prediction. The simplest systems employ a linear projection of the current position and velocity of the aircraft, assuming the aircraft continues in a straight line at constant velocity into the near future [10]. This state-based approach is adequate for many short-term CD applications (less than 1 minute to LOS), but is unusable for long-term prediction. As the time horizon for prediction is pushed further into the future, variations in the aircraft's velocity, along with environmental uncertainty such as wind cause the state projection to become unreliable for the detection of conflicts.

To improve the long-range accuracy of conflict detection, a trajectory predictor can also incorporate information about an aircraft's trajectory intent [11]. Trajectory intent consists of information such as the flight plan and clearances as managed by the ANSP, as well as the more detailed horizontal and vertical path contained in an aircraft's flight management system. By using this information, a CD algorithm may incorporate the planned changes in course, speed, and altitude for more accurate predictions. Using intent information can improve the reliability of CD in today's operational environment to about 30 minutes from LOS. Beyond this limit, the variation in the along-track position due to wind uncertainty limits the accuracy of en route CD.

The amount of surveillance and intent information required for conflict detection is important especially for airborne self separation concepts. Whereas today's ground-based separation assurance system relies on surveillance radar and a flight plan management system along with the air traffic controller's situation awareness to perform conflict detection, the same information is not yet widely deployed to the flight deck. While NextGen solutions such as ADS-B and System-Wide Information Management may provide access to this information on the flight deck, each new requirement comes at a cost to the ANSP and the aircraft operator. Thus, there has been a great deal of research in identifying the impacts of varying levels of surveillance and intent information on trajectory prediction performance, and ultimately the impact to conflict detection and resolution [12–14].

Where reliable intent information is not available, solutions such as intent inference have been proposed [15]. Intent inference proposes to infer the trajectory intent of an aircraft from information about its current state and immediate environment. For example, even if an aircraft's full trajectory intent is not known, it can safely be assumed that the aircrew will not usually elect to fly into an oncoming weather cell or restricted airspace. Further, in today's operational environment, aircraft typically fly between a set of fixed, named waypoints, and thus one might anticipate an aircraft's route based on what waypoint it appears to be flying directly towards. The immediate maneuver of an aircraft can also be estimated from state data measurements, such as the detection of an in-progress turn maneuver [16]. Intent inference is particularly applicable to the problem of conformance monitoring, facilitating the early detection of a maneuver that deviates from an aircraft's previously indicated trajectory.

A CD algorithm may also be classified by whether it uses a single, nominal trajectory for detection or whether it represents uncertainty using a range of possible future trajectories. In the nominal approach, a trajectory predictor produces a single "best guess" for the trajectory of each aircraft for CD. While this is

straightforward to implement, the use of a nominal trajectory alone does not represent the uncertainty in this prediction and may lead to missed detections.

One approach to incorporating uncertainty into CD is the use of geometric prediction buffers around the nominal trajectory, in which a CD algorithm uses the intersection of two buffered trajectory regions to form the basis for detection [17]. More sophisticated approaches use probabilistic modeling, Monte Carlo sampling, and other techniques to produce a distribution of future trajectories. A probabilistic conflict detector then uses these trajectory distributions to form a probability of loss of separation as the basis for alerting [18].

3.2 Conflict Resolution

A conflict resolution algorithm may be described by the type of resolution maneuvers it generates. A tactical resolver [19,20] is one that generates simple heading, altitude, or speed changes to be executed immediately for the purposes of resolving a short-term conflict (less than 5 minutes to LOS). A tactical resolver is typically designed around a straightforward algorithm to minimize the complexity of implementation, in order to act as a reliable safety layer to ensure that separation is maintained.

In contrast to a tactical resolver that is focused only on the immediate avoidance of traffic, a strategic resolver [21,22] is more concerned with the long-term optimization of the flight in addition to separation assurance. A strategic CR algorithm may offer resolutions in the form of flight plan changes that maintain separation while simultaneously optimizing the path for fuel and time. The algorithm may also work to satisfy TFM constraints, such as the conformance with an RTA at a specified fix, and the avoidance of weather hazards and special use airspace. Strategic conflict resolution, along with these other trajectory optimizations, are commonly grouped together under the umbrella of trajectory management.

