NASA/CR-2008-215121

Trajectory-Oriented Approach to Managing Traffic Complexity

Operational Concept and Preliminary Metrics Definition

Husni Idris, Robert Vivona, and Jose L. Garcia-Chico
L3 Communications, Billerica, Massachusetts

April 2008

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/CR-2008-215121

Trajectory-Oriented Approach to Managing Traffic Complexity

Operational Concept and Preliminary Metrics Definition

Husni Idris, Robert Vivona, and Jose L. Garcia-Chico
L3 Communications, Billerica, Massachusetts

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for the National Aeronautics and Space
Administration under Ames Contract NNA07BB26C

April 2008

Available from:

NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Preface

This document describes preliminary research on a distributed, trajectory-oriented approach for traffic complexity management. The approach is to manage traffic complexity in a distributed control environment, based on preserving trajectory flexibility and minimizing constraints. In particular, the document presents an analytical framework to study trajectory flexibility and the impact of trajectory constraints on it. The document proposes preliminary flexibility metrics that can be interpreted and measured within the framework.

This document was prepared by L3 Communications, 300 Concord Rd., Billerica, MA, under NASA Research Announcement (NRA) Contract Number NNA07BB26C. It represents the deliverable “2007 summary report” for NRA Task: “Traffic Complexity Management through Trajectory Flexibility and Minimizing Constraints”

This page intentionally left blank

Table of Contents

List of Figures

List of Acronyms

4D	Four Dimensional
ADP	Adaptability
ADS-B	Automatic Dependent Surveillance – Broadcast
AOC	Airline Operations Center
AOP	Autonomous Operations Planner
ATM	Air Traffic Management
ATOL	Air Traffic Operations Laboratory
EDA	En-route Descent Advisor
ETA	Estimated Time of Arrival
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
RBT	Robustness
RTA	Required Time of Arrival
TFM	Traffic Flow Management
UAV	Unmanned Air Vehicle
UGV	Unmanned Ground Vehicle

1 Introduction

The Next Generation Air Transportation System (NextGen) is expected to receive up to three times the current traffic demand by the year 2025 [1]. In order to handle the expected increase in air traffic NextGen will introduce major transformations in Air Traffic Management (ATM); three examples of which are net-enabled information access, performance-based services, and aircraft trajectory-based operations [1]. Net-enabled information access will substantially increase information availability promoting greater shared awareness of system operations among users and service providers. Net-enabled information access is exemplified by emerging technologies such as the Automatic Dependent Surveillance Broadcast (ADS-B) which enables sharing of aircraft-based position and intent information among airborne and ground-based agents. Performance-based services will make access to National Airspace System (NAS) resources, such as runways and airspace volumes, dependent on the equipage and capability of the aircraft. This promotes users to equip their aircraft and service providers to provide access to scarce NAS resources according to performance levels of aircraft. Trajectory-based operations will manage NAS resources by requiring aircraft to precisely follow custom-made four dimensional (4D) trajectories consisting of a specified path and along-path time conformance requirements. This promotes prescribing and accurately following trajectories that ensure separation and optimize traffic flow management over different time horizons.

These capabilities enable a more optimal allocation of functions among the agents of the air traffic system [2]. One such allocation scheme proposes moving the ATM system towards a distributed control architecture [3], [4]. This distributed architecture delegates to the pilot more authority in determining and modifying the aircraft trajectory; currently this authority resides mainly with the ground-based controller. The premise is that distributed control mitigates the controller workload as a constraint against increasing airspace capacity, because introducing more traffic introduces additional responsible decision makers (pilots) enabled by advanced sensor, communication, and decision support technologies.

While the architecture of the ATM system becomes less centralized and more distributed, its goal remains to achieve objectives such as maintaining safety and efficiency at acceptable levels. A key research question asks whether a distributed control architecture will be capable of satisfying these ATM objectives. A positive answer has important implications on the new role of centralized control, taking on higher level supervisory control functions such as monitoring and intervention, as opposed to lower level active control, thus enabling capacity gains and cost savings. Therefore, in the distributed control architecture each individual aircraft is responsible for generating and maintaining a trajectory that achieves the ATM objectives for that flight in addition to any self-interest objectives. To this end it is critical to design the distributed architecture with appropriate elements that ensure individual aircraft actions achieve the overall ATM objectives.

Prior research on distributed ATM concentrated on the investigation of sharing the primary function of separation assurance between pilots and controllers. A number of research efforts investigated and reported algorithms suitable for conflict resolution in a distributed control environment: Hill, et al. suggested a satisfying game theoretic approach for distributed air traffic control [5]. Wollkind, et al. reported a cooperative negotiation algorithm for conflict resolution, trading shared utility information using a monotonic concession protocol [6]. Versteegt and Visser used traffic complexity as a criterion to resolve conflicts in a free flight sector while reducing the traffic load [7]. To assist the pilot in separation assurance, automated decision support systems, such as the Autonomous Operations Planner (AOP), are designed to provide conflict detection and resolution advisories in the cockpit [8]. Genetic algorithms to resolve conflicts between aircraft pairs were reported associated with the AOP research [9], [10]. Early experiments of mixed distributed and centralized separation assurance showed promising results in terms of the impact on controller workload and efficiency [11], [12], [13].

This research deals with two newly proposed functions for the distributed ATM system: A trajectory flexibility preservation function and a trajectory constraint minimization function. The trajectory flexibility preservation function enables an aircraft to plan its trajectory such that it preserves a requisite level of maneuvering flexibility in accommodating unforeseen disturbances, stemming for example from other traffic and from weather activity. The trajectory constraint minimization function enables ground-based agents, in collaboration with air-based agents, to impose just-enough constraints on trajectories to achieve ATM objectives, such as separation assurance and flow management.

In this report, Section 2 describes the research questions consisting of two main hypotheses to test. In Section 3, a literature review of related topics such as motion planning, distributed airborne-based conflict resolution, traffic complexity and constraint minimization is collected. Section 4 describes conceptually how the two functions of trajectory flexibility preservation and constraint minimization operate in a distributed control architecture that includes self separation. The concept and its underlying hypotheses are illustrated through hypothetical scenarios involving conflict resolution and flow management. Then, a functional analysis is described in Section 5 where each of the three functions is decomposed into monitoring and action components, and the interaction and information flow between them is demonstrated schematically. Sections 4 and 5 are based on material published in [14]. Section 6 gives further insight into the concept by describing trajectory flexibility in an analytical framework of an aircraft trajectory solution space and defining flexibility metrics. In this framework flexibility is defined in terms of robustness and adaptability to disturbances. Furthermore, the impact of constraints is illustrated through analysis of a trajectory solution space with limited degrees of freedom, namely speed variation along the aircraft path, and in simple constraint situations involving meeting multiple times of arrival and resolving a conflict. Section 6 is based on material published in [15]. Section 7 presents methods to estimate the metrics applied to situations using speed and path stretch, as single degree of freedom. The case of path stretch is in an initial stage of research requiring further research. Section 8 describes, also based on material published in [15], the use of the proposed metrics for trajectory planning in simple scenarios involving selecting a path and using speed as the only degree of freedom to accommodate disturbances. Namely two examples are used, one to demonstrate how selecting a path based on flexibility may impact traffic complexity and one to demonstrate how flexibility increases by relaxing constraints. Finally future work is summarized in Section 9.

2 Research Questions

The ATM system ensures high level objectives such as safety, stability, cost effectiveness, among other objectives. To ensure these objectives constraints are imposed on aircraft trajectories. For example to ensure safety separation requirements are imposed between aircraft and to ensure stability required times of arrival are scheduled in order to maintain demand below capacity. As shown in Figure 2-1, this research introduces two new functions of the distributed ATM system: a flexibility preservation function by which an individual aircraft generates a trajectory that preserves its ability to accommodate unforeseen events above a requisite level, and a constraint minimization function by which a distributed agent (aircraft or ground unit) applies only the necessary constraints on a trajectory to achieve the ATM objectives.

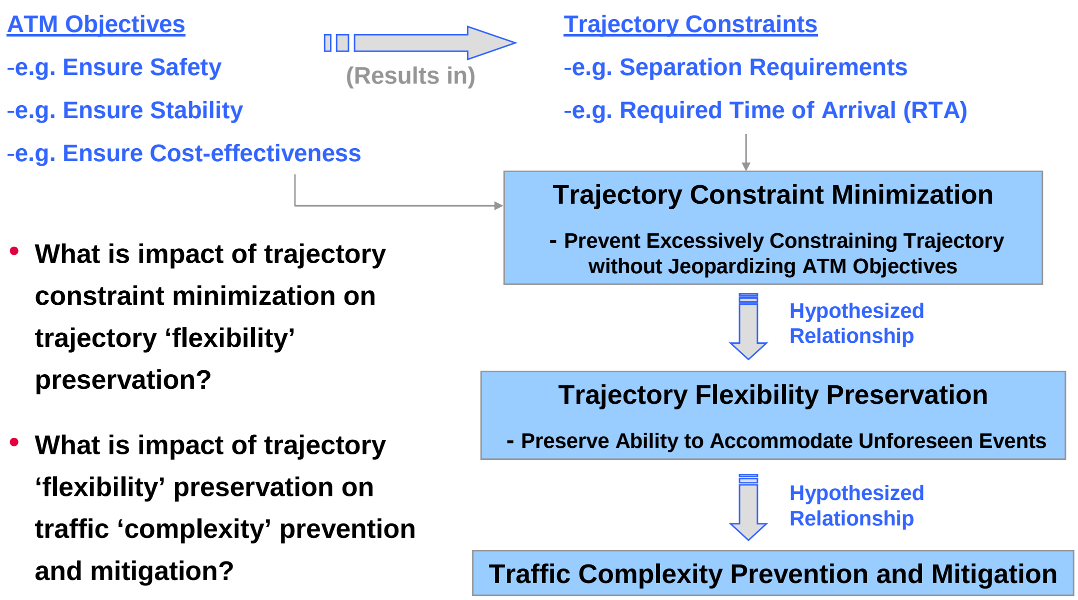

Figure 2-1 Main functions and their hypothesized relationships

The objective of this research is to investigate the relationships between these functions and their impact on the aggregate ATM system performance. Namely, this research will test two underlying hypotheses displayed in Figure 2-1:

a. by each individual aircraft preserving its own trajectory flexibility, aggregate system objectives, such as maintaining acceptable traffic complexity (complexity defined as proneness to compromising safety), are naturally achieved, and

b. by minimizing the constraints imposed on a trajectory, without jeopardizing the intended ATM objectives, the trajectory flexibility is increased, and hence traffic complexity is further mitigated.

3 Literature Review

A literature search was made on past research concepts ranging from topics on motion planning in robotics and other autonomous agents to distributed airborne-based conflict resolution. Some literature about complexity and constraint minimization is also included. The literature is summarized and organized by themes in the following sub-sections.

3.1 Motion Planning in Robotics and other Multiple Moving Agent Systems

Significant research has been conducted in the area of robotics for planning coordinated motion and trajectories of robots and autonomous vehicles of different types. This work which concentrated in the late eighties and the nineties has been reinvigorated recently in the context of multiple rovers and multiple unmanned air and ground vehicles (UAV and UGV) for applications such as space exploration and hazard area operations. In such applications autonomous aerial or ground vehicles are expected to coordinate their motions to avoid each other and other obstacles while achieving certain goals.

In general this problem involves deriving a world model based on partial information of the objects surrounding each vehicle including current and intended states of obstacles and other moving vehicles. This information is available through sensing and communication, such as through vision sensors and data links. Then motion plans for each vehicle are generated in a centralized or distributed fashion to avoid the obstacles and other objects and attain its goals.

<u>Geometric approaches:</u>

One of the earlier approaches to motion planning is based on geometrically defining the environment, using methods such as Voronoi diagrams [16], and planning trajectories through geometric entities or cells. These approaches are mainly used to plan trajectories off-line.

<u>Artificial potential fields:</u>

One popular approach is based on artificial potential fields proposed by Khatib [17]. In this approach obstacles are modeled as repellers and goals as attractors. The approach is attractive because it allows adaptive on-line motion planning, in a reactive manner while vehicles move. The most serious shortcoming of this approach is the risk of deadlock due to local minima and of oscillations near obstacles and in narrow passages [18]. However the use of potential fields is still a popular approach and has been suggested for navigation of unmanned vehicles using actual magnetic field sensors [19], [20]. Shimoda [21] applied an artificial potential field approach in the trajectory space (the space of the actuation degrees of freedom of a vehicle) to account for kinematic constraints, uneven terrain as well as avoiding moving obstacles. Two advantages were described for using the degrees of freedom space as opposed to the conventional Cartesian space: directly computing actuation command inputs that obey the vehicle constraints and easily expressing the terrain constraints in terms of actuation variables.

Randomized approaches:

Randomized motion planning approaches avoid the deadlock problem inherent in potential field approaches. One such approach uses probabilistic road maps by randomly selecting milestones from the robot's configuration space and connecting them to produce collision free paths [22]. This approach was described in Hsu 1997 and extended to account for any kinodyamic constraints by building the roadmap in the space-time domain [23], [24], [25].

Lamiraux [26] used randomized exploration trees (introduced previously by Barraquand [27] and extended in LaValle [28]) from the initial state and from the goal state, and then potential field methods to modify the two resulting partial trajectories such that they connect. Combining randomized exploration trees and trajectory deformation using potential fields reduced the size of the trees and the exploration time. The paper has a mathematical formulation for a generic perturbation of a trajectory using artificial potential field approach, which is based on earlier work of Lamiraux [29]. When a local minimum results in the potential field modification, further tree exploration is used to avoid the deadlock.

3.2 Distributed Airborne Based Conflict Resolution

Wollkind et al. [6] reported a cooperative negotiation algorithm for conflict resolution. The approach used utilities of the agents involved in a conflict that are traded using a monotonic concession protocol. The approach assumes the agents share their respective utility values.

A number of algorithm efforts have also been reported associated with the AOP research and experiments. These algorithms use genetic algorithms to resolve conflicts between aircraft pairs [9], [10], [30].

Versteegt and Visser used complexity (dynamic density) as a criterion to resolve conflicts in a free flight sector while reducing the traffic load [7].

Hill et al. [5] suggested a satisficing game theoretic approach for distributed air traffic control.

Using hybrid control, Tomlin et al [31], [32] analyzed the safety of trajectory patterns with continuous dynamics between discrete states. They used relative geometry of kinematics for modeling the continuous state evolution between discrete states, which were turns between straight segments. They analyzed a worst case scenario based on a game theoretic assumption that each aircraft assumes the worst action by the other.

Clark et al. [33] reported an approach to robot planning motion based on dynamic networks. They proposed centralized control within networked vehicles and decentralized when not networked. Centralized control used priority rules within networked vehicles.

3.3 Traffic Complexity

Traffic complexity is essential to this research because of the need to test and demonstrate the impact of trajectory flexibility preservation and constraint minimization on traffic complexity.

The vast majority of the air traffic control literature dealing with complexity has tackled the complexity issue focusing on factors that make the air traffic situation more complex and result in an increase of controller workload, ultimately limiting the airspace capacity. These studies assumed a centralized environment in which the controller controls traffic within a sector of airspace and the major motivation was to approximate controller workload, and hence sector capacity, by a more realistic measure than a simple traffic count, as it is the practice today. The approaches used in these efforts include:

Kopardekar and Magyarits [34] listed a large number of factors (from a number of studies) that affect traffic complexity (and hypothetically controller workload) along with associated metrics. The metrics were mostly derived from the airspace geometry based on the notion of dynamic density, and included, for example, aircraft count and density, sector geometry, traffic mix and distribution, traffic flow structure, mix of aircraft types and performance characteristics, and weather. Then using the linear regression technique, they found the factors/metrics that best fit controller workload data. The workload data was obtained from subjective controller ratings of the difficulty to control traffic scenarios of different complexities.

Histon et al. [35] and Davison et al. [36] emphasized cognitive elements of complexity, in particular the use of structure by controllers to simplify the control cognitive processes. Examples of structure that they determined include standard flows, grouping of traffic, and critical points such as merge points. Athenes et al. [37] developed and analyzed a metric that measures the effect of uncertainty and time pressure on controller workload. They used objective measures such as heart rate to demonstrate the validity of their metrics.

Delahaye and Puechmorel [38] introduced several complexity metrics based on traffic geometry (proximity, convergence, sensitivity to control maneuver) and traffic flow pattern organization or disorder (topological entropy). They extended the entropy metric effort building linear and nonlinear dynamical system models to fit actual aircraft trajectories [39]. Building on this effort, Ishutkina et al. [40] estimated traffic complexity by the ability of a mathematical linear program to interpolate a vector flow field between aircraft positions and velocities, given a set of constraints on speed and turn rate. These efforts tend to be computationally expensive and were demonstrated for simple 2 dimensional situations.

Aigoin [41] used clustering techniques to measure complexity. Granger and Durant [42] analyzed the impact of the cluster size of aircraft in conflict. Clustering techniques were also used by Billimoria and Lee [43] to determine airspace congestion independent of sectors.

More relevant to a distributed control environment, Riley et al. [44] analyzed the pilot perception of airspace complexity. This study built on the controller perception studies by Koperdekar and Magyarits [34]. It reduced the list of factors to the ones relevant to a pilot resolving conflicts and used pilot ratings and regression to analyze the factors that represent pilot perception the best. Then a neural network model was used to create a complexity prediction utility.

Some efforts were made to use complexity prediction for traffic flow management decision aid. These efforts include Sridar et al. [45], and Masalonis et al [46].

