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The Viability of Digital Flight, Part 2: Requiring Conflict Management Performance

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Abstract

With automation increasingly permeating nearly all aspects of aircraft design and operation, the need is growing to also automate their safe passage through airspace populated with traffic and other hazards. Today's operating modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) are human-centric in their methods of conflict management. Their ability to accommodate increasingly autonomous operations is quite limited and may significantly restrain their growth and future operational utility. Creating an additional, digitally enabled operating mode is a paradigm shift that could unlock a new era of aviation in which highly automated aircraft operate cooperatively throughout the airspace alongside conventional (i.e., VFR and IFR) operations.

The NASA Digital Flight concept envisions an additional operating mode that employs automated self-separation and which may be a more appropriate match than VFR or IFR for aircraft capable of increasingly autonomous flight. However, as a significant paradigm shift in conflict management, its viability hinges on the regulator's ability to authorize its use. The application of *accountability*, an accepted construct in aviation used as part of safety assurance, helps in addressing this viability question. Accountability is the obligation to answer for an action taken (or not taken) by a responsible entity. Understanding the answers to the following critical accountability questions is necessary for effective oversight by the regulator: *who* will be accountable for separation; *to whom* they will be accountable; and *for what* they will be held accountable. This paper (Part 2) is the second of two that directly investigate these questions. The companion paper (Part 1) introduces these basic questions of accountability and discusses the first two accountability questions (*who* and *to whom*) in detail by analyzing an operator-centric scheme similar to VFR, but for automated conflict management (i.e., automated self-separation). This paper (Part 2) discusses the third accountability question (*for what*) in detail by introducing a new performance construct: *Required Conflict Management Performance (RCMP)*.

RCMP offers a structured approach for (a) authorizing operators to employ automated conflict management as the sole means for separation from traffic and hazards, and (b) specifying the minimum authorized separation value based on their conflict management system performance. The paper discusses RCMP motivations, early community-led foundations of automated conflict management including Unmanned aircraft system Traffic Management (UTM) and Detect and Avoid (DAA) technologies, and the ability for RCMP to fill the "separation provision" gap between them. The paper presents an approach for constructing RCMP, leveraging the precedent of performance-based navigation and new self-separation capabilities proposed in the Digital Flight concept. Multiple systems contributing to automated self-separation are qualitatively discussed for their performance contributions and impacts, and a phased implementation approach to RCMP is discussed.

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Finally we thank the rest of the CAS DECO research team for the extensive analyses, simulations, and flight tests that rounded out the DECO research portfolio and contributed significantly to substantiating the desirability, viability, and feasibility of Digital Flight. Along with the authors, the DECO team includes Dr. Elaine Blount, Kaleb Gould, Ana Jain, Dr. Jinhua Li, Dr. John Maris, Jerry Smith, David Thipphavong, Paul Vajda, Dr. Fred Wieland, and Harrison Wolf.

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Executive Summary

With automation increasingly permeating nearly all aspects of aircraft design and operation, the need is growing to also automate their safe passage through airspace populated with traffic and other hazards. Today's operating modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) are human-centric in their methods of conflict management, and their ability to accommodate increasingly autonomous operations is quite limited and may significantly restrain the future operational utility of these new operations. Creating an additional, *digitally enabled* operating mode is a paradigm shift that could unlock a new era of aviation in which highly automated aircraft operate cooperatively alongside conventional (i.e., VFR and IFR) operations in integrated airspace. The term *digitally enabled* here refers to leveraging digital technologies such as information services, digital connectivity and communications, and automation algorithms which maintain situation awareness (i.e., a model of the operating environment) and are capable of managing conflicts. These capabilities can be on the aircraft, on the ground, or in the cloud.

The concept of Digital Flight, documented in 2022 (NASA/TM-20220013225), offers a framework for a digitally enabled cooperative operating mode for integrated airspace. The framework could be applicable to any concept that includes cooperative operations, such as Urban Air Mobility (UAM), Upper E Traffic Management (ETM), and Extensible Traffic Management (xTM). Envisioned for future use by any qualified operator of any aircraft type, the concept leverages information services, shared traffic and intent awareness, cooperative practices, and automated conflict management capabilities to provide operators with an alternative means from VFR and IFR to safely conduct their missions, eventually in all airspace classes, without the constraints and limitations of human-centered conflict management. By allowing for automated conflict management, the national airspace will benefit from the cumulative technological advancements of nearly 100 years since the first instrument flight. Automated conflict management has the potential to enable operations to scale efficiently and safely to unprecedented levels of traffic density, complexity, and operational tempo.

A significant challenge to realizing automated conflict management is regulatory approval. Currently no basis exists in regulations to authorize operators to use conflict management automation as the means for ensuring an aircraft's separation from traffic and hazards. To propose conditions under which a regulator may grant such approval, a companion paper (Part 1, NASA/TM-20250007128) and this paper (Part 2) together explore a candidate two-part approach to enhancing the real-world viability of a digitally enabled operating mode: Part 1, establishing formal operator accountability for automated self-separation; and Part 2, defining Required Conflict Management Performance (RCMP) as a measurable basis for the safety case.

Ongoing industry initiatives in Uncrewed aircraft systems Traffic Management (UTM) and Detect and Avoid (DAA) technologies are producing the foundations upon which fully automated conflict management is achievable; however their functionality is incomplete, and the gap between them needs to be filled. The International Civil Aviation Organization (ICAO) categorizes three layers of conflict management: (1) strategic conflict management, (2) separation provision, and (3) collision avoidance. UTM employs primarily strategic conflict management capabilities for small drones in largely segregated airspace. DAA employs sensors for highly tactical (close range) separation and collision avoidance, currently without regard to operational intent or performance-based separation minima. RCMP is envisioned to fill the gap in the traffic separation provision layer, enabling operator-accountable, performance-based, automated self-separation.

RCMP is a performance-based construct which could provide an accountability basis for operators to gain operational approval to use automated conflict management. In fact, any concept employing automated conflict management, including provider-centric concepts, could leverage RCMP. In this paper, the term RCMP is used in two ways: it is the means by which an operator can demonstrate the adequacy of their automated conflict management system to the regulator for operational approval, and it is the value of the minimum separation that may be applied between a Digital Flight and another aircraft. Described qualitatively in this concept paper, RCMP could provide a quantitative link between conflict management system performance and an approved safety outcome (i.e., collision risk). Higher performing conflict management systems would qualify for reduced separation values, unlocking significant efficiency and capacity benefits for their operators.

A phased implementation of RCMP, complemented by rigorous design assurance, could support early operations that rely on larger separation values to build regulator trust in automated conflict management through safe gathering of operational evidence and acceptance of residual risk. As higher levels of RCMP performance and reduced

separation are approved, diverse operations with different performance capabilities and operational needs could be enabled, while still being unified under a single performance-based construct. In this way, the diverse industry advances together.