A strategic CD&R system may be coupled with an independent tactical system as a safety-critical backup to form a layered solution for separation assurance. However, the use of separate algorithms in this arrangement presents an interoperability problem. In practical experience, two algorithms that work well independently may exhibit undesirable behavior when coupled together [23]. For instance, executing the clear resolution from a strategic, intent-based system may trigger a false conflict alert from the tactical, state-based backup, since the tactical system does not incorporate the intent information used by the strategic system. Thus, it can pose design challenges when the two systems disagree during operation. It is not always clear how to harmonize two such systems while maintaining their independence for the purposes of redundancy.

While this report has heretofore discussed CD and CR as two separate steps in a discrete process, there is yet another class of approaches that attempt to solve the separation problem as a continuous control optimization. In [24], aircraft conflicts are resolved by an analogy to the repulsion of charged particles. In this approach, aircraft receive continuous control actions derived from a fictitious force of repulsion that ensures the aircraft avoid each other with minimal deviation from the ideal path to destination. In such an approach, an aircraft may continuously make small, automatic trajectory adjustments in order to avoid nearby traffic while otherwise achieving an optimal trajectory. However, the continuous optimization approach is appropriate for an automatic flight control algorithm, but is difficult for human pilots and controllers to manage without significant automation assistance. Whereas pilots and controllers today routinely share route changes as a short sequence of named waypoints over voice communication, a complex and continuously varying 4D trajectory must be exchanged between computer systems via data link.

3.3 Conflict Prevention

While CD&R is traditionally a reactive function that is not engaged until two aircraft enter into a conflict, the purpose of conflict prevention is to prevent such conflicts from arising in the first place. A CP algorithm seeks actions to be taken by aircraft at the present time that decrease the likelihood of future conflicts in the

airspace. The simplest form of conflict prevention is to check that any proposed trajectory change, whether for purposes of conflict resolution or flight optimization, does not itself create any new conflicts with other aircraft [25].

A number of CP approaches are related to the management of the complexity of the airspace [26, 27]. Under complexity management, aircraft trajectories are proactively modified to limit such factors as the number of aircraft in a region of airspace or the frequency of crossing routes and other traffic complications [28–30]. Similar is the notion of flexibility preservation [31], in which trajectory changes are made to maximize the space of future maneuver options for a given aircraft. Complexity management and flexibility preservation are both intended to prevent conflicts, reduce overall airspace congestion, and reduce the intensity of required control actions for any given aircraft.

3.4 Discussion

The foundational work on conflict detection and resolution algorithms for air traffic was focused on proving the basic feasibility of these systems from a technical standpoint. This body of work has demonstrated that at a basic level, these functions can be performed by a computer, at least in an idealized laboratory setting. This work also demonstrated the potential for management of far greater numbers of aircraft than is possible in today’s system, and with greater route efficiency. While there are innumerable variations that have been examined, it can be confidently stated that the lowest-level separation assurance functions can be automated under the right conditions.

However, a number of issues in CD&R automation remain. The first relates to automation reliability and higher-level decision making. Whereas a state-of-the-art CD&R algorithm might perform well within the scope of a given traffic encounter at an instant in time, some algorithms exhibit behavior which might be described as “unstable” when examined over longer periods of time. An algorithm which previously produced a “turn left” command might suddenly indicate “turn right” in response to a momentary change to an aircraft’s trajectory. While the algorithm might be technically correct in both responses at each instant, the behavior is nevertheless “unstable” when compared to the actions of a human controller. While a number of heuristics can be applied to filter and smooth the output of a CD&R system [32], these patches are no substitute for the higher-level “big picture” that a human controller applies when managing traffic.