3.4 Constraint Minimization

Little literature has been found and reviewed dealing with the minimization of constraints and its effects. For example, Ishutkina et al. [40] suggest a lineal program formulation that determines the minimum number of constraints that should be relaxed in their vector field formulation.

4 Concept Definition

Figure 4-1 illustrates the allocation in the distributed ATM architecture of the three functions: separation assurance, trajectory flexibility preservation and trajectory constraint minimization.

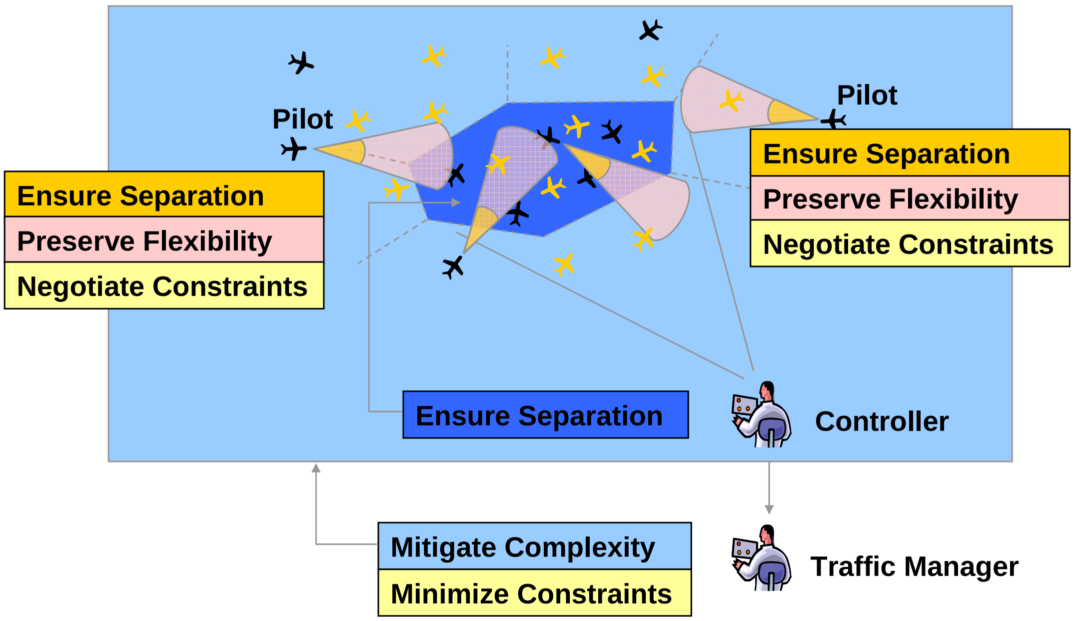

Figure 4-1 Distributed ATM architecture with separation assurance, trajectory flexibility preservation, and trajectory constraint minimization

In this mixed operations, distributed environment separation assurance is shared between the pilot (for self-separating aircraft) and the air traffic controller (for ground-controlled aircraft) and acts in a time horizon depicted by the shorter cones extending from each aircraft. The flexibility preservation function is a pilot function that complements the pilot's separation assurance function but acting on a larger time horizon as depicted by the extended cone shapes. The constraint minimization function is allocated mainly to the ground based traffic manager to impose just-enough restrictions on the aircraft to meet ATM objectives. However, a collaborative role allows the pilot to negotiate constraints with the ground traffic manager. Each of the three key functions, the relationships between them, and their impact on NAS performance indicators such as capacity and complexity, are described next.

4.1 Separation Assurance

Separation assurance is the most central function of air traffic control, taking in its time horizon and for safety reasons priority over other functions such as expediting traffic and implementing traffic flow management initiatives. In centralized control separation assurance is the responsibility of the air traffic controller who monitors and manages aircraft within an airspace volume to maintain the minimum separation requirements. In a distributed control architecture, each aircraft (i.e. pilot/automation system) is responsible for maintaining separation from surrounding traffic. Pilots are assisted in conflict detection and resolution by cockpit automation, such as the AOP system, maintaining their workload at an acceptable level. As a result of the allocation of separation assurance tasks to pilots, traffic complexity from a centralized perspective, which represents controller workload and proneness to commit separation violation errors [34] [35] [36] [38], is reduced because the controller is relieved from the active separation assurance task for self-separating aircraft. In addition, a notion of distributed/automated traffic complexity is introduced that represents the level of proneness to separation violation errors in the new distributed/automated environment. For example, Riley et al. [44] analyzed a number of factors in terms of how well they represent a pilot's perception of traffic complexity in airborne conflict resolution scenarios. Therefore, traffic complexity may be represented and mitigated differently in a distributed/automated-control environment than in the usual centralized/human-control environment. The premise of the distributed control architecture is that the airspace can accommodate more traffic because the capacity to assure separation is increased through the participation of pilots. Furthermore, as the traffic level increases, the capacity of the NAS in terms of separation assurance increases, because introducing more traffic introduces more pilot decision makers for self separating aircraft, adding scalability of capacity with demand.

Centralized or distributed, resolving predicted conflicts is more critical and required to be more accurate for conflicts that are predicted closer to the current position of aircraft. The further out the predicted conflicts, the less time-critical their resolution is because prediction is less accurate and the situation is subject to change as time progresses. Separation assurance is, therefore, the most critical function of cockpit automation in the near time horizon taking priority over other functions in this horizon. The strategic separation assurance horizon is typically on the order of tens of minutes. For example, in the current AOP logic conflict resolution is performed only for conflicts predicted in the next ten minutes from the current aircraft state, and these conflicts are resolved for the next twenty minutes. The separation assurance horizon is depicted as the dark short cone expanding from each aircraft in Figure 4-1.

4.2 Trajectory Flexibility Preservation

Trajectory flexibility preservation is envisioned as an airborne function that complements airborne-based separation assurance. The main objective of this function is to plan the aircraft trajectory in a manner that affords the aircraft sufficient flexibility, particularly in preserving its ability to accommodate disturbances. These disturbances may stem for example from other traffic or from weather activity. Flexibility preservation complements separation assurance both within the conflict resolution horizon and outside it within an extended flexibility planning horizon as shown by the extended cone shapes in Figure 4-1.

In the conflict resolution horizon flexibility is used to select from many conflict resolution solutions one that affords the aircraft more flexibility, for example to adapt to unexpected behavior by the intruder traffic. One example of such behavior is the coincidence conflict situation shown in Figure 4-2. In this situation two conflicts are predicted between two unrelated pairs of aircraft as shown in the left side of the figure. If the two ownship aircraft maneuvered as shown by dotted lines in the left side of the figure to resolve their respective predicted conflict, without coordination, a new coincidental conflict may arise between them. Although the flexibility preservation function does not explicitly coordinate between the two aircraft, it assists each ownship in reducing the risk of conflict due to the unpredicted behavior of the surrounding traffic, thus resulting in implicit coordination. Hence with this function, each ownship aircraft may select a more flexible trajectory anticipating the potential behavior of the other aircraft and minimizing the exposure to it. For example, in the right side of Figure 4-2 each of the ownship aircraft decided instead to maneuver away from the other ownship, reducing or eliminating the chance of a coincidence conflict situation.

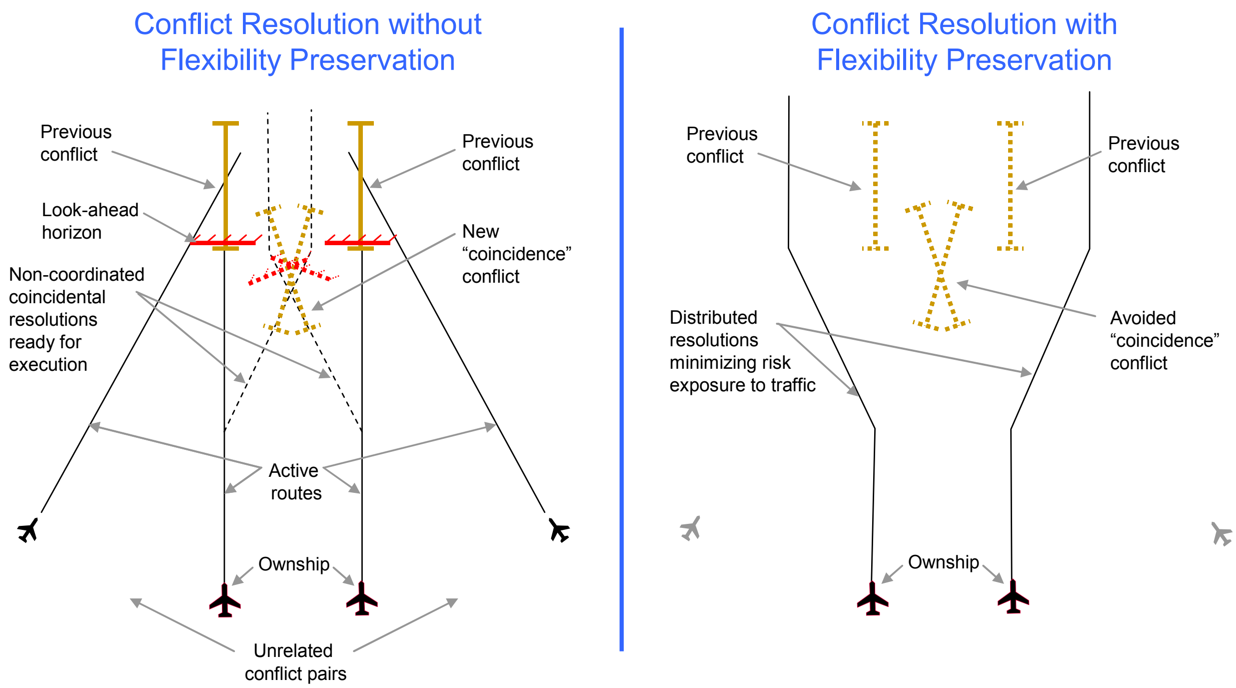

Figure 4-2 Flexibility preservation avoiding coincidence conflicts

Outside the conflict resolution horizon and within the flexibility preservation horizon the flexibility preservation function plans the aircraft trajectory to minimize its exposure to disturbances such as weather cells and dense traffic areas. In this long horizon the possibility of loss of separation is not critical because conflict prediction is rather inaccurate and does not warrant conflict resolution. While the required separation from the other traffic is not ensured in this horizon, the flexibility preservation function positions the aircraft optimally to reduce the probability of conflict in the future, by minimizing its exposure to weather cells and dense traffic areas. More generally it is hypothesized that the flexibility preservation function results in naturally producing traffic situations that are less complex than without the application of the function.

Figure 4-3 depicts an example involving aircraft maneuvering around convective weather cells. Because of the reduced airspace capacity, aircraft compete for small gaps between the weather cells. On the left side of the figure each aircraft, while planning its trajectory, assesses its flexibility using a flexibility metric that reflects its exposure to risk and ability to mitigate it. Given the weather and traffic situation, each aircraft questions whether it should avoid the airspace entirely or could modify its trajectory to increase its flexibility. If the aircraft proceeded along their headings as depicted in the left side of the figure, a complex traffic situation arises causing excessive congestion and possibly a high conflict rate in the airspace between the weather cells. On the other hand, the right side of the figure displays a more structured and streamlined traffic pattern that is hypothesized to result if each aircraft made a decision to increase its flexibility – by limiting its exposure to congestion and proximity to the other traffic and the weather cells. Because the flexibility preservation function results in reducing the traffic complexity in the new distributed environment, the ground controller workload is also reduced, while performing monitoring and supervision roles, as the traffic is more structured and the chance of conflict is reduced.

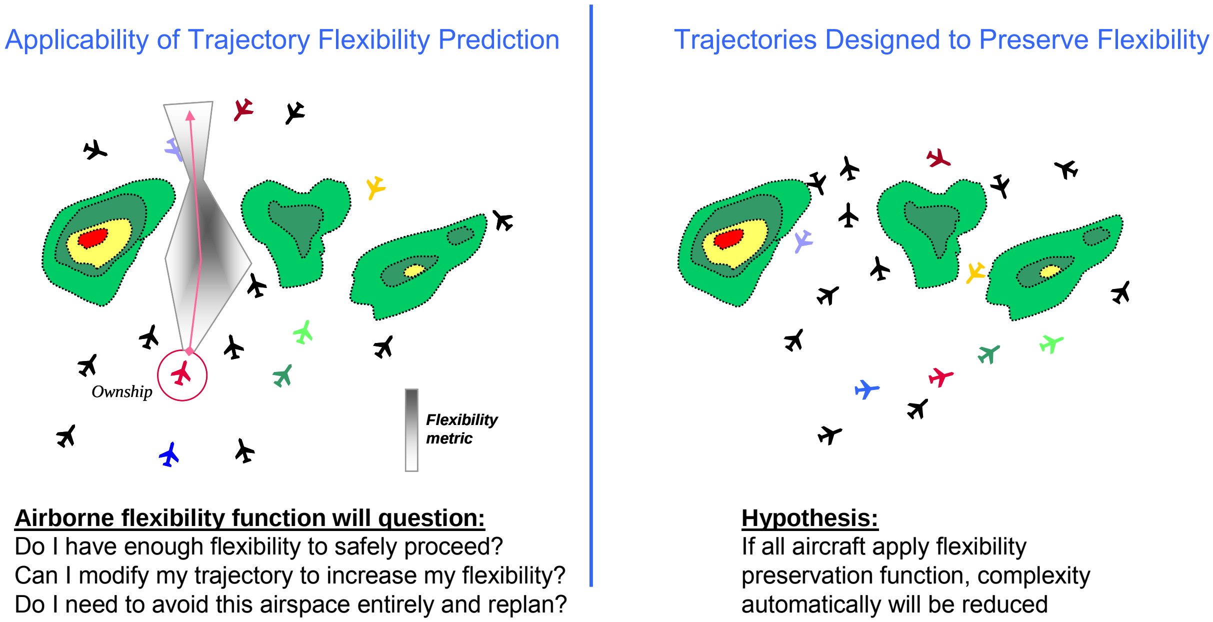

Figure 4-3 Flexibility preservation avoiding complex traffic situations

The size of the flexibility planning horizon depends on a number of factors. One important factor is the range of traffic information that is available to an aircraft. If cockpit information about the surrounding traffic is based on ADS-B, then the horizon may be limited by the ADS-B reception range. If information is up-linked from the ground then flexibility planning may be available over a greater range, ultimately extending to the destination of the aircraft.

4.3 Trajectory Constraint Minimization

Trajectory constraint minimization is envisioned as primarily a ground-based function, with a possible collaboration role for the pilot, as was shown in Figure 4-1. An aircraft trajectory is continually planned to abide by a set of constraints that are imposed on it to achieve ATM objectives. For example, in order to achieve the objective of safety with respect to collision, an aircraft 4D state should not be within 5 miles and 1000 feet from another aircraft 4D state at any time. In addition, in order to meet flow management objectives an aircraft is often required to maintain an increased spacing from other aircraft in the same flow or to absorb a certain amount of delay on the ground or in the air. Constraint minimization is a function by which a traffic manager reduces the amount of constraints imposed on aircraft to the extent possible without jeopardizing the intended ATM objectives. This is accomplished by imposing just enough constraints on the aircraft to meet the objective; for example, if a single required time of arrival (RTA) at a specified fix will sufficiently meter the traffic flow, multiple RTAs per aircraft are deemed too excessive and hence candidate for relaxation. Such constraint minimization has benefits in terms of more efficient utilization of NAS resources; but it also affords pilots more flexibility as it increases their ability to maneuver freely with fewer constraints in order to accommodate disturbances. Therefore, while constraint minimization is a function performed mainly by the ground-based traffic manager, who has the ability to monitor and achieve ATM objectives that involve a large number of aircraft, the pilot may negotiate constraint reduction from the cockpit perspective. For example, the pilot may determine that the aircraft is not able to abide by certain constraints with enough flexibility, and hence provide useful information to the traffic manager to determine how to adjust the constraints.

Figure 4-4 shows an example demonstrating the hypothesized role and impact of constraint minimization with respect to trajectory flexibility preservation and hence traffic complexity.