The RCMP concept expands on Performance Based Navigation (PBN) principles of Area Navigation (RNAV) and Required Navigation Performance (RNP) with three additional specific capabilities of automated conflict management proposed in the Digital Flight framework: Operator Self-Separation, Shared Separation, and Pairwise Coordinated Separation. Enabling these capabilities are six separate technical systems that together comprise an integrated conflict management system, the performance of which is the subject of RCMP and which establishes the safety outcome. The higher the performance of the integrated system, the smaller the minimum separation values that could be authorized for the same safety outcome. In-Time Safety Management Systems (IASMS) could complement RCMP with independent performance monitoring and alerting.

The six technical systems contributing to automated self-separation are diverse: information/connectivity systems enable digital modeling of the operating environment; surveillance systems locate and track relevant traffic within that modeled environment; communication systems share intent and enable coordination; separation automation systems predict trajectories, detect and resolve conflicts, and monitor conformance; command and control systems transmit flight path changes to the aircraft; and navigation systems execute the flight path change with intended precision. Each of these systems are qualitatively reviewed in this paper for attributes that may contribute to or impact the performance of the integrated conflict management system. An argument is made for extending RNP, which can protect aircraft from terrain on fixed routes, to dynamically computed flight paths that separate aircraft from encountered aircraft. Each of the remaining systems are explored for their performance roles in informing, defining, transmitting, or executing this separated path.

Following the PBN model, RCMP X is proposed as a conflict management specification, where the value of “X” is the minimum separation value (in time or distance, as appropriate) approved for that flight. For basic encounters between two Digital Flights of different RCMP levels, the separation to be applied would be based on the more conservative of the two RCMP levels (i.e., the larger of the two values of “X” becomes the requirement for both flights). In a future RCMP evolution, peer-to-peer active coordination during an encounter could enable even closer separation. For encounters with VFR or IFR aircraft, separation minima appropriate to those operations would be used (e.g., “well clear” values for VFR encounters, airspace-appropriate values for IFR encounters).

Realizing the vision of Digital Flight, or any other concept of operator-centric, automated conflict management will ultimately require regulator approval. To be successful, any proposal for a new operating mode must establish *explicit* operator accountability to the regulator for automated self-separation, clarify *implicit* operator accountability, and offer a measurable performance construct establishing for what the operator will be held accountable (e.g., RCMP). These components would significantly enhance the viability of a new operating mode in the eyes of the regulator and thus accelerate its authorization. This paper and its companion paper are intended to provide a foundation from which these issues can be explored further towards implementation.

1. Introduction

Aviation is at a transformative moment, with many pursuing technology that would enable a shift towards increasingly autonomous flight [1]. Aerial missions envisioned are diverse and far reaching, including low-altitude Unmanned Aircraft Systems (UAS); air taxies in metropolitan areas; uncrewed regional cargo operations; long-endurance aircraft operating at ultrahigh altitudes; automated search and rescue missions; drones as first responders; robotic infrastructure inspection; and much more. A common thread among these proposed operations is the high degree of reliance on automated flight functions, a necessity because in the future most of these aircraft are envisioned to have no onboard pilot. Furthermore, the economics of some missions are driving fleet operators toward so-called "m:N" (pronounced "m to n") operations in which teams of "m" remote pilots supervise a larger number of "N" simultaneous flights, breaking the paradigm of having at least one pilot dedicated to each aircraft. Flight functions have been increasingly automated over decades leading to the success in automating nearly all phases of aircraft operation, including taxiing, takeoff, cruise, approach, and landing. While not ubiquitously available, steady progress is being made towards certification of these automated capabilities.

Included in these advancements are technologies to aid in operating flights in an environment with other air traffic where conflicts need to be managed, including adjusting flight paths if needed. The umbrella term for this activity is "conflict management" and is the process of limiting, to an acceptable level, the risk of collision between aircraft and hazards, including other traffic. Detect and Avoid (DAA) is a category of conflict management technology intended to replace the pilot's "see and avoid" responsibility [2]. Current DAA systems are designed for close-in tactical separation and collision avoidance, operating with short time horizons and no intent information about the intruder aircraft.

Advancements are also being made in automating strategic conflict management, the most notable being UAS Traffic Management (UTM) [3]. While UTM is initially intended for small drones operating at low altitudes (e.g., uncontrolled airspace like Class G), many envision derivative concepts, collectively referred to as Extensible Traffic Management (xTM), that are intended for larger aircraft operating at higher altitudes in positive control airspace [4][5]. UTM technologies help to ensure that airspace volumes are not contested among participating aircraft, using a service-oriented architecture to identify and communicate potential airspace volume usage conflicts among operators for them to resolve in strategic timeframes, often before departure. The progress being made in both DAA and UTM is establishing solid foundations for creating a fully automated end-to-end conflict management capability for future operators.

Fully automating conflict management requires bridging the gap between highly tactical DAA and strategic UTM capabilities. This augmentation will enable future operators to accrue the efficiency benefits of fully automated hazard separation, a function performed manually today by air traffic controllers for aircraft operating under Instrument Flight Rules (IFR). Under the IFR operating mode, separation provision considers both aircraft state and intent information and operates in timeframes generally beyond current DAA systems. In 2022, NASA published a conceptual framework in which operators could in the future employ automated self-separation in lieu of pilot-provided visual separation under Visual Flight Rules (VFR) or receiving separation services from Air Traffic Control (ATC) under IFR. The framework, referred to as Digital Flight, outlines a potential new operating mode founded on digital information and digital capabilities for automated conflict management [6]. A Digital Flight operating mode could distribute decision-making among participants who will need to have appropriate operational capabilities and comply with yet-to-be established operating practices. The paradigm shift of this digitally enabled operating mode is the leveraging of digital technologies for automated conflict management, including information services, digital connectivity and communications, and automation algorithms which maintain situation awareness (i.e., a model of the operating environment) and are capable of managing conflicts. These capabilities can be on the aircraft, on the ground, or in the cloud.

A key challenge to using technologies for safety-critical purposes in aviation is the need for potential changes in regulations that authorize their use. Once the technology matures and can be proven effective, paradigm-shifting concepts like automated conflict management must overcome a particularly complex challenge: *Operational Approval*. Operational approval of automated conflict management is necessary for it to be an enabler of future automated operations at scale. Since 2023, the NASA Convergent Aeronautics Solutions (CAS) Project has been exploring the desirability, viability, and feasibility of Digitally Enabled Cooperative Operations (DECO) using the

Digital Flight conceptual framework [6]. This research, that builds upon decades of relevant research performed at NASA and elsewhere [7][8][9], identified operational approval of automated conflict management by the regulator[1] as a key viability issue.