Other operational issues occur at the interface between the separation assurance automation and the rest of the air traffic operation. For instance, a system may be adequate at detecting and resolving traffic conflicts and maintaining separation, but these actions may be sub-optimal when considering larger, strategic traffic management concerns. Consider a CD&R algorithm that insists an aircraft should turn left to avoid a conflict, whereas a controller or pilot’s preference would be for the aircraft to turn right because of weather, restricted airspace, etc. If the separation assurance system is isolated from the rest of the overall system, then it falls to a human operator to somehow resolve the differences. Thus, these algorithms should be aware of other relevant constraints and attempt to satisfy them simultaneously along with the separation constraint.

The state-of-the-art CD&R algorithms also perform much better when all actors in the system are “well-behaved.” For instance, simulation results are generally very good when accurate, up-to-date trajectory information for all aircraft is available to all agents performing CD&R. When accurate trajectory information is available to all agents involved, the conflict detection problem is much simplified and the overall effectiveness of the separation assurance system increases dramatically. However, when an insufficiently robust algorithm makes incorrect assumptions in an environment where trajectory information is unavailable or unreliable, results are generally unacceptable. Thus, either the algorithms must have a sophisticated treatment of uncertainty in trajectory prediction, along with the operational buffers necessary to account for this uncertainty, or the overall system must be designed with the necessary infrastructure to provide accurate trajectory data to each responsible agent.

A basic problem also remains in the formal safety assessment and assurance of any given CD&R al-

gorithm. Given the open-ended and non-deterministic nature of the separation assurance traffic problem and software algorithms, it is difficult to apply traditional aviation certification processes. There is also a mismatch between the greater level of rigor required in the development of airborne avionics compared with ground-based computer systems. While some progress has been made in the application of formal methods from the field of computer science [33], they have as yet only been applied to the simplest of CD&R algorithms.

4 Concepts of Operation and System Architectures

While CD&R algorithms are a key enabler for automated separation assurance, their application to real world operations requires a more complete system architecture and concept of operations. This section discusses some of the major paradigms that have been developed to address the separation assurance problem.

4.1 Ground-based separation

Concepts for automation-assisted ground-based separation developed out of the natural course of evolution of the air traffic control system. In this general paradigm, the separation responsibility between the air traffic controller and the pilot does not change from today. Rather, the controller is augmented by a growing set of decision support tools and other automation to allow for the management of greater numbers of aircraft with fewer required control actions along more efficient routes.

The first such separation assurance automation tool to be widely deployed in the U.S is the User Request Evaluation Tool (URET), developed by the MITRE Center for Advanced Aviation System Development [34]. URET provides a conflict probe that scans for conflicts up to 20 minutes into the future and allows the controller to check clearances and potential route changes for conflicts before execution. However, not all of these capabilities are used consistently in practice, and acceptance varies from facility to facility and from controller to controller [35]. While URET provides some convenient functionality (e.g., the replacement of paper flight strips), it has not fundamentally changed the function allocation of separation assurance in air traffic control.

Another concept for controller automation is the Center-TRACON Automation System (CTAS), developed at NASA Ames Research Center. CTAS combines a number of automation tools intended to improve controller productivity, including both strategic and tactical conflict detection and resolution algorithms for en route separation management [32]. CTAS was extensively evaluated under simulation and field testing [36, 37], demonstrating potential workload and efficiency benefits for controllers and airspace users. While the en route CD&R components of CTAS are not used operationally, its Traffic Management Advisor [38] has been deployed to all 20 air route traffic control centers in the U.S. CTAS remains an active research platform used as the foundation for a number of other efforts, such as the Dynamic Weather Routes system [39].

Work on CTAS later evolved into another effort known as the Advanced Airspace Concept (AAC) [1,40]. Under AAC, the responsibility for primary separation assurance shifts from the human controller to the automated CD&R system. This system continuously scans for conflicts, and upon detection will generate an appropriate resolution maneuver and automatically uplinks it to the appropriate aircraft for execution by the aircrew. By automating the routine monitoring and control tasks, the human controller is free to devote more time to solving higher-level, strategic traffic management problems, as well as handling off-nominal situations. This arrangement is intended to dramatically increase the number of aircraft that can be safely managed in the airspace, beyond the gains that are possible through incremental changes to today's system. The AAC concept has been extensively evaluated in fast-time simulation as well as human-in-the-loop (HITL) experiments [41,42].