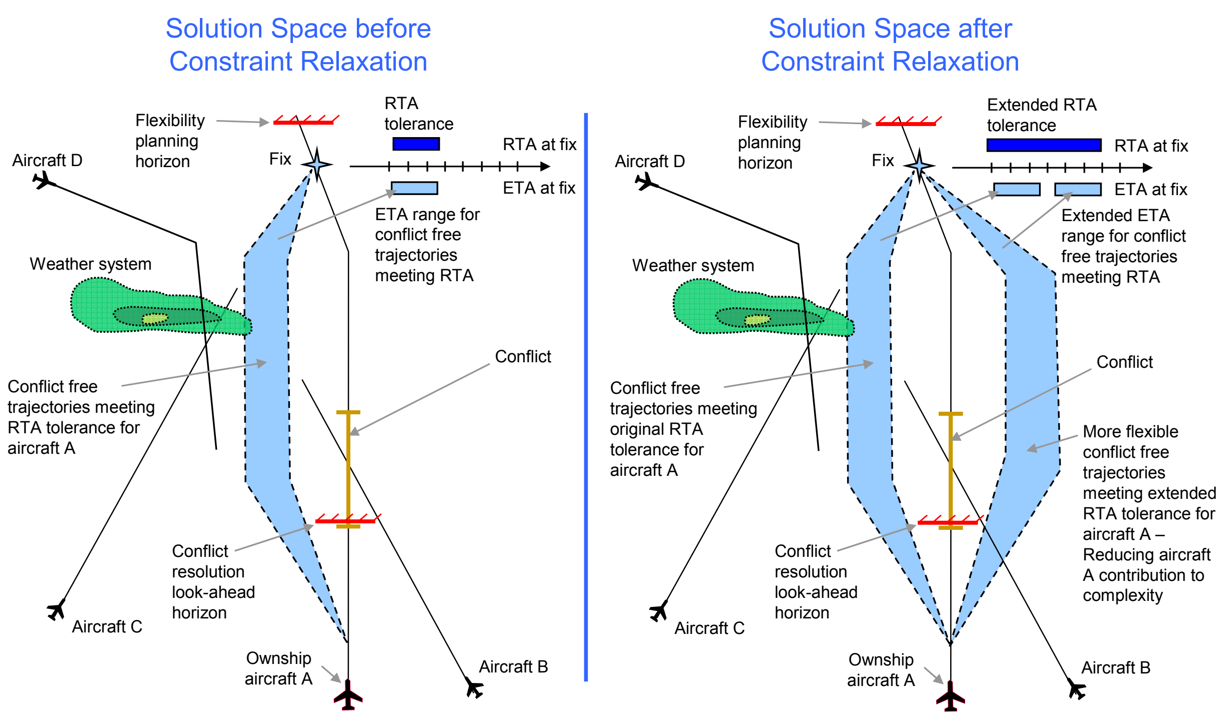

Figure 4-4 Constraint minimization example – relaxing RTA tolerance

Aircraft 'A' attempts to plan its trajectory to resolve a predicted loss of separation with aircraft 'B' and at the same time to meet an RTA at a downstream fix. The RTA tolerance initially allows aircraft 'A' to avoid the predicted conflict only by stretching its path to the left, which exposes the aircraft to nearby traffic (Aircraft C and D) and to an inclement weather system (left side of figure). The aircraft has to select from a small set of trajectories (represented by the left-hand shaded region) with expected time of arrival

(ETA) at the fix that lie within the RTA tolerance. These trajectories do not afford the aircraft enough flexibility to accommodate disturbances from the weather and the traffic, and they would increase the contribution of aircraft ‘A’ to traffic complexity. With this information or independently, the traffic manager relaxes the RTA constraint by increasing the allowable tolerance in meeting it as shown in the right side of the figure. This is done having determined that the ATM objectives intended by the RTA can still be met sufficiently with the increased tolerance. With the extended RTA tolerance, more trajectory solutions become available to aircraft ‘A’, which is now able to avoid the predicted conflict by maneuvering to the right with no risk exposure to the weather or nearby traffic. As a result, by selecting a more flexible trajectory with less exposure to disturbances from weather and traffic, the contribution of the aircraft to traffic complexity is reduced. In addition, the aircraft is enabled to more reliably meet its RTA constraint and hence achieve the intended ATM objectives.

The constraint minimization function assesses the effectiveness of the constraints imposed on aircraft trajectories in achieving the intended ATM objectives. As shown in Figure 4-5, this is a hierarchical process. ATM objectives are posed at the highest level in abstract terms such as maintaining safety, stability, equity, efficiency, cost-effectiveness, among others. Each high level goal is then mapped into trajectory constraints and objectives that establish the criteria needed to meet the goal. For example, in order to maintain stability demand is balanced with capacity; otherwise delays grow unstable. The constraint minimization function assesses if it is possible to relax the demand-capacity balance, for a short duration for example, without jeopardizing stability. This is done if needed, for example, to accommodate aircraft flexibility needs. Then as shown in Figure 4-5 balancing demand and capacity forms an intermediate goal that results in imposing lower level constraints and objectives on aircraft trajectories. For example, a flow management program may impose on an aircraft meeting an RTA at a fix to achieve the demand-capacity balance. The constraint minimization function then assesses if it is possible to relax the RTA constraint without jeopardizing the balance. One possible method to accomplish this is swapping RTAs between aircraft which does not impact the demand rate but may accommodate aircraft needs. Another example is increasing the tolerance for meeting the RTA (as described in Figure 4-4) or removing redundant RTA constraints at certain locations while keeping them at critical locations.

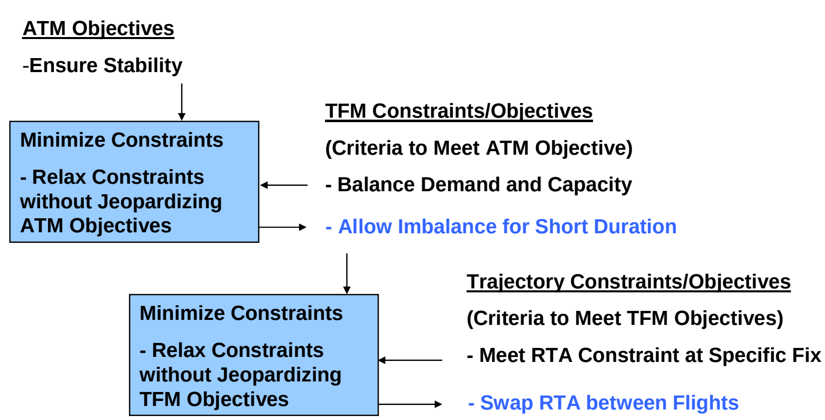

Figure 4-5 Constraint minimization hierarchy example

5 Functional Analysis

In order to realize the concepts described above a functional analysis is conducted to identify key functions and the information flow between them. Figure 5-1 depicts a diagram of the key functional blocks and information flows for the three main functions: separation assurance (A), flexibility preservation (B) and constraint minimization (C). The functional relationships depicted are abstractly independent of the allocation/sharing of functions between the air or ground agents. However, for this discussion the allocation proposed at the beginning of section 4 is assumed.

At the heart of the functional diagram in Figure 5-1 is a trajectory generation engine. It generates a trajectory for an aircraft given as input the set of all constraints imposed on it, some by cockpit concerns and some from controllers, traffic managers and company operators. Both the airborne and the ground systems may contain a trajectory generation engine to support their functionalities. The diagram separates out inputs to trajectory generation coming from the separation assurance function, the flexibility preservation function, and the constraint minimization function.

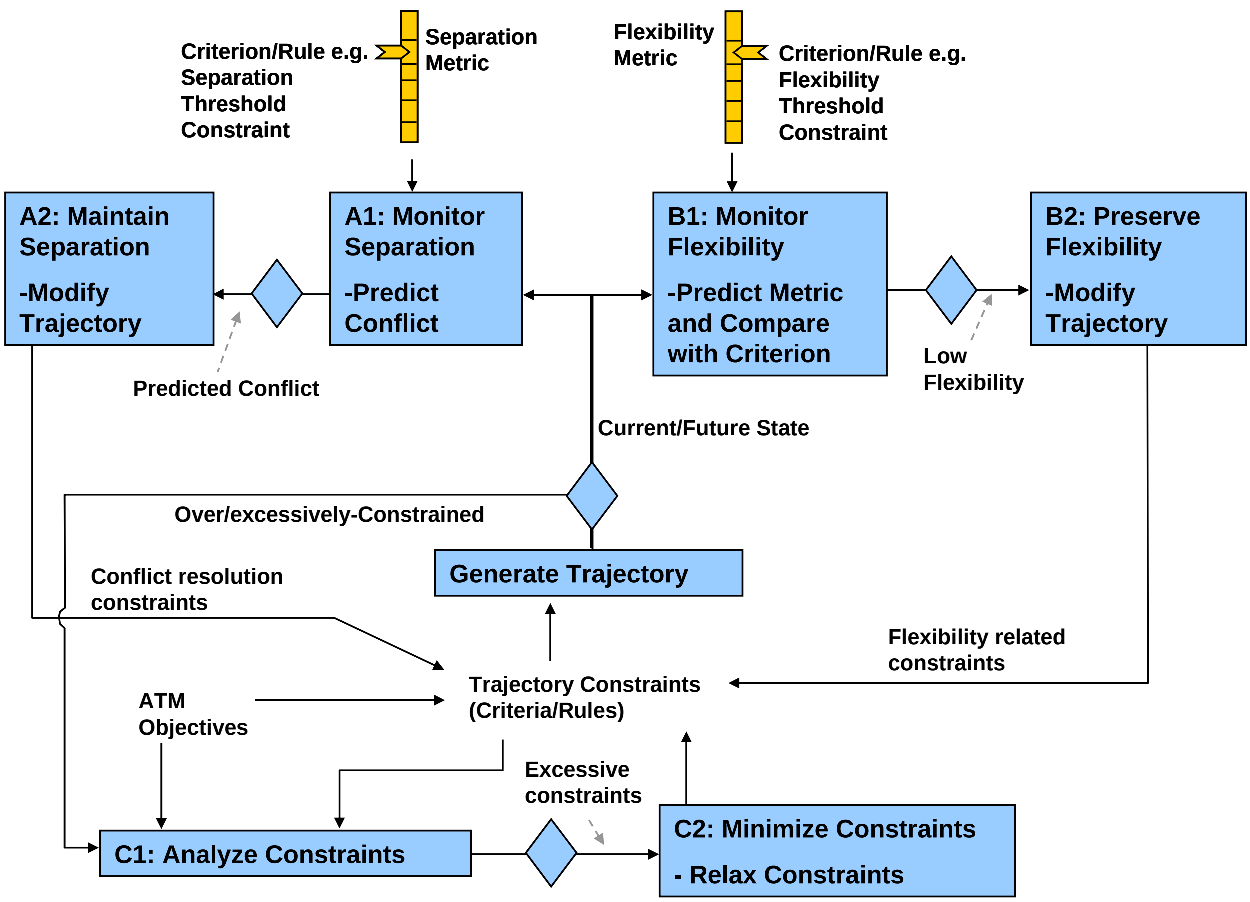

Figure 5-1 Functional framework

To simplify the analysis each function is divided into only two components, a monitoring/assessment component to identify the need for action and a solution/action component to select a solution and implement it. The separation assurance function monitors the current and predicted future states of all aircraft within its horizon and predicts loss of separation based on the separation requirement criteria (A1 in Figure 5-1). The metric is the estimated separation between aircraft and the criteria are the separation requirements which are well established for ground-based control for each type of airspace and aircraft. (For example, the separation requirements are: 5 miles horizontally or 1000 feet vertically for the en-route airspace.) If a conflict is predicted the separation assurance function selects a conflict resolution solution (A2) and sets the corresponding constraints (conflict resolution advisories) to the trajectory generation engine. This is performed on board by a cockpit system like AOP and/or on the ground by a controller decision support tool like the En-route Descent Advisor (EDA) [47].

Similarly the onboard flexibility preservation function monitors the current and future states of the aircraft and of all aircraft within its horizon and predicts a flexibility metric that measures the risk exposure of the aircraft to disturbances such as from weather and traffic (B1). It compares this measure to criteria that dictate an acceptable level of flexibility. Based on this assessment, if the predicted flexibility is low the flexibility preservation function selects more flexible solutions (B2) and advises the trajectory generation engine by setting the corresponding constraints and objectives. Unlike the classical separation assurance function, the flexibility metrics and criteria are not well established and are a subject of ongoing research. Preliminary investigations will be discussed in the next sections and more mature results will be presented in follow-on reports and papers.

Finally, the ground-based constraint minimization function monitors the constraints imposed on aircraft trajectories for the aircraft within its horizon, and analyzes their effectiveness in achieving the intended ATM objectives (C1). If opportunities to reduce constraints without jeopardizing the intended objectives are identified these constraints are relaxed (C2) and conveyed to the trajectory generation engine. In this mode the constraint minimization function is continuously performed by the ground-based manager/automation identifying opportunities to reduce constraints and afford aircraft more flexibility as long as the ATM objectives are sufficiently met. Action to minimize constraints may also be invoked from the aircraft. An aircraft may determine that its flexibility is insufficient and can only be increased by relaxing certain constraints imposed on it. This may occur if an aircraft is either overly constrained or excessively constrained. An overly constrained aircraft is one that cannot find a feasible trajectory that meets all the constraints imposed on it, in which case the trajectory generation fails. An excessively constrained aircraft is one that can find feasible trajectories but ones that are not sufficiently flexible, in which case the flexibility preservation function may indicate a need to relax certain constraints. In such cases the aircraft may invoke the ground-based function to attempt to relax certain constraints with recommendations from the aircraft as shown in Figure 5-1.

6 Definition of Trajectory Flexibility and Metrics

In order to develop metrics and methods for trajectory flexibility preservation and constraint minimization, these functions are posed in the framework of an aircraft trajectory solution space. A trajectory of an aircraft is generated by selecting values for its degrees of freedom over a time horizon. This trajectory is required to abide by a set of constraints that are imposed to achieve certain ATM objectives such as maintaining separation requirements and balancing demand and capacity. Therefore, these constraints define the limits of a solution space of feasible trajectories for the aircraft. Out of these trajectories the aircraft selects one that optimizes its preferences, such as meeting company profit objectives by minimizing fuel burn, delay, passenger discomfort, and other factors. In this section the functions of trajectory flexibility preservation and constraint minimization are posed in the framework of the trajectory solution space and its defining constraints. In this section limited-scope examples are used for the purpose of providing analytical insight into the concept. The trajectory solution space of an aircraft with speed as the single degree of freedom and with RTA constraints at specific locations is investigated. The notion of trajectory flexibility and the effect of the RTA constraints and of conflict constraints on it are highlighted in this analytical framework. Finally, definition of flexibility metrics is provided using this framework to illustrate them.

6.1 Trajectory Solution Space with Multiple RTAs and Conflict Constraints

A trajectory is represented by a 3-dimensional path (s) and a speed profile (V(s)) that determines the time (t(s)) at each location along the path. Using this representation, Figure 6-1depicts a simple scenario of a single aircraft required to meet an RTA at a distance d along its path s, as shown in the right side of the figure. The RTA is to be met within a given tolerance in time t. The left side of the figure displays the trajectory solution space of the aircraft in an s-t space, assuming speed is the only available degree of freedom. The set of times that are reachable at any distance s are bound by traveling at maximum speed V_{max} and at minimum speed V_{min}. This set is reduced by the RTA tolerance requirement at distance d and the set of feasible trajectories is correspondingly reduced as shown in the figure by eliminating the non-feasible region. The non-feasible region consists of the reachable states that, if reached, the full speed range is not effective in meeting the RTA tolerance. The remaining states are feasible in the sense that if reached at least one solution using speed exists to meet the RTA tolerance. Any trajectory that contains non-feasible states is infeasible in the sense that it violates the RTA constraint (Trajectory B in Figure 6-1) and any trajectory that does not contain any non-feasible states is feasible (Trajectory A in Figure 6-1). The set of feasible states is the convex hull bound by straight lines with slopes V_{min} and V_{max} drawn from the current state, a straight line with slope V_{max} drawn through the later RTA tolerance end, and a straight line with slope V_{min} drawn through the earlier RTA tolerance end, as depicted in Figure 6-1.

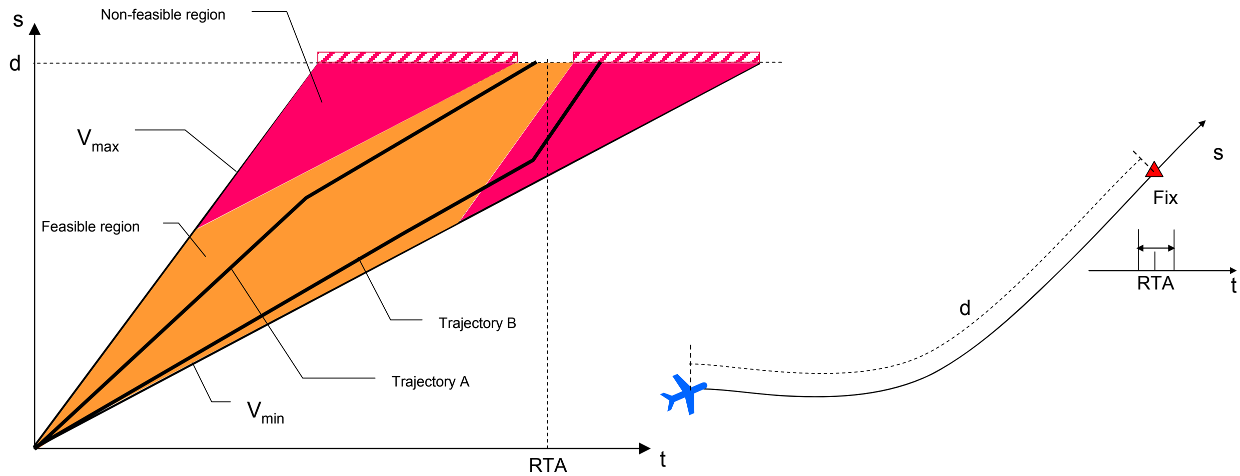

Figure 6-1 Solution space with single RTA constraint

Imposing more constraints further limits the trajectory solution space of the aircraft. For example, Figure 6-2 shows the effect of adding a second RTA constraint (RTA_2) at distance d_2 in addition to a constraint RTA_1 at $d_1 > d_2$, along another aircraft path s_1. RTA_2 may result from a congestion region at distance d_2 along s_1, while path s_0, for example, does not go through such congestion and its solution space would be as depicted in Figure 6-1. The feasible region of the solution space is reduced dramatically to the set of trajectories that meet both RTA tolerances. For example, trajectory B which would be feasible in terms of meeting RTA_1 becomes infeasible if RTA_2 is imposed because it does not meet RTA_2.