This paper and a companion paper [10] together outline a potential conceptual approach to resolving this viability issue of automated conflict management using the established aviation concept of *accountability*. Accountability is the obligation to answer for an action taken (or not taken) by a responsible entity. Applying an appropriate accountability scheme to automated conflict management may provide the necessary clarity on *who* should be accountable for automated conflict management, *to whom* they should be accountable, and *for what* they should be accountable. This clarity is necessary but may not be sufficient for the regulator to be able to authorize operators[2] to self-separate their aircraft from other aircraft using automated capabilities without a human reversionary mode (i.e., not having pilots or controllers serving as backup). Furthermore, this authorization could apply to any operator capable of meeting the accountability requirements, and could apply in any airspace in which the requirements can be met, including integrated airspace alongside traditional IFR and VFR operations. By basing its formulation on the Digital Flight framework, which was designed for such integrated operations, the accountability structure imposed by the regulator should be able to accommodate the integration of increasingly autonomous operations and traditional operations in integrated airspace.

1.1. Purpose

The purpose of this paper is to introduce *Required Conflict Management Performance (RCMP)*, a concept for specifying the performance requirements of automated self-separation. This construct would constitute the basis of *for what* the regulator could hold the operator accountable in their authorization to self-separate. Furthermore, the paper discusses how RCMP could be used to dynamically tailor the separation minima to individual encounters in both cooperating (among RCMP-capable) and non-cooperating (RCMP encountering non-RCMP) conflict management based on quantified risk specific to each encounter.

1.2. Document Scope

The paper qualitatively describes RCMP and its approach to establishing performance requirements for automated conflict management with emphasis on aircraft-to-aircraft separation for which assured performance is paramount. It discusses individual subsystems that comprise the total conflict management system and qualitatively considers how their individual performances may contribute to a net RCMP value for use in authorizing automated self-separation and establishing separation minima. The paper describes how operators with varying levels of RCMP may interact and derive benefit from authorized use of automated self-separation. The paper presents considerations in formulating a risk-based phased implementation of the performance concept that ensures satisfactory safety at each step.

It is beyond the scope of this document to present quantitative modeling and analytics associated with establishing actual quantified system requirements for conflict management performance or the associated separation minima. It is beyond the scope of this document to discuss in detail the performance requirements for strategic conflict management capabilities or collision avoidance.

The performance concept described is intended to be applicable to a future digital operating mode in which the operator is accountable for separation and uses digital information and automation to achieve it. The performance concept would apply to any operator using this digital operating mode, regardless of aircraft size, aerodynamic performance, operating location, or mission, provided that the required performance can be met.

[1] In The United States (U.S.) the main regulator of aviation is the Federal Aviation Administration (FAA). Each country has their own aviation regulatory agency. Generically these regulatory bodies are often referred to a Civil Aviation Authority (CAA).

[2] For the purposes of this paper, the term operator will mean the organizational entity responsibility for maintaining operational control over flight activity. Per 14 CFR § 1.1, Operational control, with respect to a flight, means the exercise of authority over initiating, conducting, or terminating a flight.

1.3. Background

The aviation industry is spawning new missions to be conducted by increasingly autonomous aircraft, often operating in airspace regions not extensively used today but which could experience significant growth. Proponents envision rapid expansion and high operating tempos, calling into question the ability for today's human-centered conflict management processes to meet the future needs of this budding industry while ensuring services to current user types are not compromised.

Two primary processes for aircraft-to-aircraft separation are in use today: the "see and avoid" function of pilots, and the separation services provided by air traffic controllers. These human-centered processes are augmented by various strategic conflict management procedures (traffic flow management) and structures (airspace design) that reduce the likelihood of direct conflicts between aircraft. But reliance on the strategic elements alone does not satisfy the need to use airspace efficiently. The capabilities to *tactically separate* aircraft (under IFR) or visually "see and avoid" (under VFR and IFR) continue to be essential features of safe and efficient aircraft operations. This remains true with the emergence of increasingly autonomous operations, and therefore a viable approach to automating the tactical separation of highly automated aircraft is needed. The companion paper [10] identifies accountability as key to the viability of automating the separation function, and it clarifies the questions of *who* and *to whom* accountability could be established by the regulator to ensure its viability. This paper clarifies the *for what* accountability question.

"See and avoid" is inherent to all VFR operations. It is retained in IFR operations for delegated separation and as an extra protective layer to ATC services, visibility permitting. Some characteristics of "see and avoid" are as follows. The accountability for aircraft separation using "see and avoid" is distributed among the pilots of the aircraft involved, and the separation criterion is the pilots' subjective assessment of remaining "well clear" of each other. "See and avoid" assumes a pilot is onboard the aircraft and does not impose any technology requirement beyond a transparent cockpit windshield (although many technologies do support the pilot in "see and avoid" without supplanting the pilot's role). "See and avoid" requires pilot vigilance, and VFR imposes flight visibility and cloud clearance requirements to enhance the pilot's opportunity to see traffic and have time to maneuver clear of, say, an aircraft emerging from the haze or from around a cloud. The procedure is inherently limited by pilot visibility of traffic (and other hazards). The aviation community accepts that the residual collision risk, after taking "see and avoid" into account, is not quantified.

For IFR operations, ATC provides separation services as one of their primary functions. As the service provider, the air traffic controller is directly accountable for the separation of IFR aircraft in their sector. Whereas "see and avoid" accountability is distributed among the pilots in each encounter, ATC separation accountability is centralized for all IFR aircraft (and VFR aircraft in certain airspace classes) in each sector, including their handoff to neighboring sectors. As such, it requires every aircraft under the controller's separation responsibility to operate under an ATC clearance, and it assumes two-way communications between the controller and the pilots. Whereas "see and avoid" outcomes are subjective ("well clear"), the controller is accountable to objective standards for separation (quantified minimum values, of which a wide variety are applied, depending on the conditions). Technology plays a significant role in ATC separation services (e.g., radar, communications), and yet like "see and avoid," ATC separation is a human-centered process; the controller remains accountable even when the technology fails. ATC separation is inherently limited by surveillance and communication technologies, frequency congestion, and controller workload. Despite the objective separation standards in use, the residual collision risk after accounting for the separation service is also not quantified and again is accepted by the aviation community.

For advanced aircraft operations that may otherwise be fully automated from takeoff to landing, the application of human-centered separation processes in flight presents significant challenges in initial deployments and a barrier to scaled operations. Aircraft without onboard pilots will not be able to "see and avoid" traffic directly, at least not beyond visual line of sight of the remote pilots and visual observers, forcing reliance on sensing solutions. ATC separation services, already at capacity in some areas with conventional traffic, may constrain growth of increasingly autonomous operations if restricted to the existing operating modes and IFR separation standards. Additionally, the assumption of ongoing communications between the controller and the pilots becomes challenged with the industry's vision for m:N operations which have more aircraft flying than the number of remote pilots supervising them. [11] For the nation to derive the full benefits of a future aviation system with increasingly autonomous operations, it may be necessary to enable operators to "self-separate" using digital technologies in a safety-critical role, without reverting to pilot or controller intervention using traditional separation processes.