4.2 Airborne self separation

The general concept of airborne self separation involves the transfer of the primary separation assurance functions from the ANSP to the flight deck. The pilot, assisted by onboard equipment for surveillance of nearby traffic, becomes responsible for conflict detection and resolution and other separation assurance functions. This is analogous to the duty of the pilot to see and avoid other traffic under Visual Flight Rules in uncontrolled airspace, except that the pilot is enabled to do so in instrument conditions by the onboard separation assurance technology. The concept of self separation has existed for decades, predating the technology necessary to make it feasible [43].

The most basic form of this concept provides the pilot with a cockpit display of traffic information (CDTI) with some conflict alerting functions but no automated conflict resolution support [44–46]. In this form, the pilot is responsible for creating resolution maneuvers and avoiding traffic without automation assistance. While HITL studies have shown some basic ability for pilots to avoid traffic with this capability, it is generally considered that a CDTI and conflict alerting alone are insufficient to allow the aircrew to reliably perform separation assurance in typical operations with acceptable performance and workload. The aircrew will require a more comprehensive airborne separation assurance system providing the tools of conflict resolution and prevention in order to realize a robust system for self separation operations.

One such attempt to provide a complete solution for self separation, called Autonomous Flight Rules (AFR), has been developed at NASA Langley Research Center [47]. AFR is proposed as a new set of rules for operations in which the aircrew assume full responsibility for en route separation assurance, provided that they are equipped with surveillance technology such as ADS-B as well as onboard decision support tools for CD&R. Since the AFR aircrews are self-managing, it is envisioned that many of the airspace constraints and traffic flow management initiatives of today's system will be relaxed, e.g., sector capacity and miles-in-trail restrictions. The intended benefits of this arrangement are increased flexibility for the operator to realize the business-optimal trajectory for each flight, as well as providing an alternative implementation path to ground-based infrastructure deployments. AFR and an associated prototype system for onboard CD&R have been extensively tested in batch-mode and human-in-the-loop simulations [12, 48–50].

A number of other significant self separation concepts have been developed and tested in Europe. Under the Mediterranean Free Flight project, the Netherlands Aerospace Centre (NLR) developed and evaluated a concept for airborne self separation intended for en route operations in low density airspace over the Mediterranean. This concept and the supporting tools for CD&R were evaluated extensively in Monte Carlo simulation [51] as well as in a flight trial [52]. Under the iFly project, NLR continued this work to investigate the limits of airborne self separation in high density airspace [53].

4.3 Mixed operations

While advanced ground-based and airborne separation concepts are presented here as separate paradigms, a practical view of the mid-term period requires the consideration of mixed equipage operations. In this period, the system must accommodate newer aircraft equipped to perform advanced, automated separation assurance operations alongside the legacy fleet of aircraft that are still flying under IFR operations as they are conducted today. The mid-term period, due to its target time frame, will most likely be one of transition.

The harmonization of self-separating and ground-managed traffic is of particular concern since the separation responsibility for these distinct operations is divided between different agents (the aircrew and the ANSP). The concern is that where different aircraft are being controlled by separate and uncoordinated agents in the same airspace, there is the opportunity for confusion and ambiguity of responsibility, leading to unresolved conflicts and losses of separation. Clearly, a separation assurance system supporting mixed operations must have mechanisms to prevent this.

A conceptually simple solution is to segregate self-separating traffic in a different airspace from the

ground-managed traffic, i.e., a form of procedural separation. Such proposals include restriction of self-separation operations to certain altitudes, within designated flow corridors, or other geographic areas [54–56]. While this procedural separation may eliminate some operational concerns, it raises other issues. For one, if a new self-separation operation is relegated to undesirable airspace, this imposes limitations on the flexibility and benefit to potential operators, which may invalidate the business case for self separation in the first place. Thus, airspace segregation may challenge the equitable accessibility of the airspace to all users.