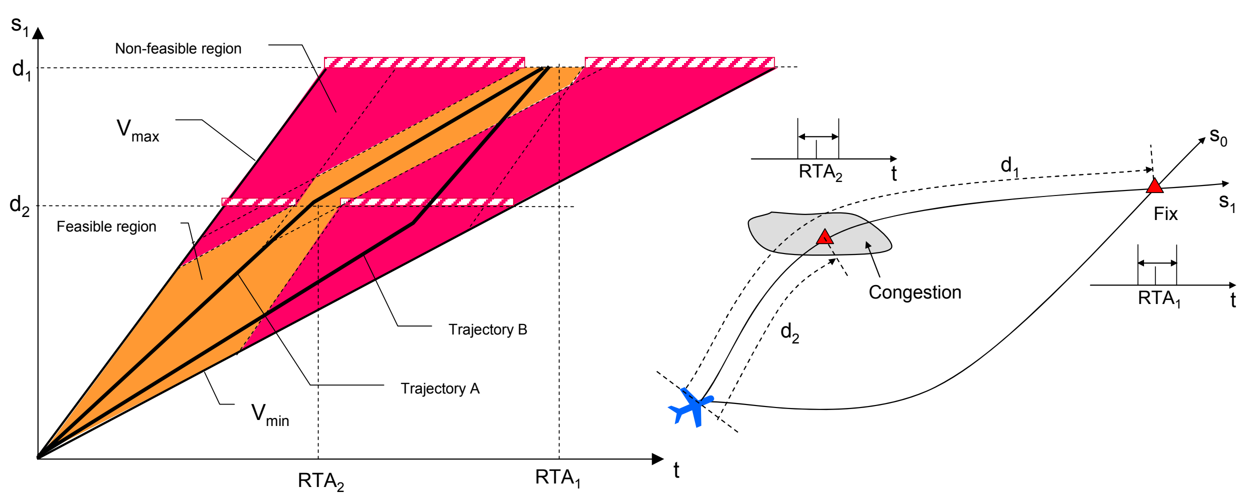

Figure 6-2 Solution space with multiple RTA constraints

As depicted in Figure 6-2, the feasible region is the union of the feasible regions between the current state and the first RTA and between each successive pair of RTAs. The feasible region between two successive RTAs is the convex hull between the following lines: Straight lines with slope V_{max} drawn through the earlier tolerance end of the earlier RTA and the later tolerance end of the later RTA, straight lines with slopes V_{min} drawn through the later tolerance end of the earlier RTA and the earlier tolerance end of the later RTA, and horizontal lines drawn at the distances d_1 and d_2. If the location of RTA_2 in Figure 6-2 is shifted to the right or left over time, or its tolerance is reduced, it is possible that no trajectories would be available that meet both RTA_1 and RTA_2. This occurs when no feasible region connects the aircraft current position to the destination RTA_1. In this case the aircraft trajectory is over-constrained as mentioned in Section 5 and requires relaxation of some constraints. Therefore, as Figure 6-2 demonstrates, relaxing an RTA constraint by, for example, increasing the tolerance or changing the timing has a clear impact on opening up solution space and allowing more feasible trajectories, as was hypothesized by the example in Figure 4-4.

Figure 6-3 adds to the examples above a conflict with an intruder aircraft B (which may also represent a moving weather cell). Along s_0 the aircraft is required to meet RTA_1 at distance d_1 within a tolerance in time, and in addition s_0 is impacted by the intruder aircraft B whose separation zone is expected to cross s_0 between distances d_3 and d_4. The geometry and timing of the conflict translates into an elliptical region in the s_0-t domain with all points within corresponding to loss of separation. A trajectory that crosses this region loses separation with the intruder and is hence infeasible.[1] As shown in Figure 6-3 the conflict cuts out an additional infeasible region bound by the V_{max} and V_{min} tangents to the elliptical conflict region [48]. Trajectory B is infeasible because of loss of separation with the intruder aircraft while trajectory A is feasible being conflict free and meeting RTA_1.

Imposing more constraints further limits the trajectory solution space of the aircraft. For example, along s_1 the aircraft is required to meet two RTA constraints within tolerance: RTA_2 at distance d_2 because of a congestion region, and RTA_1 at $d_1 > d_2$, in addition to the impact of the predicted conflict between d_3 and d_4. For convenience, the geometry in the figure is chosen such that d_1, d_3, and d_4 are equal along s_0 and s_1. As shown in the diagram at the bottom of Figure 6-3 the solution space is smaller than that along s_0; trajectory B is infeasible because of loss of separation with the intruder aircraft or not meeting RTA_2 while trajectory A remains feasible by meeting both RTAs and maintaining separation.

[1] Idris et al. gives a mathematical formulation of the conflict region for a circular separation zone around an intruder aircraft moving at a constant speed [48]. In words: The separation zone occupies a line segment along s_i that starts as a point when the zone first touches s_i, grows in size to the diameter length and shrinks to a point when the zone leaves the path s_i.

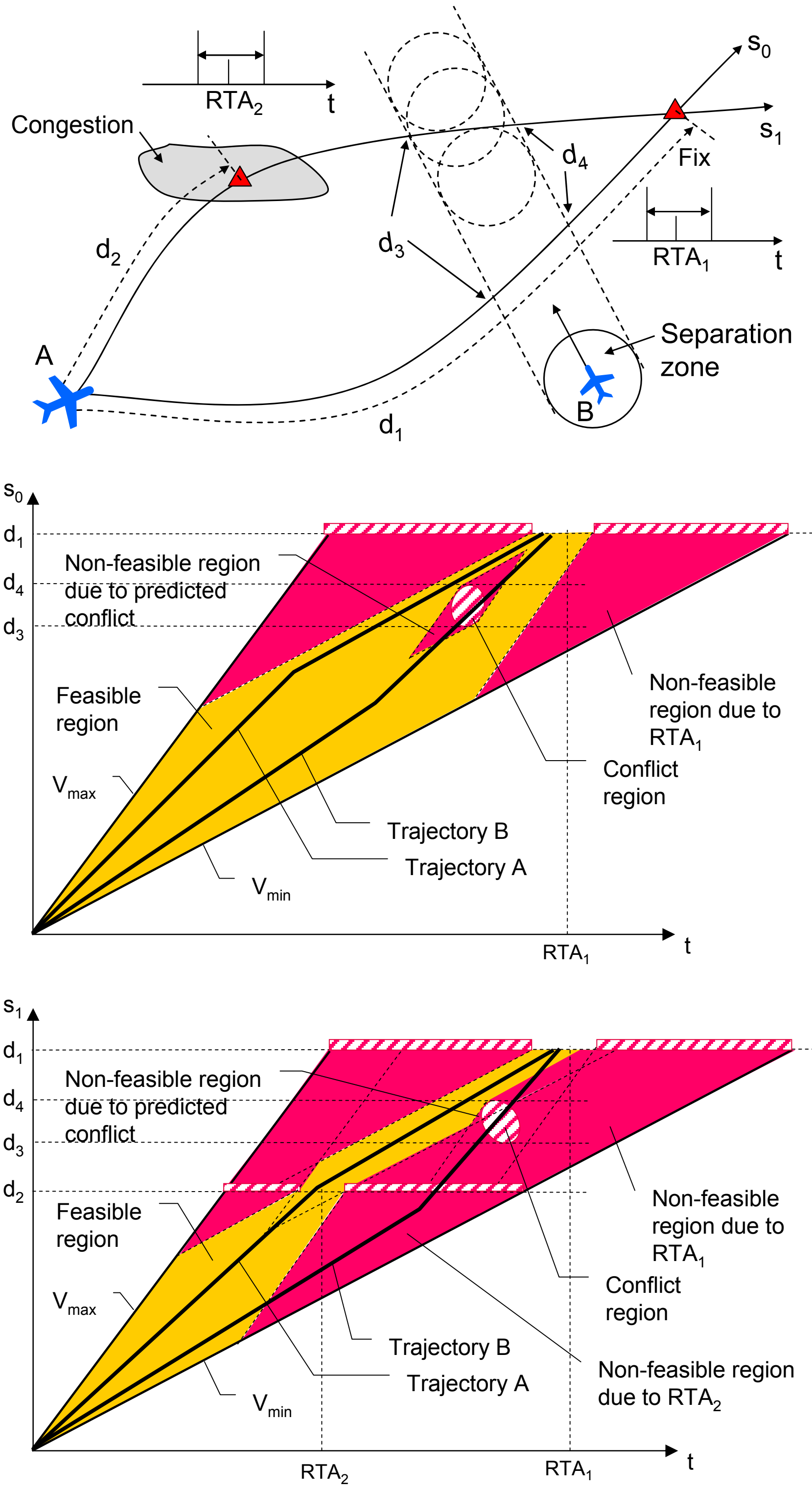

Figure 6-3 Solution space with RTA and conflict constraints

The locations and tolerances of RTA_1, RTA_2 or the conflict region in Figure 6-3, may leave no feasible trajectory that is conflict free and meets both RTAs. In this case the aircraft trajectory is over-constrained and requires relaxation of some constraints. This example demonstrates how the introduction of additional constraints, such as RTAs and conflicts, reduces the adaptability of the aircraft by blocking out parts of the maneuverability solution space. Conversely, relaxing these constraints, when possible without jeopardizing the intended ATM objectives, increases the adaptability and hence flexibility of the aircraft, as was hypothesized in Sections 2 and 4. For example, removing RTA_2 in Figure 6-3 increases the size of the feasible region and reduces the chance that the prediction of the conflict renders the aircraft over-constrained or excessively constrained. The aircraft may also select path s_0, which has less probability of incurring the RTA_2 constraint, over path s_1 to achieve lower exposure to constraints. The multiplicity of the constraints and their types also gives rise to a prioritization among them, which is important when the aircraft is unable to meet all of the constraints. For example, if the aircraft in Figure 6-3 is over-constrained, it may report to the ground-based traffic manager that it is unable to meet RTA_2 ("Unable RTA_2") because of the conflict. In this case the traffic manager may relax RTA_2 ensuring safety at the expense of less important objectives.

6.2 Definition of Flexibility as Accommodation of Disturbances

Given the solution space defined in Figure 6-3 the aircraft selects a trajectory that meets all the imposed constraints, if not over-constrained. If the environment is deterministic the aircraft proceeds along the trajectory as predicted and the aircraft meets its objectives without violating any constraints. However, disturbances may occur that may alter the images depicted in these figures from what is predicted. The notion of trajectory flexibility is defined as the ability of the aircraft to accommodate such disturbances while abiding by the constraints.

Disturbances may be classified into two types, one related to the state of the aircraft and the other to the constraints that define the solution space:

State disturbances result in deviations in the aircraft state from what is predicted by the trajectory. If some information is available about such disturbances they may be modeled into an envelope around the aircraft trajectory over the time horizon. For example, if the aircraft trajectory prediction was based on a wind speed model the imperfect information in the wind forecast may be modeled as a range on the ground speed and hence a range on the state of the aircraft at each time over the horizon of the trajectory prediction. Such a range typically grows over time.

Constraint disturbances result in deviations in the constraints that define the solution space for the aircraft trajectory. These deviations may be in the form of introduction of new constraints or modifications in currently imposed/predicted constraints. For example, RTA_2 in Figure 6-2 may be introduced as a disturbance to the situation depicted in Figure 6-1, thus drastically changing the solution space. Or, the RTAs may shift in time or change in tolerance relative to what was predicted, thus perturbing the boundaries of the solution space. Such disturbances may result from traffic flow management actions of which limited information is available at the time of prediction. Constraint disturbances include many types of constraints such as the introduction and movement of traffic and weather cells.

In order to increase its ability to accommodate such disturbances the aircraft selects out of its solution space a trajectory that affords it sufficient flexibility. Two characteristics have been identified as relevant to measuring flexibility: robustness and adaptability to disturbances. These characteristics are defined and illustrated through an example in analytical terms. The use of the robustness and adaptability characteristics to develop metrics and methods to preserve the flexibility of the aircraft in accommodating different types of disturbances is a topic of ongoing research of which preliminary results are given in the next section.

1. Robustness is defined as the ability of the aircraft to keep its planned trajectory[2] unchanged in response to the occurrence of a disturbance. A trajectory that can withstand a disturbance without having to change is more robust than other trajectories that become infeasible when the disturbance occurs. In the context of the RTA/conflict constraint scenario of Figure 6-3 and considering the introduction of the conflict as a disturbance, a trajectory that remains feasible in terms of meeting the tolerances of both RTA_1 and RTA_2 and avoiding the conflict despite the disturbance, which significantly reduced the solution space, is robust to this disturbance.

2. Adaptability is defined as the ability of the aircraft to change its planned trajectory[2] in response to the occurrence of a disturbance that renders the current planned trajectory infeasible. A trajectory that positions the aircraft such that other feasible trajectories remain accessible to it if a disturbance occurred and rendered the current trajectory infeasible is more adaptable than another trajectory for which the disturbance leaves fewer or no feasible trajectories. In the context of the multiple RTA/conflict scenario of Figure 6-3, if trajectory B was selected it becomes infeasible when the conflict is predicted. The prediction of the conflict reduced the solution space. However, it left a set of trajectories for the aircraft that are feasible in terms of meeting both RTA_1 and RTA_2 and resolving the conflict. Therefore, the aircraft is able to adapt to this disturbance over a certain time, for example, by changing its planned trajectory from B to A.

6.3 Definition of Flexibility Metrics

Selecting appropriate metrics for measuring flexibility in terms of its two characteristics, robustness and adaptability, requires generalization to a wide range of situations involving various degrees of freedom and types of disturbances. For illustration purposes the definition of these metrics are posed in the context of a simple scenario that involves a single aircraft selecting from a set of pre-specified paths to fly between its current position and a destination fix with the ability to vary speed along each path, as was depicted in Figure 6-3. The aircraft has to meet an RTA at the destination fix regardless of the selected path. Some paths pass through a congestion region which results in a second RTA constraint along these paths at the congestion region. The paths in the scenario may be impacted by one constraint disturbance: a predicted

---

[2] The robustness and adaptability characteristics apply to the full or part of a trajectory plan, such as a path or speed profile.

conflict with traffic that crosses the paths. State type disturbances are not considered, where the aircraft is assumed to fly its planned trajectory accurately.

The discrete path choice and the speed profile choice constitute a hierarchal decision process where it is assumed here that the aircraft selects a path first and then the speed profile to achieve its objectives. Once the aircraft selected the path, its only degree of freedom is selecting the speed profile along the path. The decision analyzed here is the selection of the path, where the only objective of the selection is to preserve (or maximize) flexibility (represented by the robustness and adaptability characteristics defined in the previous section) in accommodating the conflict prediction disturbance, using the speed degree of freedom. With these assumptions, the decision process is analyzed using initial definitions of metrics that measure robustness and adaptability of each path to the predicted conflict disturbance. It is important to note that this hierarchical decision process may not result in the most flexible trajectory (including path and speed profile). This is because the path is selected first based on aggregate flexibility metrics over the set of trajectories that the speed provides along each path. An integrated trajectory selection approach may result in a more optimal trajectory and will be addressed in future research.

In the context of this scenario, the solution space along each path is analyzed in terms of its flexibility to the prediction of the conflict with the intruder aircraft. Figure 6-4 depicts the solution space along a path s that is impacted by an RTA constraint at distance d_1 and a specific instance[3] of the conflict prediction at a location prior to d_1 and a time prior to RTA_1 (as was analyzed in Figure 6-3). The conflict region divides the solution space into the following regions:

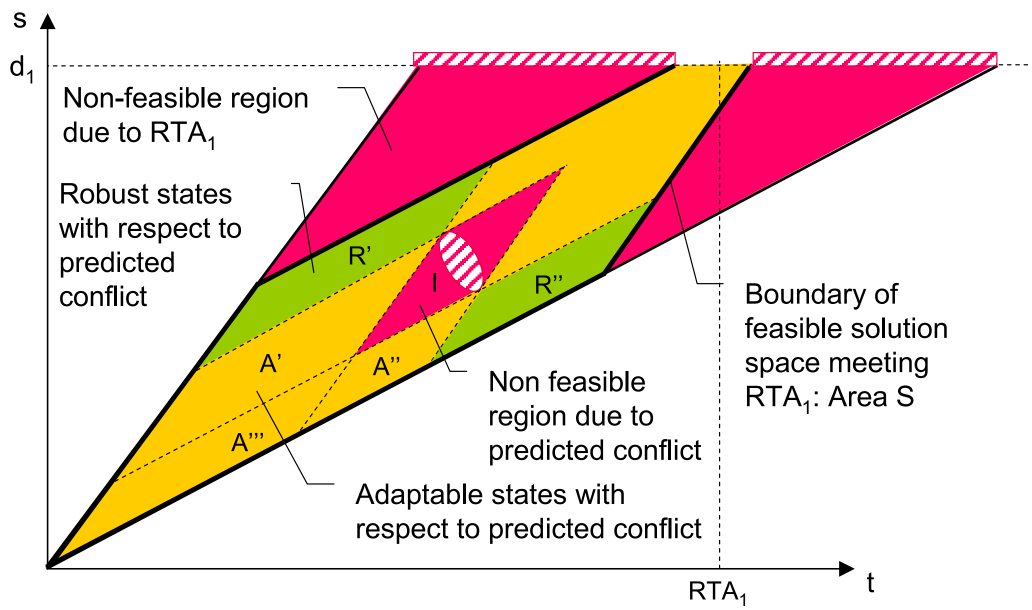

Figure 6-4 Robust and adaptable states

[3] Other instances correspond, for example, to variability in the intruder aircraft trajectory prediction.