1.4. Problem Statements

Based on the context provided in the background, the following problem statements are made with regard to automated self-separation and its operational approval by the regulator.

Incompatibility of the current operating modes. Currently, no operating mode authorizes automated self-separation. The accountability structures of the human-centric VFR and IFR operating modes are incompatible with automated self-separation because they would put the human as the backup to the automation and therefore inhibit the potential to expand beyond human limitations. At the same time, increasingly autonomous operations are likely incompatible with relying on the human-centric separation processes of VFR and IFR in the long term, given the built-in human roles and the need for a new accountability structure for autonomous operations [10].

No current basis for the regulator to approve automated self-separation. Concepts like Digital Flight [6] envision an additional operating mode that employs automated self-separation and which may be a more appropriate choice for aircraft capable of increasingly automated flight. However, as a significant paradigm shift in conflict management, its viability hinges on how the regulator will be willing to authorize its use. The application of *accountability*, an accepted construct in aviation, may address this viability question. Understanding the answers to the following critical accountability questions is necessary for effective regulator oversight: *who* will be accountable for separation; *to whom* they will be accountable (and others accountable to them); and *for what* they will be held accountable. The companion paper [10] introduces these basic questions of accountability and addresses the first two questions in detail by analyzing an operator-centric scheme similar to VFR, but for *automated* self-separation. A principal conclusion of the companion paper [10] is that establishing a formal new operating mode, akin to VFR in its lack of reliance on centralized ATC separation services, but that relies on digital information exchange and automated processes for separation, may be a viable mechanism for the regulator to hold the operator explicitly accountable. However, the regulator would need to accept this premise, and therefore a sound argument must be presented to them by the operator community in order for such an operating mode to be established.

No quantifiable, generalizable construct for automated self-separation performance. In this operator-centric scheme, the operator would be explicitly accountable to the regulator for automated self-separation [10]; more specifically they would be accountable for the *outcome* – the reliable achievement of aircraft-to-aircraft separation. However, any automated function requires a *measurable* standard of performance. This holds for several stakeholders: for the system developer who must produce a system design capable of the expected performance, for the user who needs data to monitor performance and answer for the outcome, and in aviation, for the regulator who requires a basis on which to hold the user (the aircraft operator, in the Digital Flight concept) of the automated function accountable. The problem herein is to define a formal, measurable (i.e., quantifiable) construct on which to base accountability for the outcome of automated self-separation. Ideally, the construct would be standardizable across all potential operators, and flexible to accommodate the rapid pace of technology advancement. It would also ideally support variable performance *levels* which in turn would accommodate a diversity of use cases that may not all require – or be capable of achieving – the same level of performance. The problem this paper and its companion paper [10] are addressing is to explore a more generalized approach to authorizing automated self-separation without placing the human in a reversionary role.

No basis for establishing or dynamically adapting the separation minima. An additional problem is the quantification of *for what* the operator is accountable. The safety goal of conflict management in general – and separation provision in particular – is to prevent collisions between aircraft. The practical, operational application of a conflict management performance construct is to size the allowable minimum separation value between aircraft to meet a quantified residual collision risk, commensurate with the system's performance level. To answer the *for what* question of accountability, then, the operator would therefore be accountable *for their adherence to this minimum permitted separation value* at a stated maximum failure rate (e.g., 10^{-x} loss of separation per flight hour). This allowed separation failure rate would be set based on analytical modeling in relation to a probability of near midair collision (NMAC), which leads to another challenge: how to establish an acceptable NMAC rate (e.g., 10^{-y} NMAC per flight hour), i.e., a target level of safety (TLS). Community deliberation would need to assess whether to use an absolute value TLS or a risk ratio relative to the NMAC rate of current human-centered conflict management operations, the latter following the historical precedents used in the developments of DAA standards and the Traffic Alert and Collision Avoidance System (TCAS).

If the operator and regulator communities accept the premise of this approach of quantified, performance-based accountability, the next step is to develop a construct that connects the conflict management system's performance to the minimum separation value, and to establish the rules by which this performance construct can be used operationally. If done well, this performance construct could enable the safe use of dynamic, encounter-defined separation values in a range of operating conditions, thereby unlocking significant operational benefits to the operator community and the public it serves.

2. A New Mode of Automated Self-Separation

From this point forward, the discussion will be in the context of an envisioned, future operating mode designed specifically to employ automated self-separation (rather than "see and avoid" or ATC separation services) and that would be broadly available to all operators that can meet an also newly envisioned performance requirement, which this paper introduces as RCMP. This section discusses the following: (2.1) what is meant by automated self-separation, (2.2) two motivations for establishing a performance basis for the new operating mode, (2.3) community progress on automating conflict management in the strategic and tactical/collision layers, and (2.4) the motivation for filling the unaddressed gap in automating the intermediate layer of separation provision. With these topics as context, the following sections (3, 4, 5) will then discuss the concept of RCMP in more detail.

2.1. Automated Self-Separation

The meaning of automated self-separation can be understood within the context of conflict management overall, as defined by the Global Air Traffic Management (ATM) Operational Concept of the International Civil Aviation Organization (ICAO), which states: "*The function of conflict management will be to limit, to an acceptable level, the risk of collision between aircraft and hazards*." [12] It further describes conflict management in three layers: *strategic conflict management*, *separation provision*, and *collision avoidance*. Figure 1 illustrates their basic relationship.

Figure 1. Simplified model of ICAO conflict management layers.

Regarding each layer, the ICAO concept states the following:

- *"Strategic conflict management through airspace organization and management, demand and capacity balancing, and traffic synchronization ... will reduce the need for separation provision to a designated level."*
- *"Separation provision is the tactical process of keeping aircraft away from hazards by at least the appropriate separation minima. ... Separation provision will only be used when strategic conflict management…cannot be used efficiently. ... The predetermined separator will be the airspace user, unless safety or ATM system design requires a separation provision service."*
- *"Collision avoidance must activate when the separation mode has been compromised… will be part of ATM safety management but will not be included in determining the calculated level of safety required for separation provision."[12]*

Several relevant insights can be gleaned about the separation layer from these statements. First, the role of strategic conflict management is not to eliminate the need for separation provision, but to ensure its use is maintained at an appropriate ("designated") level. This suggests that separation provision's performance must be defined and maintained to a level that enables it to be effective (i.e., perform well). It also makes clear that separation provision's performance level cannot take quantitative credit for the actions of any collision avoidance systems.

Second, the role of separation provision (the middle layer) is to increase efficient airspace utilization. This suggests that while safety (i.e., the risk of collision relative to an acceptable level) could be maintained without any separation provision, airspace efficiency may suffer as user demand increases. Strategic conflict management is therefore incomplete without the separation provision layer from the perspective of operational efficiency. This statement is applicable regardless of whether conflict management is human-centric, automated, or some combination.