Other concepts propose to integrate self-separating and ground-managed traffic in the same airspace. One such concept was developed under NASA’s Distributed Air Ground Traffic Management project. In this concept, AFR aircrews perform self separation in the same airspace as IFR aircraft being managed by the ANSP. The most important aspect of this concept is the formalization of the responsibility of each agent to resolve which conflicts through a set of unambiguous priority rules [57]. However, the effectiveness of this arrangement is limited by the amount of information available to each agent about the intent of the aircraft managed by the other agents. For instance, if an AFR aircrew is responsible for resolving a conflict with an IFR aircraft, its ability to do so is affected by whether or not the IFR aircraft’s intent is available for trajectory prediction and conflict detection. Thus the effectiveness of the mixed operations architecture is directly linked to the communications and information sharing infrastructure that is available, and in turn the amount of explicit coordination that is possible between various agents.

4.4 Hybrid air/ground concepts

Whereas ground-based and airborne separation concepts may be seen as opposite extremes along the air-ground axis, many proposals offer some kind of shared responsibility between controller and pilot. Under the paradigm of trajectory negotiation [58], the pilot and controller each use a set of decision support tools to engage in an automatic trajectory optimization process that considers factors such as traffic, weather, and user preferences to produce a solution that simultaneously satisfies air traffic management constraints while maximizing the user’s business objectives. In this case, both the ANSP and the aircrew (and the AOC, either directly or by proxy) participate in the function of conflict resolution, although it is usually said that the ultimate responsibility for separation assurance remains with the ANSP.

4.5 Discussion

Work to develop CTAS, AAC, and AFR has shown a great deal of promise in both advanced ground-based separation and airborne self separation, as well as their hybrid and derivative iterations. Basic technical feasibility of all of these concepts has been demonstrated, including basic integration of separation assurance automation tools and airspace operations and procedures in relevant NextGen/mid-term operational scenarios. This work has also generated preliminary support for the potential operational benefits of increased airspace capacity and flight efficiency.

Work remains on several fronts. First, as discussed in the previous section, continued maturation of the separation assurance algorithms for automated conflict detection, resolution, and prevention is needed to provide robust tools for real-world operations. These prototype separation assurance systems can perform well in the laboratory under ideal conditions, but more work is needed to understand their behavior in a wider variety of practical scenarios. Simulation experiments are necessarily limited in the scope and realism that they can recreate, and field evaluations are very difficult to carry out in practice.

Second, there are many variations on these concepts that perform well in future scenarios but with infrastructure and equipment that does not yet exist. For instance, the key enablers of ADS-B and controller-pilot data link communications have not yet been widely deployed. Nor have the necessary computer upgrades to support advanced automation tools been installed on the flight deck or in ground-based control facilities. Without these enablers, it is difficult to make headway on any significant improvement to today’s separa-

tion assurance system. Thus, work remains to provide further justification for investments in this enabling infrastructure, including spin-off efforts to provide substantial system benefits in the near-term.

5 Function Allocation

Compared to the wealth of research in separation assurance automation technology and the development of specific concepts of operation, comparatively little work has been done to compare these systems from the basis of function allocation.

There are several review papers, covering a variety of separation assurance concepts, that make a qualitative attempt to compare them. Reference [59] compares a set of ground-based, airborne, and mixed concepts with varying levels of automation on the basis of technological readiness as well as impacts to controller and pilot situation awareness and workload. Reference [60] performs a similar analysis, classifying prior work along the air-ground and human-automation axes. Both papers highlight maturity differences among the range of concepts, pointing to the nearer-term readiness of controller automation tools compared to the more dramatic paradigm shift of full airborne separation.

5.1 Heuristic Design and Evaluation

Function allocation methods contained in this category generally involve designing or evaluating a function allocation concept against a set of specific pre-defined criteria. These criteria may take the form of design guidelines, requirements, or metrics created by experts knowledgeable in the design of function allocation concepts.

The problem of effectively allocating tasks along the two axes is unique to the primary function of maintaining separation assurance. However, Ref. [61] provides a high level philosophy for distributing tasks between humans and varying levels of automation. This features ten levels of automation of decision and action selection, as well as a simple four stage model of information processing (e.g., sensory processing, perception and working memory, decision making, and response selection).