1. Area I consists of the infeasible states which, once reached, violating the conflict constraint is unavoidable. These states cannot be part of a conflict free trajectory. This area is bound by the straight line tangents to the conflict region, with minimum and maximum speed slopes.
2. Area R consists of robust states which, once reached, conflict violation cannot occur however speed is varied. These states cannot be part of an infeasible trajectory with the predicted conflict. R may consist of multiple areas (R' and R'' depicted in Figure 6-4).
3. Area A consists of adaptable states that may be part of either feasible or infeasible trajectories, with respect to the predicted conflict. Area A is divided into multiple areas in Figure 6-4 indicating which area reaches the I and R states. The infeasible states, I, can be reached from all A', A'' and A''' states. On the other hand, states R' can be reached from A' and A''' states, while states in R'' can be reached from states in A'' and A'''.

The robustness of an aircraft planned trajectory to a disturbance is measured by the probability that the trajectory stays feasible (by not violating any constraint) if the disturbance occurred. The robustness of the path depicted in Figure 6-4, which is a partial trajectory plan, may be measured by the probability that an arbitrarily selected trajectory along the path (i.e. a speed profile) falls in the feasible area R, as opposed to the infeasible area I, after the prediction of the conflict. Assuming an equally likely trajectory selection, one metric (RBT) that measures this probability is the ratio of the number of feasible trajectories that fall in the R area (i.e., despite the disturbance) to the total number of feasible trajectories along the path that fall in area S (i.e., without considering the disturbance):

$$\text{RBT (given disturbance)} = \frac{\text{Number of feasible trajectories (given disturbance)}}{\text{Total number of feasible trajectories (without disturbance)}}$$

Computing this metric requires estimating the total number of trajectories abiding by all constraints except the predicted conflict and the number of feasible trajectories with respect to the predicted conflict. Then, assuming a stochastic behavior of the intruder aircraft of which the predicted conflict situation depicted in Figure 6-4 is one instance 'i', the metric is averaged over the instances. For example, if the intruder stochastic behavior is characterized by a distribution P_i over instances i:1-N, then the robustness metric is integrated over the instances: $RBT = \Sigma_{i:1\text{-}N}[P_i \times RBT_i]$.

A planned trajectory that falls in the infeasible area I in Figure 6-4 should be adapted by changing it to a feasible trajectory that contains states in area R. This adaptation is meaningful only for trajectories that contain infeasible states in I and is possible as long as the current state is an adaptive state in area A. Therefore, the adaptability of the path is dictated by the availability of area R and how reachable it is from states in area A, using the speed degree of freedom. Therefore, one metric that measures adaptability (ADP) is the absolute number of feasible trajectories that fall in area R:

$$\text{ADP (Given disturbance)} = \text{Number of feasible trajectories (given disturbance)}.$$

Then, assuming a stochastic behavior of the intruder aircraft characterized by a distribution P_i over conflict instances i:1-N, the metric is averaged over the instances as described for the robustness metric: ADP = $\Sigma_{i:1\text{-}N}[P_i \times ADP_i]$.

The robustness and adaptability metrics proposed are used in this scenario to compare flexibility among different paths by measuring the set of feasible trajectories that the speed degree of freedom provides along each path. This comparison is used to make a path selection based on properties aggregated over the set of trajectories along the path. The flexibility metric is ultimately used to plan a full trajectory including the path and the speed profile. It is important to note that the robustness and adaptability metrics proposed can be extended to the integrated planning by maintaining or preserving their values at each step along a trajectory. For example, adaptability decreases as the aircraft moves along a trajectory because the number of feasible trajectories decreases. This can be seen from Figure 6-4 where the states in area A''' are more adaptable having access to both R' and R'', while states in areas A' and A'' are less adaptable having access only to R' or R'' respectively. Hence, adaptability decreases continuously as the aircraft proceeds along a trajectory transitioning through A''' and then from A''' to either A' or A''. An adaptable trajectory may be planned by minimizing the rate at which such reduction in adaptability occurs along the trajectory.

These metrics are instantiated in the cases of speed and path stretch degrees of freedom, along with methods to compute them, in the following section.

7 Estimation of Trajectory Flexibility Metrics

Trajectory characteristic metrics relevant to flexibility in accommodating disturbances, namely robustness and adaptability, and their use for trajectory planning are extended to more generic scenarios and degrees of freedom in this section. A scenario is presented in the next subsection, followed by an example of computation of the flexibility metric using speed as the single degree of freedom. Then preliminary efforts extending the metrics to the case of using path stretch as the single degree of freedom are presented in the following subsection.

7.1 Scenario Description

The scenario considered involves a single aircraft planning its trajectory in the presence of disturbances. The trajectory plan includes selecting a two-dimensional path (s) as a series of straight segments, s_i, and a speed profile along the path. Specifically, Figure 7-1 shows an example where the path consists of up to three segments (s_1 – s_3), where s_1 starts at the aircraft current state and extends along a selected heading, s_3 ends at the destination fix along a selected heading, and s_2 is a possible intermediate segment with a selected orientation. In this example, s_2 is selected with a specific orientation parallel to the straight line connecting the current state with the destination state, but in general other orientations are possible. The speed profile is any series of speeds that are bounded by minimum and maximum speeds V_{min} and V_{max} respectively.

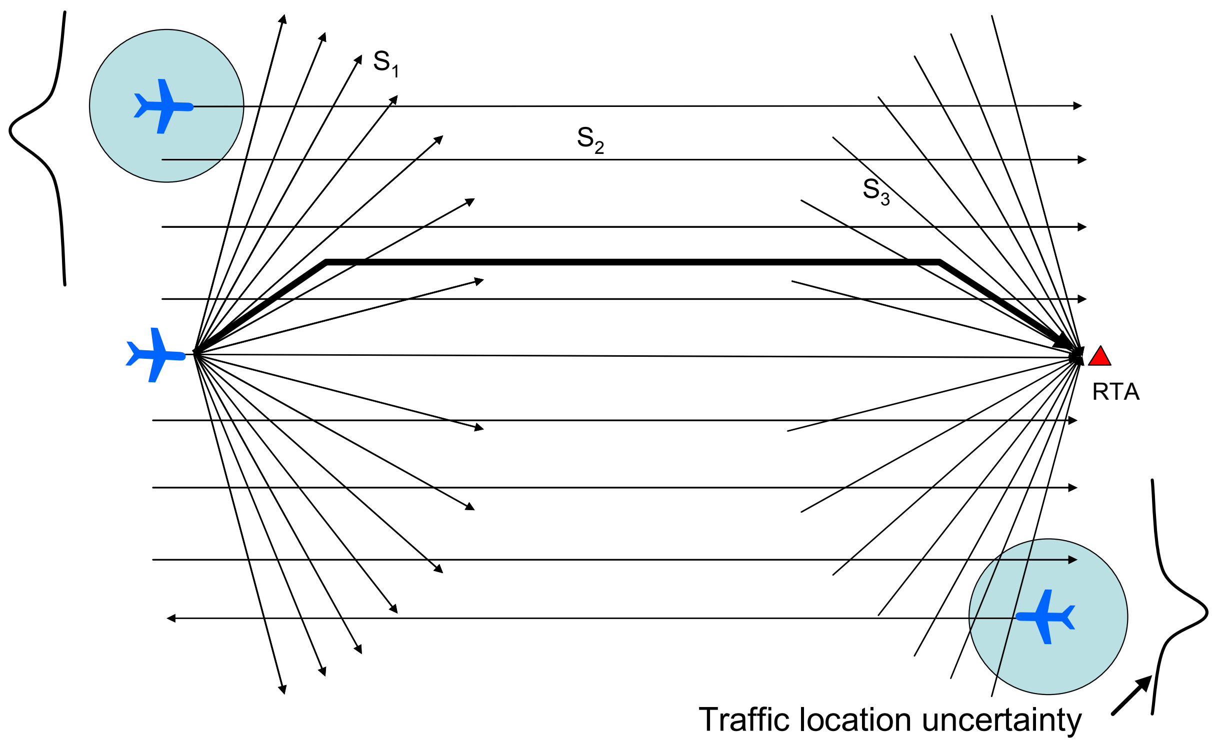

Figure 7-1 Simple scenario

The aircraft is assumed to select a path and a speed profile such that its flexibility is maximized (or preserved above a threshold) along the trajectory, in accommodating disturbances while meeting constraints. The aircraft has to meet an RTA at the destination fix regardless of the selected path. The disturbance considered in the scenario is possible conflict along the path with moving hazards, namely conflict with other traffic. The moving hazard may also represent weather cells or clusters of traffic. State type disturbances are not considered, where the aircraft is assumed to fly its planned trajectory accurately. In Figure 7-1, the disturbances consist of two traffic flows at either side of the aircraft, along the orientation of the segment s_2 (but in general may be in any orientation). The traffic may be characterized by uncertainty, for example, in its location as shown in the figure. The aircraft may meet the RTA constraints and accommodate the disturbance using either speed or path stretch as degrees of freedom. The flexibility of the aircraft as defined by robustness and adaptability metrics is analyzed using these degrees of freedom in the next sections.

7.2 Flexibility Using Speed

In the context of this scenario, the solution space along a fixed path while varying only speed was analyzed in Section 6 in terms of its flexibility to the prediction of a conflict and depicted in Figure 6-4. Namely, Figure 6-4 depicted the solution space that corresponds to varying speed between V_{min} and V_{max} along a fixed path s constrained to meet one RTA (with tolerance window) at distance d_1 and impacted by one predicted conflict disturbance, represented by the elliptical shape conflict region. Summarizing from Section 6: The robustness metric (RBT) of the path depicted in Figure 6-4, which is a partial trajectory plan, may be measured by the probability that an arbitrarily selected trajectory along the path falls in the feasible area R as opposed to the infeasible area I, after the prediction of the conflict. A planned trajectory that falls in the infeasible area I should be adapted by changing it to a feasible trajectory that contains states in area R. This adaptation is meaningful only for trajectories that contain infeasible states in I and is possible as long as the current state is an adaptive state in area A. Therefore, the adaptability of the path is dictated by the availability of area R and how reachable it is from states in area A, using the speed degree of freedom. Therefore, the adaptability metric (ADP) is represented by the absolute number of feasible trajectories that fall in area R.

Computing the robustness and adaptability metrics requires estimating the total number of trajectories that pass through the area R, abiding by the RTA constraint as well as avoiding the predicted conflict. Computing the robustness metric requires estimating the number of trajectories that abide by all constraints except the predicted disturbance (conflict in this case). This corresponds to the total feasible area S after removing area I in Figure 6-4. Appendix A illustrates a special case with a single speed change only. In this case the number of trajectories in a region of the solution space can be measured by the area of the region. In a general situation, Figure 7-2 shows a method for estimating the number of trajectories that pass through any parallelepiped area (Area I from Figure 6-4 is used as an example). The method consists of the following two steps:

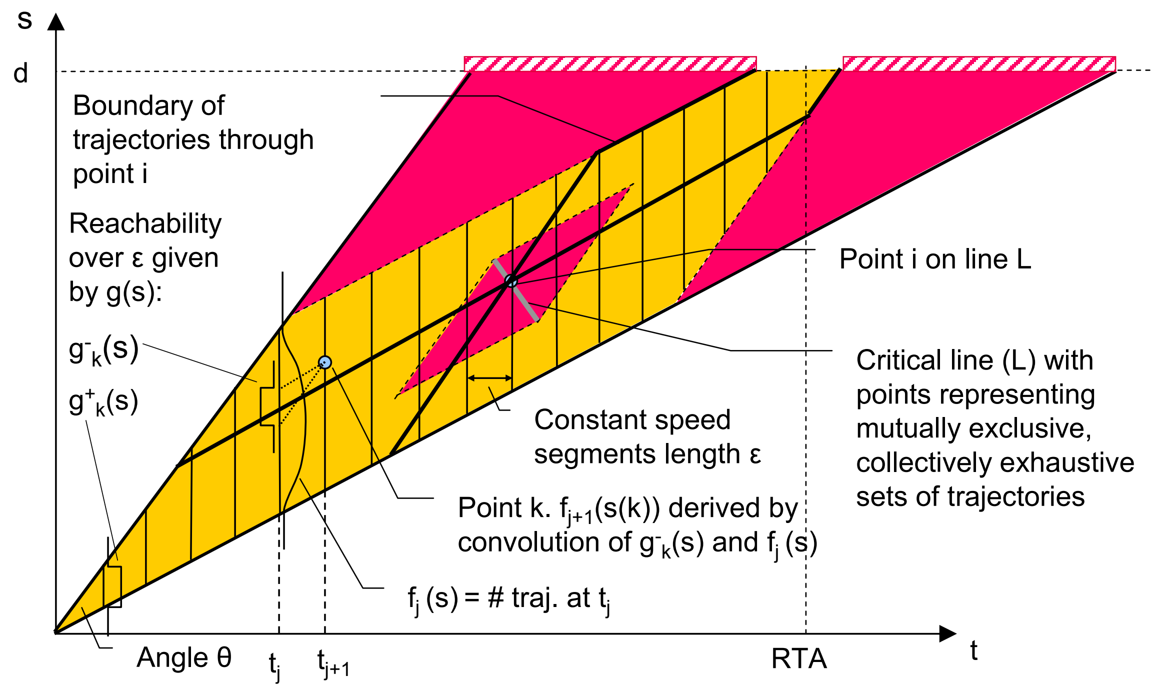

Figure 7-2 Estimating number of trajectories

1. First, a line segment (L) is selected across the area (I) through which passes every trajectory that passes through the area. This line is the cross diagonal of the parallelepiped area. The trajectories that pass through each point (i) of this line segment form mutually exclusive and collectively exhaustive subsets of the set of trajectories that pass through the area. Therefore, the number of trajectories that go through the area is the sum of the trajectories that go through each point along this line segment (L).

2. Second, the number of trajectories N(i) that pass through a point (i) is estimated by multiplying the number of trajectories N(origin — i) that lead from the current state of the aircraft (origin) to that point times the number of trajectories N(i — dest) that lead from that point to the destination state (dest). Each one of these two sets is estimated by discretizing the t-dimension into equal increments (t_j) of length (ε) as shown in Figure 7-2. The speed is assumed constant within each increment, where the width (ε) of the resulting strips in the t-dimension represents the minimum time required or desired between speed changes. Therefore, there might be as many speed changes in the trajectory as increments t_j are considered.

   Let k=(t(k), s(k)) be a point of the solution space. Let the function $g^{+}_{k}(s)$ be a function that represents the number of trajectories that reach from the point k forward over one time step from t(k) to t(k)+ε. An example is shown in Figure 7-2 reaching from the origin to the first time step. If only specific discrete speed values are allowed between V_{min} and V_{max} then $g^{+}_{k}(s)$ is a discrete function with two possible values: one unit at each s-value reachable at t(k)+ε with each discrete allowed speed value, and null at any other s-value. In other words, each unit represents one constant-speed trajectory corresponding to each allowable speed value and reaching to a single s value. This is represented by the following formula.

$$g_k^+(s) = 1 : s \in [s(k) + V_{\min} \times \varepsilon,\ s(k) + V_{\max} \times \varepsilon] \ and\ s \in solution\ space\ ;$$
$$0\ otherwise$$

If a continuous speed range is allowed between V_{min} and V_{max} then $g^+_k(s)$ is a rectangular continuous function that has an area underneath it equal to the total number of constant-speed trajectories leading between the two time steps. This number of trajectories is measured by the angle (θ) between the lines with slopes V_{min} and V_{max} extending forward from the single point k. The magnitude of the rectangular function is normalized by the span of the function over s such that the area underneath it is equal to θ. See a representation in Figure 7-3.

$$g_k^+(s) = \frac{\theta}{(V_{\max} - V_{\min}) \times \varepsilon} : s \in [s(k) + V_{\min} \times \varepsilon,\ s(k) + V_{\max} \times \varepsilon] \ and\ s \in solution\ space\ ;$$
$$0\ otherwise$$

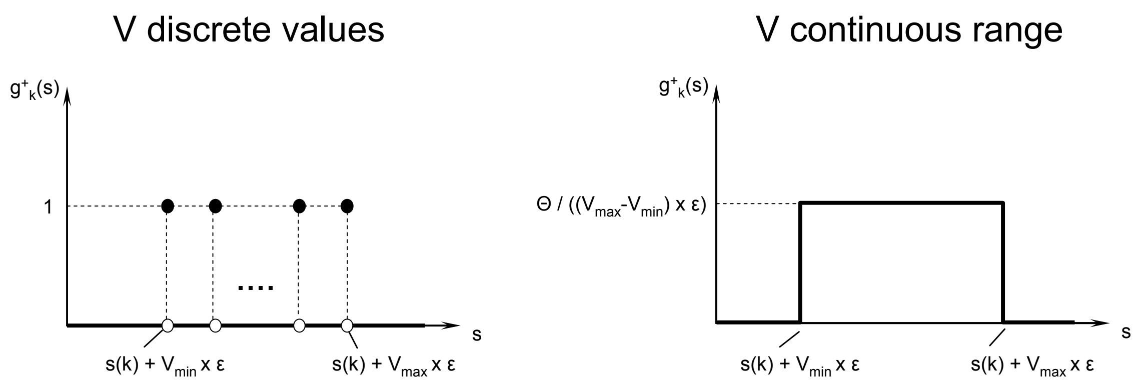

Figure 7-3 Number of trajectories $g^+_k(s)$ from a point k.