Third, the airspace user is preferred as the "predetermined" separator, i.e., the agent responsible by default for performing the separation function. The term *self-separation* aligns with this designation and is used in this paper to mean "the user provides their own separation." To hold this role, the airspace user (or "operator" in this paper) must adhere to a safety standard and maintain compatibility with the ATM system. The ATM compatibility requirement implies the need for the airspace user to have specific capabilities and to employ cooperative practices that align with how the ATM system operates. The Digital Flight concept [6] includes such elements. The safety requirement implies the need for measurable safety performance and therefore the need for a *performance basis for self-separation*, the topic of this paper.

ICAO further defines separation as an iterative process, applied to the conflict horizon (the extent to which hazards along the future trajectory of an aircraft are considered for separation provision). At a high level, the iterative process consists of the following:

a) the detection of conflict, which is based on the current position of the aircraft involved and their predicted trajectories in relation to known hazards;

b) the formulation of a solution, including selection of the separation modes, to maintain separation of aircraft from all known hazards within the appropriate conflict horizon;

c) the implementation of the solution by communicating the solution and initiating any required trajectory modification; and

d) *the monitoring of the execution of the solution to ensure that the hazards are avoided by the appropriate separation minima. [12]*

In current operations, separation is a human-centered function performed by air traffic controllers for IFR aircraft. When considering *automated self-separation* in this paper, the following provides clarity as to what automated self-separation means. In automated self-separation:

- **The operator is the predetermined separator. "**Self" implies an operator-centric mode of separation provision. The operator (e.g., air carrier) is responsible for separation of their aircraft and chiefly accountable for the outcomes. The companion paper [10] discusses the distinction between responsibility and accountability in detail. The operator may employ third-party providers for one or more subfunctions to assist the operator in meeting their responsibility, and reference [10] also discusses how this impacts accountability.

- **The separation process is fully automated, including direct linkage to flight control systems.** In automated self-separation, the automated process must be self-sufficient with no dependence on human input. No human should have the responsibility for detecting conflicts, formulating solutions, communicating the solution, executing the solution, or monitoring conformance to the separation minima. In some case, a human *may* be involved to some degree, for example in selecting one solution for automated execution from a list or envelope of acceptable solutions (e.g., a range of conflict-free headings), all of which were predetermined acceptable by the automation. However, the performance impacts of any human involvement need to be considered in the system design and performance requirements, for instance allowing for the impact resulting from execution delay caused by the human.
- **The automated system is authorized and responsible for meeting the separation requirement.** No human pilot or controller serves in a reversionary role, expected to intervene or "save the day." It does not prevent a pilot or controller from taking what they deem as safety-critical action consistent with their responsibilities, but the automated system is not designed with this expectation. This design consideration could have significant implications to graceful degradation and contingency management.
- **The information flowing to and from the separation automation system is also automated.** The automation is not reliant on human inputs regarding the operating environment, the traffic aircraft locations, or their intent. Nor is it dependent on a human to communicate solutions to a flight system or other external entities. All required information is automatically delivered and/or updated within the separation automation system, and all outputs are delivered automatically to the receiving system or entity. Therefore, from a Systems Engineering perspective, the conflict management system boundary encompasses the input, output, and execution systems in addition to the separation automation system itself.
- **The separation process is based on aircraft states and operational intent.** Automated self-separation incorporates the exchange and processing of trajectory-based intent of ownship and traffic – where available – in the detection, resolution, and prevention of conflicts. While the processing of only aircraft states (i.e., positions and velocity vectors) for separation may be adequate for separation's safety role, it may be inadequate to meet its role in increasing efficient airspace utilization. However, varying degrees of required intent sharing may be considered for specific operating environments, based on the characteristics of those environments (e.g., traffic density, operational tempo).

Given these clarifications, automated self-separation is indeed a natural fit for uncrewed aircraft that are already designed to execute a planned flight in a fully automated fashion, from takeoff to landing. The automated self-separation function simply serves as a *dynamic path planner* that automatically revises the aircraft's flight path based on dynamically identified hazards. See reference [13] for a concept description of a dynamic path planning automation system appropriate for this role. In the case of a traditionally piloted aircraft, automation would instruct the pilot on an appropriate course of action (or an envelope of acceptable actions) and the pilot should execute it, similar to how a pilot must follow ATC instructions, or a TCAS Resolution Advisory unless they have contrary information that the automation does not, e.g., a visual siting of the hazard.

2.2. Motivations for a Performance Basis for Automated Self-Separation

Two motivations are described for establishing a performance basis for automated self-separation. The first is about *operational approval*: to provide the conditions under which the regulator could decide to authorize its use. The second is about *operational benefits*: to provide a practical means by which operational benefits unique to automated self-separation could be derived.

RCMP Motivation 1: Operational Approval

To approve operators for fully automated self-separation (without a human reversionary mode), the regulator must have some basis on which to establish the safety of the operation. The companion paper [10] discusses in detail the application of accountability as a candidate underlying construct for the regulator to base an operational approval determination. Establishing new "flight rules" specifically for automated self-separation would be one explicit means of formalizing the operator's accountability to the regulator (answering the *who* and *to whom* questions of accountability). Establishing a performance requirement would be a means of formalizing the *for what* question.

The concept of Digital Flight [6] is an example of what a new operating mode (i.e., a possible new addition to the VFR and IFR operating modes) specifically designed for automated self-separation might look like. By formalizing it potentially through new flight rules, the Digital Flight operator would be formally accountable to the regulator for maintaining appropriate separation from all other traffic. More specifically, because of the dependence on technology for separation, the new flight rules or other regulation should clearly define what constitutes adequate separation performance, i.e., what "appropriate separation" means. A regulator-approved performance basis, such as through RCMP, would enable quantitatively defining the acceptable outcome while providing flexibility to the operator in how the conflict management system may be designed to meet this acceptable outcome.

With a performance construct like RCMP, Digital Flight operators would be accountable to the regulator for compliance with objective and quantifiable separation minima by ensuring the required performance of the automated conflict management system. The performance-based outcome has the potential to be more reliably achieved than VFR's pilot accountability for the "see and avoid" procedure, resulting in greater safety. Reliable performance would also enable operational approval for both visual and instrument meteorological conditions (VMC and IMC), provided that visibility or other weather conditions do not impact the automation system's performance (e.g., electro-optical sensors in haze or into the sun, or radar sensors in heavy rain). These limitations only impact the ability to separate from aircraft with non-cooperative surveillance (i.e., those not broadcasting their position), and these aircraft are not permitted in IMC.

As will be described later in the paper, the RCMP performance basis would account for separation from Digital Flights and non-Digital Flights alike, thereby providing the regulator a basis on which to authorize Digital Flight in *integrated* airspace with VFR and IFR aircraft that use the traditional human-centric conflict management methods. Approval to access integrated airspace without segregation is generally considered a significant positive attribute of airspace operating concepts.