Reference [61] recommends the use of evaluative criteria to measure the effectiveness of a given function allocation construct, along with providing a few suggestions for preferred analysis methods. This leaves the method by which a function allocation construct is designed and evaluated somewhat open to the interpretation of the individual researcher, depending on the depth or the breadth of the task.

The definition of the function allocation problem is in itself a difficult research task, given the breadth and depth of the subject. Reference [62] attempts to provide a formal framework for function allocation, proposing a method to systematically decompose the separation assurance problem into a hierarchy of functions and sub-functions along with a matrix of allocations between these functions and airspace system agents. Given a matrix of these alternatives, the paper proposes then to systematically evaluate and compare them through more detailed modeling and analysis.

Relatedly, Ref. [63] outlines the application of Work Domain Analysis (WDA) [64] to the Traffic Collision Avoidance System. WDA applies an abstraction hierarchy [65] to five conceptual layers ranging from functional purpose to physical form. The authors also discuss some of the challenges associated with the application of the abstraction hierarchy to aircraft displays.

Reference [66] outlines requirements for effective function allocation between humans and automation, including the capability of agents to perform their allocated functions, accounting for other factors such as teamwork. The paper also proposes metrics for measuring function allocation effectiveness, including mismatches between responsibility and authority, stability of the human's work environment, and the human's ability to adapt to context. The paper then provides an example function allocation for transport aircraft operations during the descent phase of flight.

Reference [67] calls for a quantitative approach to assessing human judgment during a collision detection task via the n-system lens model analysis. The n-system lens model (originally inspired by [68]) applies a quantitative approach to the analysis of human decision making. Applying this type of quantitative analysis to the tasks of CD&R could provide insight to the informational cues flight crews rely on for decision making. This information could then be used to form the basis of a more optimal function allocation between humans and automation in future separation assurance systems.

5.2 Human-in-the-Loop Simulation

Human-in-the-loop (HITL) simulation experiments have been employed to evaluate and compare a variety of separation assurance architectures [49, 50, 69]. Such experiments typically simulate one or more separation assurance architectures and evaluate them on the basis of human factors and operational performance metrics such as workload, number of losses of separation, conflict resolution efficiency, etc. Variations on the AFR and AAC concepts have been evaluated in a series of HITL experiments conducted jointly by NASA Ames and Langley, as a way to explore alternative airborne and ground-based allocations of CD&R functions in the same airspace. HITL experiments have also been used to evaluate the impact of varying levels of automation support on the workload and effectiveness of the air traffic controller in performing separation assurance functions compared to the baseline of today's operations.

Generally, HITL experiments can provide excellent insights into practical human factors issues related to an operational concept. The experience gained from observing real human operators interacting with prototype procedures and technology is unmatched by paper analysis or pure computer simulation. However, HITL experiments can be costly and time-consuming to develop and typically suffer from low sample sizes. It is also difficult to generalize the results of a HITL that examined one particular procedure or technology and draw broader conclusions about air/ground or human/automation research questions.

5.3 Computer Simulation

A variety of computer simulations have also been used to study separation assurance from a function allocation perspective [66, 70, 71]. Agent-based air traffic simulations have been used to evaluate various centralized and distributed separation assurance architectures. This approach simulates an air traffic scenario with a computer model of the behavior of the agents performing separation assurance, with varying degrees of fidelity. Typical metrics include the number of losses of separation, the number of required conflict resolution maneuvers, and other measures of operational efficiency such as arrival delay and flight path deviation.

In a fast-time, Monte Carlo simulation, a great number of operations can be simulated, yielding high-quality statistical data about the concept of interest. However, the goodness of the results are limited by the quality of the agent behavior model. In many simulations, this is a procedure-based model which does not capture the nuances of actual human behavior. Additionally, even in a Monte Carlo simulation, the number of runs required to estimate the probability of rare events can be difficult to achieve. Computer simulation suffers from the same generalization problem as HITL experiments: a simulation inherently simulates a specific concept, procedure, and technology, and it can be difficult to generalize the results to broader research questions.