Similarly, let $g^-_k(s)$ represent the number of trajectories that lead from a previous time step t(k)-ε to a point k. An example is shown in Figure 7-2 reaching from step t_j to one point in step t_{j+1}. Using similar explanation as above the function $g^-_k(s)$ takes on the following discrete and continuous forms. The function has the same shape as $g^+_k(s)$ except for its range over s.

$$g_k^-(s) = 1 : s \in [s(k) - V_{\max} \times \varepsilon,\ s(k) - V_{\min} \times \varepsilon] \ and\ s \in solution\ space\ ;$$
$$0\ otherwise$$

$$g_k^-(s) = \frac{\theta}{(V_{\max} - V_{\min}) \times \varepsilon} : s \in [s(k) - V_{\max} \times \varepsilon,\ s(k) - V_{\min} \times \varepsilon] \ and\ s \in solution\ space\ ;$$
$$0\ otherwise$$

Let the function $f_j(s)$ be the number of trajectories that lead from the current state (the origin at t_0 in Figure 7-2) to the time step t_j. As shown in Figure 7-2, at the first time step t_1, $f_1(s) = g^+_{origin}(s)$. Then at each subsequent time step t_{j+1} the function $f_{j+1}(s)$ is obtained from the function $f_j(s)$ at the previous time step t_j, through a convolution with the reachability function $g^-_k(s)$. This convolution amounts to computing the number of trajectories $f_{j+1}(s(k))$ that reach each point k along the domain s at time step t_{j+1} by adding the number of trajectories $f_j(s)$ that reach the previous time step t_j and fall within the reachability window of the function $g^-_k(s(k))$. This is shown schematically in Figure 7-2 for calculating $f_{j+1}(s)$ from $f_j(s)$ at one point k along step t_{j+1}. In the convolution $g^-_k(s)$ is translated along the s domain at t_{j+1} as $f_{j+1}(s)$ is calculated at each point k along the s-segment that lies within the solution space at t_{j+1}. In other words the function $g^-_k(s)$ acts as a moving window that slides down the s-segment at t_j and for each point k along the s-segment at t_{j+1} the number of trajectories $f_j(s)$ that are bounded within the window corresponding to k are summed to compute the number of trajectories $f_{j+1}(s(k))$ that reach that point at t_{j+1}.

Using a dummy variable τ to represent s at time step t_j and dropping the index k from the function g (because s is equivalent to s(k)), the convolution may be written as follows:

$$f_{j+1}(s) = \int f_j(\tau) g^-(s-\tau) d\tau\}$$

By applying the iterative convolution process in step (2) with an appropriate discretization of time and speed, the number of trajectories that reach any point from the current state may be computed. This includes those that reach from the origin to point i on L, N(origin — i). Also by applying this same process, the number of trajectories that lead from any point other than the origin to the destination may be computed. This includes the number of trajectories that lead from point i on L to the destination, N(i — dest). Then the total number of trajectories N(i) that go through point (i) is the multiplication of the two and the number of trajectories that go through the region (I) is the sum of the trajectories that go though each point i on L:

$$N(I) = \int_{i \in L} N(origin - i) \times N(i - dest)$$

This equation is applied to the areas R' and R'' as well as to the area S representing the full solution space (excluding the infeasible area I). The robustness and adaptability metrics can then be computed by taking the appropriate ratios as follows.

$$RBT = [N(R') + N(R'')] / N(S)$$

$$ADP = N(R') + N(R'')$$

Note: The convolution relationship discussed in step 2 has an important underlying physical significance with analogies in system dynamics and signal processing. The function $f_j(s)$ representing the number of trajectories (hence representing the flexibility of a particular aircraft maneuvering through an environment) is filtered by the function g(s) which represents the characteristics of the environment (i.e., the constraints and disturbances that define the solution space). Although derived in a limited scenario, this notion is fundamental and should generalize to comprehensive situations involving other degrees of freedom, constraints, and disturbances. Deriving the function g(s) that represents the environment is a major part of the process to determine the manner in which the flexibility represented by f(s) is filtered through the environment. This generalization will be a subject of further research.

7.3 Flexibility Using Path Stretch

In order to analyze the flexibility provided by the path stretch degree of freedom, speed is held constant and the available paths that allow the aircraft to meet the RTA at the destination fix are analyzed. Figure 7-4 shows a preliminary analysis of the solution space using path stretching and the impact of a disturbance from a predicted conflict, in a framework relative to the intruder aircraft. Therefore the intruder aircraft and its surrounding conflict region are stationary while the maneuver aircraft and meter fix move relative to it as shown in the figure. The path stretch trajectories displayed in the figure (which are relative to the intruder aircraft) include one turn only and have the same length because they all meet the meter fix at the same time t_{MT} (which is the RTA) at the same speed. The turn points (T_{Ri}) of the trajectories, therefore, lie on an ellipse with focal points at the current position and the meter fix destination. This elliptical shape is an outer bound on the path stretch solution space because any other path stretch of the same length and with more than one turn lies within the ellipse. Further research will include a formal proof of this theory.

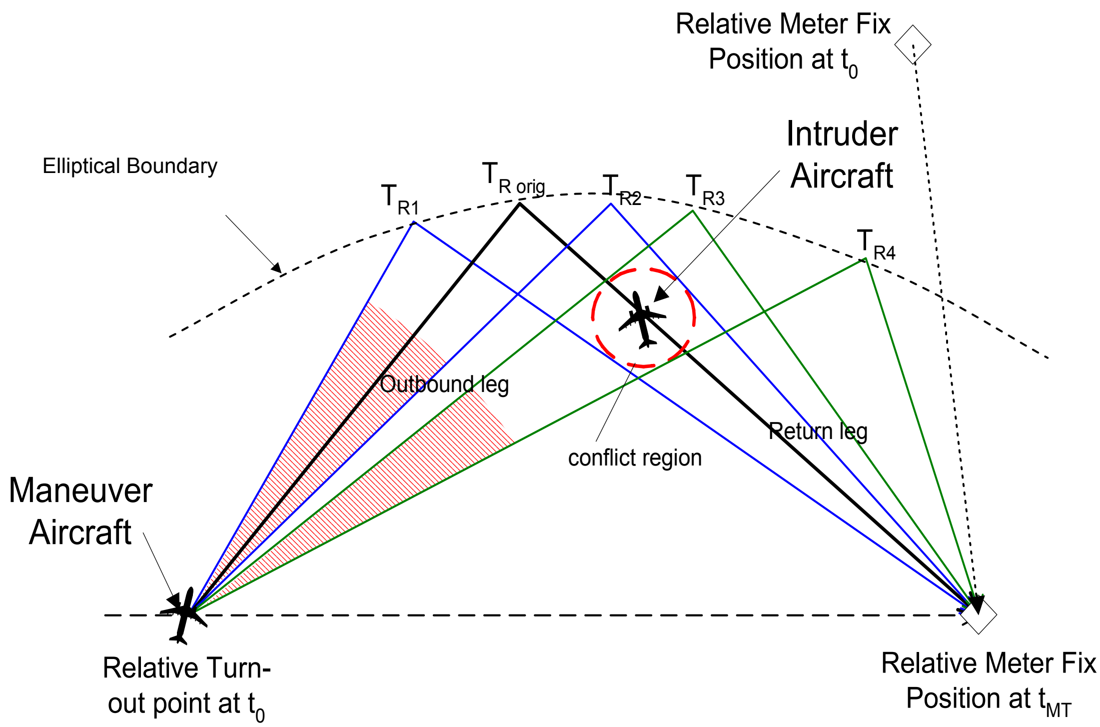

Figure 7-4 Analysis of solution space using path stretch

The impact of the predicted conflict is shown in Figure 7-4. Any trajectory that crosses the conflict region loses separation. The conflict region blocks out certain trajectories represented by the shaded turn-out angles, and hence corresponding regions of the elliptical boundary and area within. With limits on heading for the maneuver aircraft, the conflict region identifies infeasible states (I) that can only be part of infeasible trajectories (i.e., once reached the heading range cannot avoid the conflict), and robust states (R) that can only be part of feasible trajectories whatever heading is used. These areas are not shown in Figure 7-4 and will be subject of further analysis. The area of the ellipse and its blocked and unblocked areas (I and R respectively) are used to estimate the number of trajectories needed for calculating the robustness and adaptability metrics using the path stretch degree of freedom.

Further research will include analysis of the use of the ellipse area under the impact of the predicted conflict and deriving formulas for calculating the associated robustness and adaptability metrics.

Further research will contain a variation on the past two subsections that combines the flexibility metrics using speed and path stretch simultaneously.

7.4 Generalization to Stochastic Disturbances:

Assuming a stochastic behavior of the intruding traffic of which the predicted conflict situation depicted in Figure 6-4, Figure 7-2, Figure 7-4 is one instance ‘i’, the metric is averaged over the instances. For example, if the intruder stochastic behavior is characterized by a distribution P_i over instances i:1-M, then the robustness and adaptability metrics are integrated over the instances:

$$RBT = \sum_{i=1}^{M} P_i \times RBT(i)$$

$$ADP = \sum_{i=1}^{M} P_i \times ADP(i)$$

Figure 7-1 displayed schematically an example of such uncertainty in the location of the intruding traffic representing the disturbances. Uncertainty may also be in the speed or orientation of the traffic. The impact of such uncertainties results in variability in the conflict regions in Figure 6-4, Figure 7-2, and Figure 7-4, which may be accounted for in the metrics by averaging according to the two equations above, with partial information about the uncertainty represented by the distributions P.

As shown in Figure 7-1 some paths may not be impacted by the traffic while others may be impacted with a certain probability. Accounting for the uncertainty may also be used to reflect the proximity of the maneuver aircraft along a path to the surrounding traffic, even if it is not directly impacted. Further research will analyze these aspects and take into account the proximity of a path s to a disturbance as opposed to being impacted directly by the disturbance.

8 Use of Metrics for Flexibility Preservation and Constraint Minimization

The flexibility metrics are to be utilized for trajectory planning and constraint minimization. In Sections 6 and 7, the analysis and generation of flexibility metrics were conducted while simultaneously considering trajectory flexibility and the impact of constraints on it. This is because constraints imposed on trajectories, which define the trajectory solution space, were an integral part of the flexibility metrics. However, the use of the metrics in trajectory planning algorithms will be different from their use for constraint minimization algorithms. For example, while the trajectory planning function may maximize the flexibility metrics (or preserve them above a threshold), the constraint minimization function may look at the flexibility metrics sensitivity to changing constraints, in order to assist in making decisions about constraint relaxation.

The following two examples illustrate two uses of the metrics. A simplified scenario is used comparing two paths and using only speed as degree of freedom. Case 1 demonstrates the potential impact of preserving flexibility on traffic complexity and case 2 shows the potential impact of relaxing constraints on preserving flexibility.

Case 1 is presented in Figure 8-1: An aircraft is deciding to path stretch to meet an RTA constraint at a destination fix. It compares two path stretches; s_1 which infringes on a traffic flow in an opposing direction and s_2 which infringes on a traffic flow in an aligned direction. The aircraft selects one based on its flexibility using the speed degree of freedom only to avoid the disturbance of a potential conflict. For illustration, the predicted conflict geometry and timing are selected such that the conflict regions along the two paths are exactly symmetric about the vertical axis [48]. Figure 8-1 shows visually, for a specific conflict prediction instance, that the area R (including R' and R'') is significantly larger while the area I is significantly smaller, for path s_2 which is aligned with the traffic relative to path s_1 which is opposing to the traffic. Assuming a direct relationship between the R and I areas and the number of feasible/infeasible trajectories, as is illustrated in the examples in Figure 7-2 and Figure A.1 (in Appendix A), the robustness (relative number of feasible trajectories) and adaptability (absolute number of feasible trajectories) are higher for s_2 than s_1. Everything else being equal, including identical stochastic behavior of the intruder traffic for both paths, the robustness and adaptability metrics are more favorable for s_2 than s_1. Therefore, the aircraft would decide on the path stretch which is aligned with traffic. This shows that the aircraft's decision based on preserving its flexibility results in aligning the aircraft with other traffic, and hence reducing its contribution to complexity. This hypothesis will be tested under more rigorous and general scenarios.

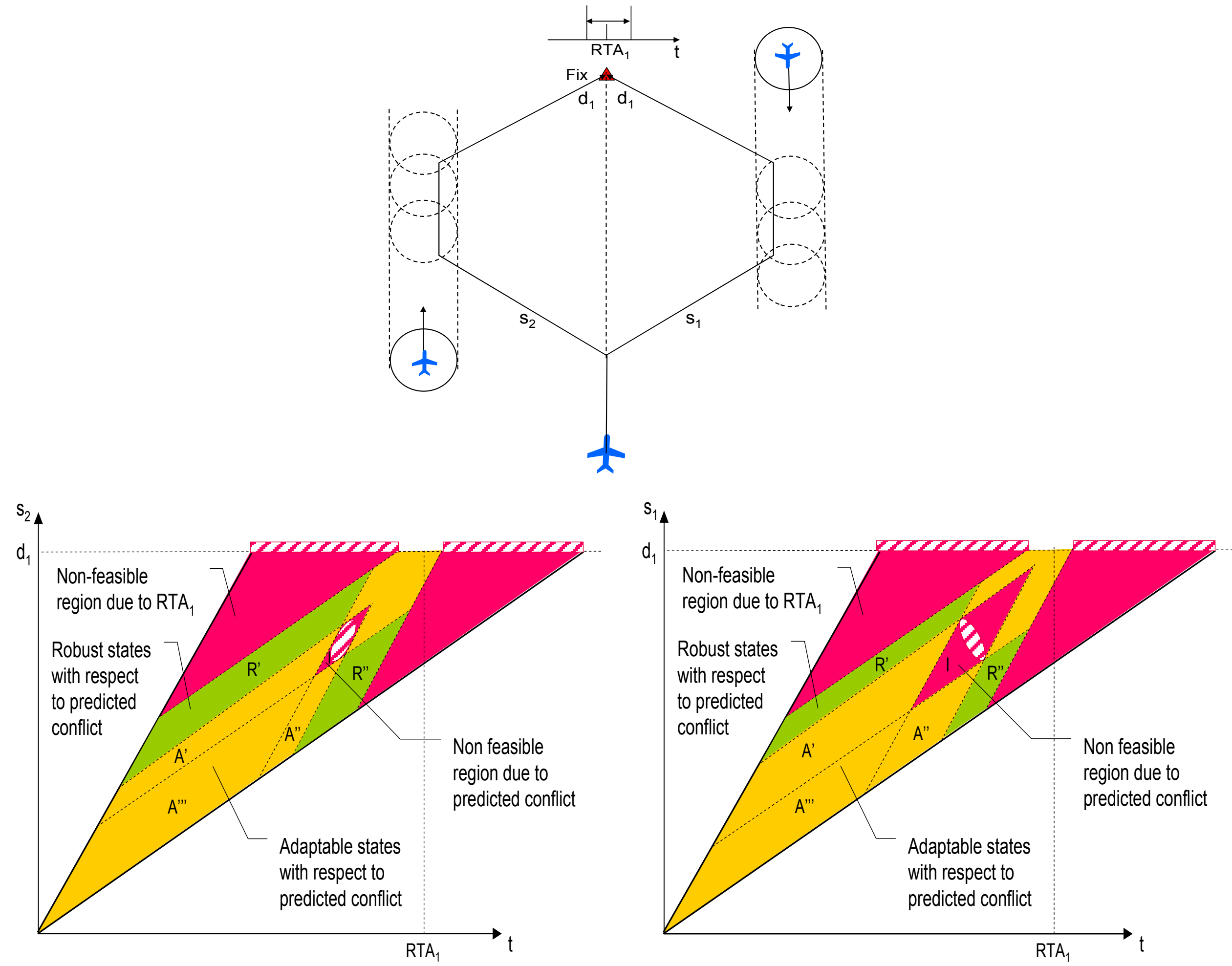

Figure 8-1 Case 1: Aligned versus opposing traffic

Case 2 is presented in Figure 8-2: An aircraft is deciding to path stretch to meet an RTA constraint (RTA_1) at a destination fix. It compares two path stretches s_1 and s_2 both infringing on a traffic flow in an opposing direction, such that the conflict prediction disturbance is identical between the two paths. However, path stretch s_2 passes through a congestion region resulting in RTA_2 at an intermediate location. Figure 8-2 shows that the RTA_2 constraint reduces the solution space considerably (R area relative to I area) for s_2 relative to s_1 resulting in lower robustness and adaptability to the conflict prediction disturbance. This example demonstrates that minimizing constraints, for example by removing RTA_2 or increasing its tolerance, results in higher flexibility. This hypothesis will be tested under more rigorous and general scenarios.