RCMP Motivation 2: Operational Benefits

A second motivation for a performance basis for automated self-separation is to provide practical value to the operator. Two examples of practical value are:

1. to enable flights to safely proceed in airspace otherwise not readily accessible under the current operating modes (e.g., accessing IMC airspace under VFR, accessing low-altitude urban environments under IFR), and
2. to enable flights to safely operate in closer proximity to traffic or in greater densities than the current operating modes permit, resulting in increased operating efficiency and airspace capacity.

Both forms of value can have significantly positive economic implications for the operator and may even be the determining factors of new-market viability. For instance, new markets that depend on uncrewed aircraft that must conform to the legacy requirements of human-centered conflict management may have significantly restricted growth potential based on the need for more pilots and higher traffic density. Also, a requirement to use IFR-sized separation standards may significantly reduce the number of increasingly autonomous operations in a market region to the point of being incompatible with the operational tempo required for fleet-level mission achievement and profitability.

Efficient Operations

While safety is paramount, a performance basis that only produces an acceptable safety result is insufficient. It must also provide an economic benefit, a point that aligns well with the earlier observation that the separation provision layer of conflict management is about *efficiency* as much as safety. The practical means of achieving efficiency is to reduce separation between aircraft without compromising safety. With reduced separation minima, operators could fly their aircraft closer to other aircraft and therefore closer to trajectories that optimize meeting business needs and market demands. This would increase flight efficiency, reduce energy consumption and environmental impact, and reduce actionable conflicts requiring a maneuver. Such a performance basis would also allow more aircraft to occupy an airspace region, increased airspace throughput, and provide more mission flexibility in the airspace because strategic conflict management could be made less conservative.

Performance Based on Need

The inherent benefit of a performance basis is that it can allow for more than one level of acceptable performance. Multiple performance levels are useful in that they lower the barrier-to-entry for operators that do not initially require high performance for their use case. If automated self-separation performance can be quantifiably tied to an acceptable collision risk, then multiple performance levels can be defined in either of two ways:

1. Multiple performance levels can be defined for a given fixed collision risk. In other words, the same collision risk can be achieved by a lower-performing system with a larger separation requirement, as by a higher-performing system with a smaller separation requirement.
2. The acceptable level of collision risk itself can be adjusted to the needs of various use cases, thereby resulting in multiple performance levels. For instance, a use case that is more collision-risk tolerant (e.g., multiple small surveillance drones over an open field, where no human lives are at stake) can accommodate a lower-performing system than can a use case with very little collision-risk tolerance (e.g., fleets of passenger-carrying air taxis in a metropolitan airspace).

Automated self-separation performance can therefore be classified by different levels of performance, each associated with its own separation minima. The minimum separation that the operator determines they need for their operation dictates both the automated self-separation performance level they need to meet for the regulator to approve and the particular conflict management system they employ.

Tailored Separation Minima

Tailoring of separation minima by need could be applied on an encounter-by-encounter basis, meaning a singular minimum separation value need not be applied unilaterally across a region of airspace. One aircraft encountering multiple aircraft may employ different separation minima for each aircraft they encounter depending on each aircraft pair's performance levels. This makes intuitive sense, because a drone encountering another drone should be permitted smaller separation between them than that same drone simultaneously encountering an air taxi operating under Digital Flight, or encountering a General Aviation (GA) aircraft operating under VFR.

The opportunity to unlock user benefits of higher performance (flight efficiency, density, tempo, etc.) exists because automation technologies can rapidly process large amounts of digital information. This also eliminates the lag and variability in human decision-making and response time and the workload barriers associated with human-centered conflict management. With fully automated self-separation, separation performance has the potential to be more methodically established and managed to specific quantitative levels, allowing separation minima to be set according to the need, and allowing operators to derive practical value from automated self-separation.

2.3. Community Foundations in Automated Conflict Management

Solid foundations in automated conflict management are today already being established in the community with significant progress in two areas: UTM and DAA. These advancements are occurring primarily in the outer two layers of the three-layer ICAO conflict management structure (Figure 1). UTM is trailblazing the automation of strategic conflict management (the first ICAO layer). In the U.S., the application is specifically for small drones operating at low altitudes that are largely devoid of non-participating aircraft. [14] Meanwhile, DAA efforts are focused on the automation of highly tactical separation and collision avoidance (the third ICAO layer, also touching the second layer). Both foundations are appropriately conservative, taking an evolutionary approach to ensuring safety while technology requirements mature, standards are written, nascent markets emerge, and operational experience is gained. They are essentially working from either end of the conflict management spectrum toward the middle.

UAS Traffic Management (UTM)

UTM [3], a concept put forth originally by NASA [15], takes a largely automation-centric approach to strategic conflict management to help ensure that airspace volumes are not contested among participating aircraft. It uses a federated, service-oriented architecture to identify and communicate potential airspace volume conflicts to operators for them to resolve in strategic timeframes, often before departure. UTM strategic deconfliction services are described as minimizing the likelihood of airborne conflicts between drones [16]. As currently envisioned by the FAA [3] and its initial operational implementation [14], UTM is only a strategic conflict management capability. ICAO, in their

UTM Framework, identifies a number of envisioned services for UTM [17] that include separation service capabilities. While research has explored expanded UTM services [16], as it stands now in the U.S., UTM remains a largely strategic deconfliction capability and serves as a starting point for fully automated conflict management.

Detect and Avoid (DAA)

Independently, DAA also serves as a foundation for a future fully automated conflict management capability. Devised as a technology-based and potentially automated means for uncrewed aircraft to meet the "see and avoid" requirement [2], DAA is intended for short time horizons and highly tactical encounters. Its conception and initial testing preceded UTM, but they are in parallel development and undergoing initial operational evaluations. The FAA has already issued DAA technical standard orders (TSO) [18][19], a critical step towards commercial DAA systems.

DAA is intended for use in integrated airspace. To be useable at altitudes where VFR aircraft routinely fly (e.g., Class G, Class E), DAA must function with intruder aircraft that participate in cooperative surveillance as well as aircraft that are non-cooperative from a surveillance perspective (i.e., not equipped with at least a transponder or Automatic Dependent Surveillance – Broadcast, ADS-B). At this time, DAA makes use of current position, aircraft track data, and if available aircraft velocity (e.g., from ADS-B) to identify potential conflicts with relatively short time horizons. It provides vector-like guidance to the DAA-equipped aircraft (e.g., turn to a heading) rather than complete trajectory-based rerouting.