5.4 Discussion

The general approach of formulating function allocation as an optimization problem is complicated on two fronts. Whereas many other traditional engineering problems may be simplified to a finite number of continuous and discrete variables, it is much more complicated to enumerate a comprehensive set of separation

assurance functions, agents, and architectures. A simplified matrix of assignment between functions and agents misses many of the practical details of operational implementation in the real world, details which have great significance to the evaluation of alternative architectures. Thus there is a serious problem in simply describing architectures at a meaningful level of detail, and doing so for enough of them in order to cover the breadth of the trade space in any one research study.

Second, there are also basic problems in the evaluation of architectures against relevant metrics. There are no simple physics-based or empirical equations that can be used to roughly evaluate the overall operational properties of a system of such scale and complexity as the global air traffic management system. This is especially true for revolutionary architectures, for which there may be no analogous systems in the real world from which to extrapolate. Many relevant factors depend on details that are notoriously difficult to model such as human operator behavior, the interactions between large regulatory and operational organizations, national economics and air traffic demand, and many others. The intractable problems of modeling complex systems-of-systems are not new in the engineering world, but are exacerbated by the scale of the problems in air traffic management.

It is generally recognized that in the middle of the human-automation axis lies a discontinuity between the capability of an automation system and the ability of the human operator to intervene during failures and off-nominal conditions. This is true for human-automation systems in general and also for separation assurance systems in particular. The discontinuity refers to the case where an automation system is sophisticated enough to take over some functions during normal operations, but is not robust enough to “never fail.” During these failures or other circumstances where a human is required to intervene, we may have a deficiency in the human’s ability to do so. For instance, if the primary function was being handled by the automation and the human was paying attention to other things, then the human may no longer be properly engaged to immediately handle the emergent situation. Additionally, human operators over time lose the skills necessary to perform a function if they don’t practice it regularly, further exacerbating the problem.

6 Conclusion

A number of conclusions can be drawn from the body of work reviewed in this report. First, a great deal of work has demonstrated the basic technical feasibility of automated separation assurance algorithms in both airborne and ground-based applications. However, much work remains to develop these pathfinder projects into mature tools for real world deployment. In particular, CD&R algorithms should incorporate more sources of information into the optimization process for more sophisticated and robust inference and decision making.

Additionally, almost every advanced separation assurance algorithm and concept of operation requires some form of communications and surveillance infrastructure beyond what is available today, including ADS-B and controller-pilot data link. These technologies continue to be the foundation for future separation assurance systems and the rest of the ATM system. A sustainable path for their full deployment is needed to realize any of the future concepts discussed in this report.

There is no clear winner in the air vs. ground debate, and the authors propose that elements of both approaches will be needed in the future. Research has shown the merits of both ground-based and airborne separation approaches in different circumstances. We can conceive of an integrated air-ground system with system-wide optimization, safety assurance, and conformance monitoring provided by the ground, accommodating user-preferred routes and other trajectory optimization requests generated by the air. With the emergence of UAS of all types within the airspace system, we see the merits of airborne self separation as a complement or backup to ground-based separation. Many of these notions have been discussed among the technical community for decades.

The problems of the human-automation axis in the separation assurance domain mirror those found else-

where in aviation and other transportation disciplines [72]. In particular, there is a significant gap between the small advances possible by the introduction of decision support tools to aid the pilot and controller vs. the leap to fully automated separation assurance. In this intermediate area lie a set of critically important research challenges in the design of human-automation teams with shared responsibility for safety critical functions such as separation assurance.

Finally, the basic tools for the design and analysis of separation assurance systems are still in their infancy. Computer-based and human-in-the-loop simulations each address part of the problem, as do the heuristic approaches to function allocation from the human factors discipline. However, we are still limited in our ability to understand the technical implications of separation assurance design choices from the perspective of complexity science. Where there is greater maturity in the technical evaluation of a given separation assurance algorithm or concept, the softer issues of economics and policy are very difficult to study in an analytical way. The ability to make stronger recommendations for separation assurance function allocation will improve as advances are made in the tools and methodology of the research in these areas.

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