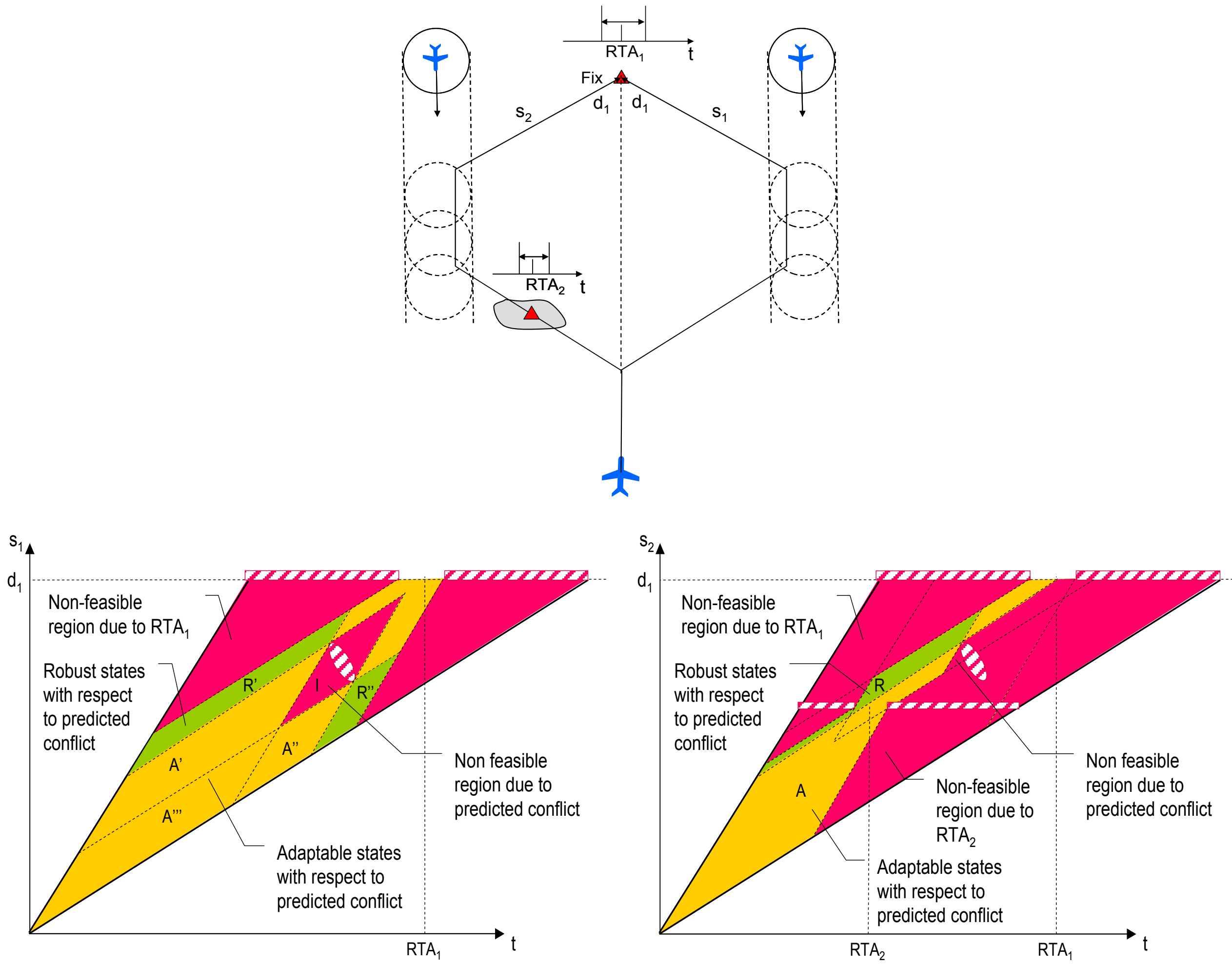

Figure 8-2 Case 2: One versus two RTA constraints

9 Summary and Conclusions

The work presented in this document constitutes preliminary research efforts towards testing the two hypotheses stated in Section 2. The first hypothesis speculates that by each individual aircraft autonomously preserving adequate flexibility in accommodating disturbances a traffic situation that is less complex will naturally result. The second hypothesis speculates that by minimizing the constraints imposed on the aircraft trajectory, without jeopardizing the intended ATM objectives, aircraft flexibility is increased and hence complexity mitigation is further enabled.

Testing these hypotheses fundamentally supports improving ATM operations, both centralized and distributed. However, a concept of operations was formulated to provide a specific operational context for the research. After a brief literature review in Section 3, the concept was described in Section 4, using hypothetical scenarios that demonstrated how the two newly proposed functions of flexibility preservation and constraint minimization interact together and with the separation assurance function. In this concept the flexibility preservation function is conceived as an airborne function that supports the pilot in autonomously selecting a trajectory which minimizes the aircraft risk exposure to disturbances. Two situations were distinguished: exposure to predicted conflicts with other traffic within a separation assurance horizon and exposure to disturbances outside the separation assurance horizon stemming for example from traffic congestion and weather systems. In both situations the flexibility preservation function is hypothesized to result in trajectories that lead to lower conflict prediction rates and less complex (more structured, predictable and safe) traffic situations. In the described concept the constraint minimization function is conceived as primarily a centralized function that supports ground-based traffic managers in imposing a just-enough amount of constraints on aircraft trajectories to achieve ATM objectives such as separation assurance and flow management. However, pilots may negotiate constraint minimization with the traffic managers when required from the airborne perspective. A functional analysis depicting this concept of operations in terms of key functions and information flows between them was presented in Section 5.

After defining the concept of operations, the focus of the remainder of the document concentrated on building an analytical framework in which preliminary metrics and methods are developed. The main objective was to gain insight into the fundamental elements and characteristics of the problem; to which end a limited scope situation was analyzed. This limited scope situation was to serve as a seed for generalization to more comprehensive ones. The situation involved a single aircraft with multiple RTA constraints and a single predicted conflict disturbance. The aircraft is to meet the constraints and accommodate the disturbances using speed as the only degree of freedom along a selection of fixed paths. The solution space of the aircraft trajectory was analyzed highlighting the effects of the constraints and disturbances on it. The analysis resulted in defining flexibility in terms of two key characteristics, robustness and adaptability to the disturbance. Then, metrics were suggested to measure robustness using the ratio of the number of feasible trajectories (meeting the constraints) given the disturbance to the number of feasible trajectories without the disturbance, and to measure adaptability using the absolute number of trajectories that are feasible given the disturbance occurrence. In Section 7 a method to estimate the number of trajectories under different constraint/disturbance impacts was suggested, along with initial efforts for generalization to other degrees of freedom, namely path stretch. The estimation method discretizes time into time steps during each speed is assumed constant and uses a convolution process to estimate the number of trajectories between time steps. The method although developed for the speed degree of freedom has potential for generalization to other degrees of freedom. Using these insights, two qualitative examples were described in Section 8 demonstrating the use of the metrics suggested in the limited scope situation to instantiate the hypotheses described in Section 2. It was demonstrated that if an aircraft maximized its robustness and adaptability (using speed only) to a predicted conflict disturbance it would select a path that aligns its direction with other traffic rather than a path that opposes other traffic. It was also demonstrated that the robustness and adaptability of the aircraft to a predicted conflict disturbance is reduced by adding RTA constraints. These fundamental insights and definitions will be extended to more comprehensive situations involving other degrees of freedom and other types of constraints and disturbances as explained in the next section.

10 Future Work

In order to test the research hypotheses presented in Section 2, the preliminary metrics proposed in this document need to be extended and matured. Then algorithms need to be developed to compute the metrics and instantiate the flexibility preservation and constraint minimization functions in support of experiment scenarios suitably designed to test the hypotheses. Before conducting the experiments, the metrics and algorithms will be tested and prototyped. First, low-to-medium fidelity testing will be performed in a desktop analysis environment (such as MATLAB). This would provide a controllable environment to test the algorithms and visualize their behavior as they are developed. Then, the metrics and algorithms will be refined based on the initial testing results. The experiments designed to test the hypotheses will be performed in the NASA Langley Air Traffic Operations Laboratory (ATOL). This will require implementing the flexibility preservation and constraint minimization metrics and algorithms within the AOP prototype and higher fidelity testing and validation.

Therefore, the next phase of research (planned for 2008) is classified into four major areas: (1) Metrics extension (2) Algorithm development (3) MATLAB testing and analysis (4) Design, development and conduct of complexity impact experiments. Each area is briefly described below.

10.1 Metrics Extension

The next phase of the research will extend the flexibility metrics described in this document into more comprehensive cases. Metrics currently have been suggested for limited scope situations: using only speed as a degree of freedom to accommodate situations with two RTA constraints, and one conflict disturbance. While the situations analyzed are limited in scope the metrics suggested are generic in nature.

These metrics need to be extended to more comprehensive situations involving more degrees of freedom, constraints, and disturbances:

10.1.1 Extending to Other Degrees of Freedom

The extension to degrees of freedom other than speed will be performed in stages. The preliminary efforts described in this document considered the path stretch degree of freedom as an outer loop to the speed degree of freedom (selecting a prespecified path while considering the flexibility using speed along each path). This effort will be pursued further considering path stretch alone without speed (initial analysis was presented in Section 7.3) and synthesizing a flexible trajectory using both degrees of freedom, path stretch and speed, in an integrated manner.

Then extension to the altitude degree of freedom will be pursued after understanding the problem in two dimensions. Incorporating altitude may also be done in two stages: First, considering altitude as an outer loop to the 2-dimensional problem (selecting an altitude while considering the flexibility using speed and path stretch in a plane at each altitude). Then, an integrated trajectory synthesis method may be developed considering speed, path stretch and altitude simultaneously.

Initial hypothesis testing may be performed first in two dimensional settings (considering only speed and path stretch). This is useful to obtain initial insights and feedback into the metrics and algorithms before expanding the setting to three dimensions. Then, extension into the 3rd dimension may be done incrementally by first considering simple climb/descent steps. This would allow aircraft seeking flexibility to consider the effect of changing flight levels, which may be important for preserving RTA adherence.

10.1.2 Extending to Other Constraints

Several types of trajectory constraints have been analyzed as reported in this document: RTA and predicted conflicts with other traffic in addition to aircraft performance constraints such as the minimum and maximum speeds. This included multiple RTA constraints with tolerance in meeting the RTA. Conflict with traffic was analyzed as a constraint disturbance that is predicted with certain probability; however, it may also be considered as a constraint if predicted with sufficient certainty. Extending to other types of constraints includes area hazards; although they are more deterministic and simpler to analyze so they may be considered as a special case of conflict prediction. Other aircraft performance constraints may also be considered such as fuel load which limits the flying time and limits on altitude, turns, and path stretching.

The multiplicity of the constraints and their types gives rise to a prioritization among them, which is an important aspect in the constraint minimization function. In this function the decision to relax some constraints may be based on ranking of the constraints. One ranking criteria is the impact of relaxing a constraint on meeting the intended ATM objective(s). For example, if an aircraft is unable to meet an RTA because of a predicted conflict, the traffic manager may relax the RTA ensuring safety at the expense of TFM objectives. Or when an aircraft is impacted by multiple RTAs the RTAs may be ranked in terms of their need for meeting the TFM objective (balancing demand and capacity) and the ones that are redundant or less effective may be relaxed. Another ranking criteria is the amount of flexibility that relaxing a constraint affords the aircraft. For example, of multiple constraints the ones whose relaxation increases the aircraft flexibility most may be prioritized candidates for relaxation. This ranking from the aircraft perspective becomes an input to the constraint relaxation negotiation process, where the pilot (or airline) may request relaxing the constraints that increases their flexibility the most. Also relaxing constraints causing over-constraining situations (no trajectory solution meets all constraints) takes priority over relaxing ones that cause excessive-constraining situations (no flexible-enough trajectory solution meets all constraints). Therefore, future work will include investigating ranking of constraints using different relevant criteria in multiple constraint situations.

10.1.3 Extending to Other Disturbances

In terms of disturbances only specific constraint type disturbances have been considered in this document. For example, conflict prediction was used as an example of a constraint disturbance that alters the solution space of the aircraft trajectory. Future work will extend the metrics and methods to other types of constraint disturbances, such as weather cell initiation and motion, dense traffic areas, and area hazards. It is expected that the analytical framework used in this document will be able to generalize to these cases, where the predicted conflict disturbance may be considered a generic form of these types of disturbances, with appropriate characterization. For example, a dense traffic area or a collection of weather cells may be modeled as a single moving cluster of individual aircraft or weather cells. Other constraint disturbances include non-planned changes to RTA constraints. The metrics will also be extended to multiple disturbance situations of the same or different types.

In analyzing constraint type disturbances the aircraft is assumed to fly its planned trajectory with high accuracy. Future research will extend the insights gained from this limited scope situation to situations involving state disturbances that force the aircraft to deviate from its planned trajectory (such as wind gusts). Differences between the impacts of constraint and state type disturbances and their combined effects will be analyzed.

10.2 Algorithm Development

The next phase of the research will include developing algorithms to instantiate the flexibility preservation and constraint minimization functions by utilizing the refined metrics in trajectory planning. For the flexibility preservation function methods will be developed for planning and synthesizing a trajectory based on objective functions that maximize or preserve the flexibility metrics. For the constraint minimization function methods for scoring different constraints based on flexibility impacts and ATM objective impacts are used for selecting constraints that are candidate for relaxation. The following are a number of related issues that the next phase of research will address.

10.2.1 Relation between Flexibility Preservation and Constraint Minimization

To date the analysis and generation of flexibility metrics were conducted while simultaneously considering trajectory flexibility and the impact of constraints on it. This is because the constraints imposed on a trajectory, which define the trajectory solution space, were an integral part of the flexibility metrics. However, the use of the metrics in trajectory flexibility preservation algorithms will be different from their use in constraint minimization algorithms. For example, while trajectory flexibility preservation may maximize the flexibility metrics (or preserve them above a threshold), constraint minimization may look at the flexibility metrics sensitivity to modifying constraints, in order to assist in making decisions about constraint relaxation. These various uses of the metrics will be investigated in the context of the experimentation needed for testing the research hypotheses.

10.2.2 Tradeoff between Metrics

In some situations a tradeoff exists between the flexibility metrics, i.e., robustness and adaptability, and with other objectives. For example, a tradeoff between robustness and adaptability may arise because of the decision maker’s risk attitude: a conservative decision maker may favor robustness to minimize having to accommodate the disturbance, while a more risk prone attitude may tolerate a certain chance of dealing with the disturbance as long as there is sufficient adaptability. Flexibility was defined as the aircraft ability to accommodate disturbances while abiding by all constraints. This goal is traded with other objectives of the aircraft such as fuel efficiency. Such objectives may be formulated as constraints on the trajectory solution space and treated in the flexibility preservation problem, or as objectives that compete with the flexibility preservation objective. Such trade-offs between metrics will be explored in the next phase of the research.

10.2.3 Time Horizon

In order to support the operational concept described in Sections 4 and 5, various time horizons need to be considered, for example, differentiating between flexibility preservation within the conflict resolution horizon and beyond where conflict resolution is not performed.

Within the conflict resolution horizon the flexibility metrics may be incorporated in the AOP conflict resolution algorithm [10] in order to select a resolution trajectory that is conflict free but also more flexible. Other algorithmic approaches to plan a trajectory using the suggested flexibility metrics will be pursued further for both within and outside the separation assurance horizon.

10.2.4 Cooperative Flexibility Planning

The initial experimentation (at least in the MATLAB environment) will test the impact of single aircraft flexibility preservation (i.e., each aircraft acting independently) on traffic complexity. If the research hypothesis is correct these autonomous actions should result in traffic complexity reduction, to a certain extent. However, an important question is whether such distributed uncoordinated actions are effective or sufficient to reduce traffic complexity. If not, further complexity reduction may be achieved through coordination of the individual actions. The coordination may be achieved by explicit communication and collaboration between the distributed agents or through centralized (e.g., ground based) mediation and supervision. Therefore, algorithms for single aircraft flexibility preservation and for multiple aircraft, collaborative flexibility preservation may be required to fully explore and test the research hypotheses.

During the first part of the next research phase the focus will continue to be on a single aircraft planning its trajectory under various constraint/disturbance situations. Then the focus will extend to multiple aircraft planning their respective trajectories simultaneously in the presence of constraints and disturbances. For example, different levels of intent information sharing between aircraft may be modeled to coordinate the distributed flexibility preservation actions. This information may be used to model reduction in the disturbance uncertainties such as those associated with the conflict prediction and to enable rules of negotiating distributed actions.

It should be noted that considering collective aircraft planning should be pursued gradually and after the impact of single aircraft planning is well understood. For example, a set of second round experimentation may assess the impact of collective, collaborative behavior, after a first experiment assesses the impact of independent, single aircraft planning on traffic complexity.

10.3 MATLAB Analysis and Testing

Before conducting expensive experiments in the ATOL environment it is important to conduct low-to-medium level analysis in an environment such as MATLAB. This analysis is crucial for refining the metrics and algorithms described in the previous two subsections. Therefore, the next phase of research will involve extensive MATLAB analysis continuing from initial efforts in the first phase. Starting with the limited scope pilot case (i.e., using only speed as a degree of freedom and considering multiple RTAs as constraints and predicted conflicts as disturbances) a MATLAB test and analysis utility is being built and will continue to expand as more generic cases are analyzed. The MATLAB utilities will include:

- Utilities to compute the flexibility metrics and other metrics that are needed to analyze tradeoffs between different trajectory planning objectives and test the research hypotheses. For example, the metrics include constraints' impact on flexibility, trajectory planning metrics other than flexibility (e.g., travel time, and fuel burn), constraint relaxation impact on ATM objectives, and simple traffic complexity metrics.
- Algorithms that use the metrics for trajectory planning and constraint minimization.
- Utilities to visualize the metrics and algorithm behavior under different situations. For example, developing plots of the robustness and adaptability metrics presented in this report as a third dimension over the solution spaces in Figure 6-4, Figure 7-2, and Figure 7-4. These plots will show how the metrics vary and tradeoff over the solution space and under the impact of different disturbance situations.
- MATLAB experiments, scenario simulation, and analyses. For example, these analyses include simulation and visualization of aircraft motion in simple scenarios that bring together traffic and area hazards in a manner relevant to the hypotheses being tested (See e.g., Figure 7-1). They also include analyzing the results of the trajectory planning algorithms in such scenarios including the tradeoffs between different metrics (e.g., robustness, adaptability, travel time, fuel burn), and impacts on traffic complexity (using simple complexity metrics).