DAA as currently envisioned does not have any operational intent information available to inform identification of conflicts or potential avoidance maneuvers. During this vector-like maneuver, the trajectory intent of the DAA-equipped aircraft itself would be unknown and unavailable for sharing since the subsequent maneuvering has not yet been determined. While intent sharing is not necessarily a concern for DAA's safety objective, future operating concepts have the additional objective of producing efficient operations as well as safety and therefore would benefit from real-time operational intent sharing to account for more complex flight paths and aircraft performance characteristics. Nevertheless, DAA has a foundational role in trailblazing automated conflict management from the collision avoidance and very short time horizon (i.e., highly tactical) separation perspectives.

2.4. Bridging the Foundational Gap

Automated capabilities for strategic conflict management (e.g., UTM) and DAA form essential foundations of a future system architecture for automated conflict management, and yet a significant gap remains. To fully complete this architecture, the example of ATC separation services for IFR aircraft can serve as a model. In separating aircraft from aircraft, controllers typically consider both the current state *and* the upcoming intent (i.e., planned trajectory) of each aircraft under their control. They consider both the aircraft's performance *and* its mission (e.g., destination). They consider both safety *and* efficiency in their decision-making. When redirecting aircraft for separation, they typically have in mind not just an initial maneuver but a *trajectory plan* for each aircraft beyond the initial instruction. When practicable, they will communicate that plan to the pilot either as a clearance revision or an "expect" advisory. In other words, controllers typically use a *strategic approach to tactically separating aircraft*, even when issuing vectors.

ATC separation services can serve as an effective model for automating self-separation in the conflict management architecture: a set of automated capabilities that employ intent and performance information to detect conflicts and generate efficient trajectory solutions that comply with mission objectives, airspace constraints, and situation-appropriate separation minima. Complementing the functions of strategic conflict management and DAA, this trajectory-based approach to automated self-separation has the added benefits of improved airspace and flight efficiency and allowing participating flights to remain strategically predictable when maneuvering for conflicts.

Figure 2 illustrates the model of fully automated conflict management, with automated self-separation completing the structure founded upon UTM and DAA.

Performance Construct

Moving decision-making processes from human-based to automation-based systems requires quantifying system performance requirements. In automated conflict management, system performance is perhaps of greatest importance in the separation layer. Previous sections of this paper have discussed the value of establishing a formal performance construct for automated self-separation as a potential means for operational approval and as a basis for the operator to derive operational benefits. The paper coins the term *Required Conflict Management Performance (RCMP)* to denote this concept of a performance construct for automated self-separation.

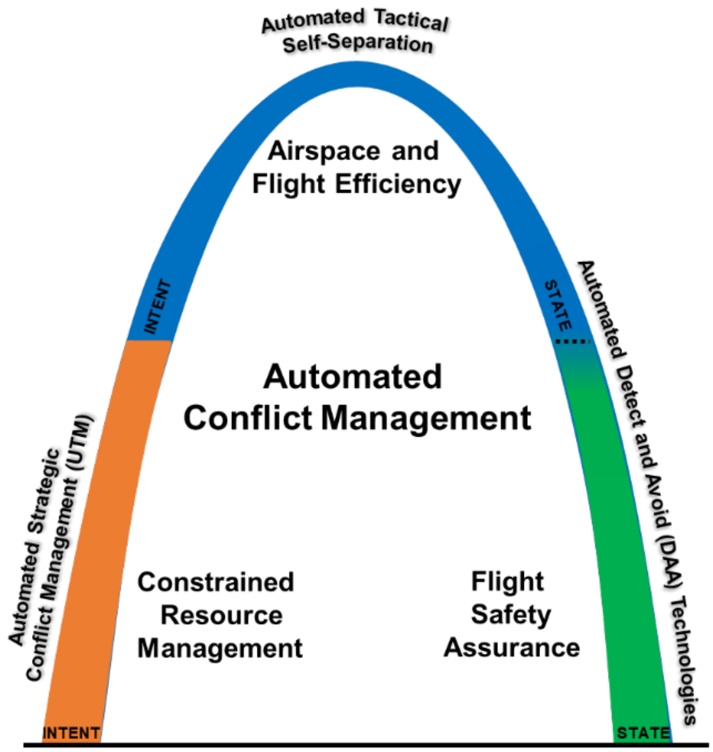

Figure 2. Automated self-separation built on the solid foundations of UTM and DAA would complete the full structure of automated conflict management. By incorporating both intent and state information, airspace and flight efficiency are added to the achieved attributes.

Naming the Performance Construct

The name choice of RCMP reflects two points. First, it leverages an accepted industry construct of *Required [Function] Performance*, where historically, the functions of Communication (C), Navigation (N), and Surveillance (S) have established the respective precedents of RCP, RNP, and RSP. Leveraging this construct for Conflict Management (CM) should not only facilitate industry and regulator understanding of RCMP due to its familiarity but also enable incorporation of these precedents into the RCMP formulation itself and its practical application.

Second, the name choice purposefully scopes the performance construct at the broader level of overall conflict management, even though the initial focus of its formulation will be the separation layer where performance is paramount. The rationale is that the multiple layers work together, and their individual performance is not as relevant as the outcome of their combined performance. If its naming were to suggest a focus only on the separation layer, it would leave unanswered the potential contributions of strategic conflict management to overall performance.

That said, RCMP's conceptual formulation will indeed start with capabilities at the separation layer, as this layer is closest to the collision risk being managed. Recall from Section 2.1 that ICAO has stated that collision avoidance will not be included in determining the calculated level of safety required for separation provision. With separation layer performance as the initial foundation, the additional contributions of any capabilities from the strategic conflict management layer to sustain separation performance can then be considered for formal inclusion in RCMP, as needed.

3. Required Conflict Management Performance

3.1. Accountability Mechanism

This paper introduces the concept of *Required Conflict Management Performance* that is envisioned as an objective accountability mechanism, establishing clarity on *for what* an operator would be held accountable, if approved by the regulator to employ automation for self-provided conflict management.

Required Conflict Management Performance (RCMP)*:*
A structured approach for authorizing operators to employ automated conflict management as the sole means for separation from traffic and hazards, and for specifying the minimum authorized separation based on their conflict management system performance.

As previously discussed, establishing clear accountability in conflict management is considered essential to the viability of any new airspace concept for future operations. The companion paper [10] articulates the conflict management accountability structure envisioned for the concept of Digital Flight [6]. Digital Flight is an envisioned future operating mode in which the operator assumes responsibility for separation (i.e., self-separation), employs automation to perform the separation function (i.e., automated self-separation), and operates according to established cooperative practices (i.e., digitally enabled cooperative operations). To clarify accountability in Digital Flight, reference [10] identifies the operator as the top-level, principal accountable party for their own conflict management, and it discusses the accountability relationships to the regulator and other associated parties (e.g., other operators, the air navigation service provider (ANSP), commercial service providers). These clarifications address the *who* is accountable and *to whom* are they accountable (and who is accountable to them) questions of automated conflict management accountability.