Initial testing of the hypotheses may be done in MATLAB with simple traffic complexity metrics, if feasible. MATLAB analysis in the next phase of research will also be crucial to support of the AOP experimentation in the ATOL environment, in order to support initial testing of iterations on the AOP experimentation and analysis of the results of the experiments.

10.4 Design and Conduct of Complexity Impact Experiments

Experiments need to be designed and conducted in the next phase of research in order to test the hypothesis that preserving trajectory flexibility mitigates traffic complexity. The experiments will also include testing the relationship between constraint minimization and trajectory flexibility. In addition to the results of the research efforts described in the previous three subsections, the experimentation exercise includes two major components: traffic complexity metric selection and experiment scenario selection.

10.4.1 Traffic Complexity Metric Selection

The critical factor in the selection of a traffic complexity metric is to ensure that the metric represents the appropriate physical characteristic of the traffic that is intended. According to the literature search in Section 3.3, traffic complexity has referred in the abstract sense to the proneness of the system to commit safety compromising errors; and in particular has been used to refer to the rate of conflicts predicted and hence the workload of the (ground-based) air traffic controller whose primary task is to monitor and resolve such conflicts. However, as described in Section 4, traffic complexity, which still refers in the abstract sense to the proneness of the system to commit safety compromising errors, may represent different characteristics in the distributed control environment, in which the pilots maintain or share responsibility for separation assurance. Therefore, it is critical to select and use complexity metrics that represent intrinsic characteristics of the traffic that reflect its safety compromising tendencies, without strict dependence on the distributed versus centralized nature of the control environment.

Given the substantial prior research and literature available on traffic complexity and its measurement, it is desirable to attempt to leverage to the extent possible traffic complexity measures that have been proposed. For example, the complexity metric in [39] has been identified as a possibly suitable metric since it attempts to measure intrinsic complexity characteristics of the traffic. This metric, among others, will be further investigated in the next phase of the research and, once a suitable measure is selected, its computation will be integrated in the experiment setup.

10.4.2 Experiment Scenario Design

A number of scenarios need to be generated to test the research hypotheses. The most critical aspect of selecting experiment scenarios that are appropriate for the hypothesis testing is to ensure that each scenario reflects and isolates the factors and relationships being analyzed. To this end initial experiment scenarios should be simple even at the expense of some realism. This is particularly true for the MATLAB analyses and preliminary experiments, discussed in Section 10.3. Then more realism and sophistication would be added gradually, starting with limited scope scenarios (limited degrees of freedom and constraint/disturbance situations as described, for example, in Section 7.1 and Figure 7-1) and proceeding to more comprehensive scenarios based on preliminary results and insights.

The ATOL experiments, because they are more expensive, need to be carefully designed and exhibit the appropriate balance between realism and simplicity. To help achieve this end leveraging previous AOP self-separation experiments [49] and the lessons learned from them will be critical.

11 References

[1]. Joint Planning and Development Office, "Next Generation Air Transportation System Integrated Plan," URL: http://www.jpdo.gov/library/NGATS_v1_1204r.pdf

[2]. Wing, D., 2005, "A Potentially Useful Role for Airborne Separation in 4D-Trajectory ATM Operations," AIAA-2005-7336.

[3]. NASA, 2004, "DAG-TM Concept Element 5 En Route Free Maneuvering for User-Preferred Separation Assurance and Local TFM Conformance Operational Concept Description," AATT Project Milestone 8.503.10, NASA Airspace Systems Program Office, Washington D.C.

[4]. NASA, 2004, "DAG-TM Concept Element 11 Terminal Arrival Self-Spacing for Merging and In-Trail Separation Operational Concept Description," AATT Project Milestone 8.652.7, NASA Airspace Systems Program Office, Washington D.C.

[5]. Hill, J.C., J.K. Archibald, W.C. Stirling, and R.L. Frost, 2005, "A Multi-Agent System Architecture for Distributed Air Traffic Control," AIAA-2005-6049.

[6]. Wollkind, S., J. Valasek, and T. Ioeger, 2004, "Automated Conflict Resolution for Air Traffic management Using Cooperative Multiagent Negotiation," AIAA-2004-4992.

[7]. Versteegt, H.H., and H.G. Visser, 2002, "Traffic Complexity Based Conflict Resolution," AIAA-2002-4443.

[8]. Ballen, M., V. Sharma, R. Vivona., E. Johnson, and E. Ramiscal, 2002, "A Flight Deck Decision Support Tool for Autonomous Airborne Operations," AIAA-2002-4554.

[9]. Mondoloni, S., and S. Conway, 2001, "An Airborne Conflict Resolution Approach Using A Genetic Algorithm," AIAA-2001-4054.

[10]. Vivona, R., D. Karr, and D. Roscoe, 2006, "Pattern-Based Genetic Algorithm for Airborne Conflict Resolution," AIAA-2006-6060.

[11]. Barhydt, R., and P. Kopardekar, 2005, "Joint NASA Ames/Langley Experimental Evaluation of Integrated Air/Ground Operations for En Route Free maneuvering," 6th USA/Europe ATM R&D Seminar, Baltimore, MD.

[12]. Krishnamurthy, K., B. Barmore, and F. Bussink, 2005, "Airborne Precision Spacing in Merging terminal Arrival Routes," 6th USA/Europe ATM R&D Seminar, Baltimore, MD.

[13]. Mediterranean Free Flight Programme Final Report, 2005, D821, http://www.medff.it/public/index.asp.

[14]. Idris H., D. Wing, R. Vivona, and J.L. Garcia-Chico, 2007, "A Distributed Trajectory-Oriented Approach to Managing Traffic Complexity," AIAA-2007-7731.

[15]. Idris H., R. Vivona, J.L. Garcia-Chico, and D. Wing, 2007, "Distributed Traffic Complexity Management By Preserving Trajectory Flexibility," DASC.

[16]. Iyengar, S., C. Jorgensen, V. Rao, and C. Weisbin, 1986, “Robot Navigation Algorithm using Learned Spatial Graphs,” Robotica, Vol. 4, No. 2, pp. 93–100.

[17]. Khatib, O., 1986, “Real-Time Obstacle Avoidance for Manipulators and Mobile Robots,” International Journal of Robotics Research, Vol. 5, No. 1, pp. 90–98.

[18]. Koren, Y.and J. Borenstein, 1991, “Potential Field Methods and Their Inherent Limitations for Mobile Robot Navigation,” In IEEE Conference on Robotics and Automation, pp. 1398-1404, Sacramento, CA, April 1991.

[19]. Sigurd, K and J. How, 2003, "UAV Trajectory Design Using Total Field Collision Avoidance," AIAA-2003-5728.

[20]. Eun, Y., and H. Bang, 2006, “Cooperative Control of Multiple Unmanned Aerial vehicles using the Potential Field Theory,” AIAA-20345-674, Journal of Aircraft, Vol 43, No. 6, pp. 1805-1814.

[21]. Shimoda, S., Y. Kuroda, and K. Iagnemma, 2005, “Potential Field Navigation of High Speed Unmanned Ground Vehicles on Uneven Terrain,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 2005.

[22]. Clark, C. and S. Rock, 2001, “Randomized Motion Planning for Groups of Nonholonomic Robots,” International Symposium of Artificial Intelligence, Robotics and Automation in Space.

[23]. Hsu, D., J.C. Latombe, and R. Motwani, 1997, “Path Planning in Expansive Configuration Spaces,” in Proceedings of the IEEE International Conference on Robotics and Automation, pp 2719-2726.

[24]. Hsu, D., R. Kindel, J.C. Latombe, and S. Rock, 2000, “Randomized Kinodynamic Motion Planning with Moving Obstracles,” in Workshop on the Algorithmic Foundations of Robotics.

[25]. Kindel, R, D. Hsu, J.C. Latombe, and S. Rock, 2000 “Kinodynamic Motion Planning Amidst Moving Obstacles,” in Proceedings of the IEEE Conference on Robotics and Automation, pp. 537-544.

[26]. Lamiraux, F., E. Ferre, and E. Valle, 2004, “Kinodynamic Motion Planning: Connecting Exploration Trees Using Trajectory Optimization Methods,” Proceedings of International Conference on Robotics and Automation, 2004

[27]. Barraquand, J.and J.C. Latombe, 1993, “Nonholonomic Multibody Mobile Robots: Controllability and Motion Planning in the Presence of Obstacles,” Algorithmica, 10:121-155.

[28]. LaValle, S. M. and J. J. Kuffner, 2001, “Randomized Kinodynamic Planning,” International Journal of Robotics Research, 20(5):378-400, May 2001.

[29]. Lamiraux, F.and D. Bonnafous, 2002, “Reactive Trajectory Deformation for Nonholonomic Systems: Application to Mobile Robots.” In Proceeding of the IEEE International Conference on Robotics and Automation, pp. 3099-3104, Washington D.C., May 2002.

[30]. Mondoloni, S., Ballin, M., and Palmer, M., 2004, "Airborne conflict resolution for flow-restricted transition airspace" AIAA-2004-4991.

[31]. Tomlin, C, G. Pappas, and S. Sastry, 1998 "Conflict Resolution for Air Traffic Management: A Study in Multiagent Hybrid Systems" IEEE transactions on Automatic Control, Vol. 43, No. 4, April, 1998.

[32]. Tomlin, C., I. Mitchell, and R. Ghosh, 2001, "Safety Verification of Conflict Resolution Maneuvers," IEEE Transactions on Intelligent Transportation Systems, Vol. 2, No. 2, June 2001.

[33]. Clark, C., Rock, S., and Latombe, J-L., 2003, "Motion Planning for Multiple Mobile Robot Systems using Dynamic Networks", Proceedings of IEEE Conference on Robot and Automation.

[34]. Kopardekar, P. and Magyarits, S., 2002. "Dynamic density: Measuring and predicting sector complexity" Proceedings of the 21st Digital Avionics Systems Conference.

[35]. Histon, J. M., Aigoin, G., Delahaye, D., Hansman, R. J., and Puechmorel, S. 2001, "Introducing structural considerations into complexity metrics." Proceedings of the 4th USA/Europe Air Traffic Management R&D Seminar, Sante Fe, NM.

[36]. Davison, J., Histon, J., Ragnarsdottir, M., Major, L., Hansman, R.J. "Impact of Operating Context on the Use of Structure in Air Traffic Controller Cognitive Processes". Proceedings of the 5th USA/Europe Air Traffic Management R&D Seminar Budapest, Hungary.

[37]. Athenes, S., Averty, P., Puechmorel, S., Delahaye, D., and Collet, C., 2002, "ATC Complexity and Controller Workload: Trying to Bridge the Gap. HCI-Aero 2002 International Conference on Human-Computer Interaction in Aeronautics.

[38]. Delahaye, D. and Puechmorel, S., 2000, "Air Traffic Complexity: towards intrinsic metrics. Proceedings of 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli, Italy.

[39]. Delahaye, D., Puechmorel, S., Hansman, J., and Histon, J., 2003, "Air traffic complexity based on non linear dynamical systems" Proceedings of the 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary.

[40]. M. Ishutkina, E. Feron, K. Billimoria, 2005, "Describing Air Traffic Complexity Using Mathematical Programming" AIAA-2005-7453.

[41]. Aigoin, G., 2001, "Air Traffic Complexity. Modeling", Master Thesis. ENAC: France.

[42]. Granger, G., and Durand, N.," A traffic complexity approach through cluster analysis," Proceedings of the 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary.

[43]. Billimoria, K., and Lee, H., 2005, "Analysis of aircraft cluster to measure sector-independent airspace congestion", AIAA 2005-7455.

[44]. Riley, V., G. Chatterji, W. Johnson, R. Mogford, P. Kopardekar, E. Sierra, and G. Lawton, 2004, "Pilot perceptions of airspace complexity, part 2," DASC.

[45]. Sridhar, S., Seth, K., and Grabbe, S., 1998, Airspace Complexity and its Application in Air Traffic Management", Proceedings of the 2nd USA/Europe Air Traffic Management R&D Seminar, Orlando, FL.

[46]. Masalonis, A., Callaham, M. Wanke, C., 2003, "Dynamic density and complexity metrics for realtime traffic flow management", Proceedings of the 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary.

[47]. Coppenbarger, R., Lanier, R., Sweet, D., and Dorsky, S., "Design and Development of the En Route Descent Advisor (EDA) for Conflict-Free Arrival Metering," AIAA-2004-4875, 2004.

[48]. Idris, H., T. Hsu, R. Vivona, and S. Green, 2003, "Time Based Conflict Resolution Algorithm and Application to Descent Conflicts," AIAA-2003-5517.

[49]. Consiglio, M.C., S.T. Hoadley, D.J. Wing, and B.T. Baxley, 2007, "Safety performance of Airborne Separation: Preliminary Baseline Testing," AIAA-2007-7739.

Appendix A. Solution Space with One Single Speed Change

For illustration, an example is given in Figure A.1 with the additional constraints that only a single change of speed is allowed along the path and with a single point (zero tolerance) RTA. The solution space that meets RTA_1 independently from the predicted conflict is bound as before by the minimum and maximum speed lines extended from the point (RTA_1 d_1) and the current state. With the additional constraints each point in this space corresponds to the speed change location of a single trajectory, and each trajectory that meets the RTA changes its speed at one point in this space. Therefore, the number of trajectories that meet the RTA (independently from the predicted conflict disturbance) corresponds exactly to the area of the solution space (S). The analysis of this solution space into areas R, I and A with respect to the predicted conflict is depicted in the figure. The infeasible area I is bounded by the two single-speed-change trajectories that are tangent to the predicted conflict region and end at RTA_1. Correspondingly the areas R' and R'' are bound by these lines and the minimum-/maximum-speed boundaries of the solution space that meets RTA_1. Area R' can be reached from area A' and area R'' can be reached from area A''. The number of feasible trajectories that fall in R is measured by the area of the R region, because any speed change outside R corresponds to an infeasible trajectory, and each point in the area R corresponds to the location of one possible speed change and hence exactly to a single feasible trajectory. Therefore, RBT = (R'+R'')/S.

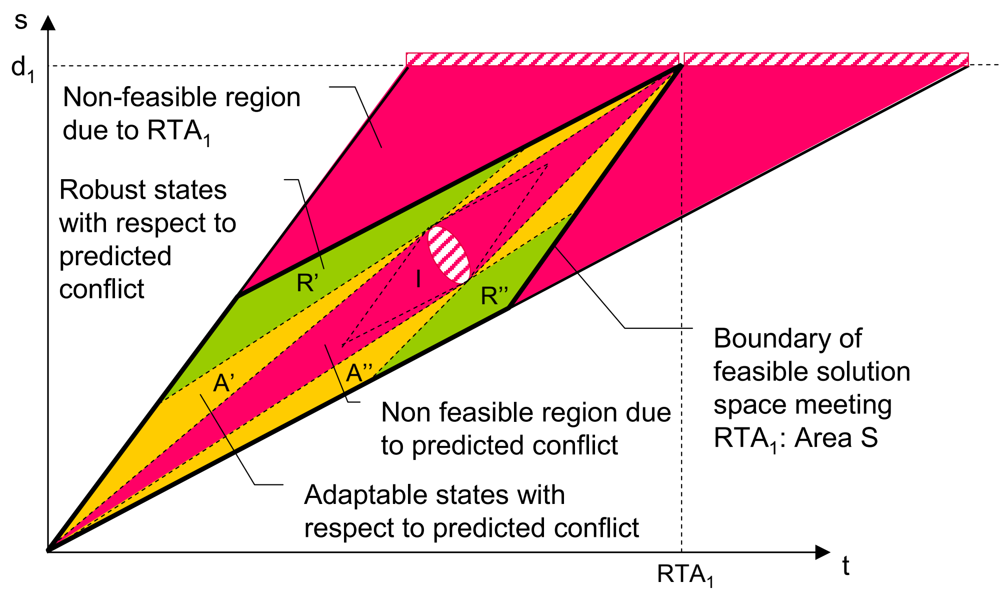

Figure A-1 Solution space with one speed change

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01- 04 - 2008

2. REPORT TYPE
Contractor Report

3. DATES COVERED *(From - To)*
Dec 2006 - Nov 2007

4. TITLE AND SUBTITLE
Trajectory-Oriented Approach to Managing Traffic Complexity: Operational Concept and Preliminary Metrics Definition

5a. CONTRACT NUMBER
NNA07BB26C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Idris, Husni; Vivona, Robert; and Garcia-Chico, Jose L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Ames Research Center
Moffett Field, CA 94035
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2008-215121

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA CASI (301) 621-0390

13. SUPPLEMENTARY NOTES
Technical Monitor: David J. Wing, Langley Research Center. This work was performed and funded under Ames contract NNA07BB26C, but monitored and published by Langley Research Center.
Idris, Vivona, and Garcia-Chico: L3 Communications, 300 Concord Road, Suite 400, Billerica, MA 01821

14. ABSTRACT
This document describes preliminary research on a distributed, trajectory-oriented approach for traffic complexity management. The approach is to manage traffic complexity in a distributed control environment, based on preserving trajectory flexibility and minimizing constraints. In particular, the document presents an analytical framework to study trajectory flexibility and the impact of trajectory constraints on it. The document proposes preliminary flexibility metrics that can be interpreted and measured within the framework.

15. SUBJECT TERMS
Air traffic management; Traffic complexity; Trajectory flexibility; Constraint minimization; Distributed control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
U	U	U	UU	58	(301) 621-0390