Addressing the *for what* question of accountability, reference [10] identifies conflict management performance as an appropriate metric of operator accountability and a further enhancement of the viability of Digital Flight. RCMP is offered in this paper as a concept for articulating the performance requirement in a manner on which the regulator could base their operational approval determination and which allows higher performance to drive reduced separation minima and the resulting greater efficiencies and operational benefits. Section 2.2 discussed these two motivations of regulator approval and operational value in greater detail. Highlighted here are three positive implications of establishing RCMP.

Positive Implications of RCMP

1. **RCMP would methodically and quantitatively link conflict management system performance to an approved safety outcome.** Any automation system with a safety-critical intended function must be designed for a safety outcome that is quantitatively specified in accordance with the risk tolerance of the use case. Whether the approved safety outcome is in absolute terms (e.g., NMAC per flight hour) or relative terms (e.g., a risk ratio relative to an already-accepted process), the system will be designed with the appropriate level of sophistication and failure mitigations needed to meet this safety target. In principle, a higher-performing system will satisfy a given safety target with smaller aircraft separations than a lower-performing system, which may require larger aircraft separations. Therefore the assigned separation minima would serve as a performance proxy by which operations could be approved and operational value could be derived.

2. **RCMP could enable a risk-based phased implementation.** With separation minima serving as a performance proxy, initial operations approved by the regulator could begin with conservatively larger separation minima or buffers. Operational safety monitoring by the operator's Safety Management Systems could verify conformance to the minima under diverse operational conditions. These conservative separation minima and operational safety monitoring could allow those operators who have invested in separation automation to derive early-adopter benefits in low density operations as the industry begins to scale. It also preempts a reactionary approach to traffic volumes exceeding the levels that can be accommodated by the

existing IFR, VFR, or segregated airspace approaches. These initial ongoing operations, in comparison to limited-duration trials, would directly benefit the early-adopter operator as they conduct their missions in their preferred airspace, and it would allow regulator confidence in automated self-separation to build gradually through risk-managed gathering of operational evidence that performance targets are being met in real-world operations. As evidence accrues, higher performance levels (i.e., reduced separations) can be authorized, as phased implementation continues.

3. **RCMP would provide regulators with a common, unified approval structure for diverse operations.** Operators constitute a highly diverse and expansive community with different mission profiles, aircraft capabilities, and even risk tolerance. Based on recent history, the operator community will likely continue to diversify and expand. A common performance basis would support that expansion, allowing those operators opting for automated self-separation over conventional VFR or IFR conflict management to select the appropriate performance level (i.e., separation minima) for their mission and aircraft capabilities, while enabling the regulator to maintain a singular basis for operational approval. This approach could significantly reduce the complexity for the regulator in accommodating new operating concepts that all involve operator accountability and automated conflict management.

3.2. Conflict Management Capabilities

To facilitate a performance construct that ties conflict management system capabilities to the separation outcome, it is helpful to start with a conceptual foundation for these conflict management capabilities. The Digital Flight concept [6] provides a well-suited, detailed framework for this purpose.

***Digital Flight:** A future operating mode for integrated airspace in which flight operations are conducted by reference to digital information, with the operator ensuring flight-path safety through cooperative practices and automated self-separation enabled by connected digital technologies and automated information exchange.*

The Digital Flight concept is framed in the context of four Essential Elements of digitally enabled cooperative operations:

- **Information Services and Connectivity** (i.e., operators getting information): The processes and infrastructure the operator uses to gather current and forecast information about the dynamic operating environment in which their aircraft is flying.
- **Shared Traffic & Intent Awareness** (i.e., operators giving information): The processes and infrastructure the operator uses to share and receive information about aircraft locations, strategic and tactical intentions, and related information (e.g., performance level, intent conformance status).
- **Cooperative Practices** (i.e., operators behaving as expected): Community-agreed, regulator-approved behaviors embedded in software where possible and akin to a "social contract" among participating operators and the ANSP. Reference [6] proposes 12 categories of cooperative practices.
- **Automated Conflict Management Capabilities** (i.e., operators automating the conflict management process): A set of specific automated capabilities that produce the desired outcomes and cooperative practices associated with distributed, automated conflict management.

Within this fourth Essential Element, the Digital Flight concept proposes six Principal Capabilities (PC) for automated conflict management that an operator would apply to meet their conflict management obligations under this future operating mode. Three PCs align with separation provision (ICAO's second layer), and three additional

PCs align with strategic conflict management (ICAO's first layer). All six capabilities are exercised while the aircraft is in flight.

Tactical (Separation) Layer Capabilities

- **PC1 Operator Self-Separation** (i.e., performing the separator role via automation):
  This capability enables the operator (through an automated process) to analyze digital information on the operating environment, the ownship, and traffic aircraft to predict future trajectories; to detect and resolve conflicts; and to prevent new conflicts when maneuvering or replanning trajectories for any reason. Any maneuvering or replanning is done in compliance with applicable separation minima and in conformance with known constraints (airspace, aircraft performance, other hazards, and mission requirements). The capability is self-sufficient in that the operator assumes the full separator role in an encounter, such that the aircraft they are separating from need not be Digital Flights with self-separation capability.

- **PC2 Shared Separation** (i.e., sharing the separator role through implicit cooperation):
  Additive to PC1, this capability enables the operator to *cooperatively* self-separate from other Digital Flights that also have self-separation capability. Communication functions allow the broadcast and receipt of additional information regarding intent and other related content to support automated, distributed decision-making for separation, for example, applying right-of-way rules to determine the separator role in real time. Broadcast rather than peer-to-peer communications are considered sufficient for achieving the level of cooperation envisioned for this capability.

- **PC3 Pairwise Coordinated Separation** (i.e., tailoring separation minima through explicit coordination):
  Additive to PC2, this optional capability enables the operator to *coordinate explicitly* with an encountered aircraft to optimize the separation minima and dynamically coordinate maneuvers if necessary to maintain separation. Peer-to-peer communications would be needed for sharing conflict-specific information such as alerts, separator roles, separation values, and maneuver plans.

Strategic Layer Capabilities

- **PC4 Constrained Resource Collaboration** (i.e., operating cooperatively with a resource manager):
  This capability enables the operator to collaborate with a resource manager (e.g., ANSP, third party resource scheduler) to alleviate conflicts at or in the vicinity of managed, constrained resources such as merge points, arrival fixes, and runways. The capability assumes the participation of an active resource manager and cooperation with the resource manager's strategic plan for balancing demand and capacity of the constrained resource or otherwise meeting constraints the resource manager assigns. The capability enables the operator to share in advance their intended use of the resource (strategic intent), receive their place in the schedule or sequence plan, and achieve precision timing at the resource in either absolute (e.g., time of arrival) or relative (e.g., interval management) terms while maintaining separation (PC1, 2, 3) from all traffic as they proceed to the constrained resource.

- **PC5 Self-Organization** (i.e., operating efficiently without a resource manager):
  This capability enables the operator to self-organize their intended flight path relative to other traffic to the degree necessary to preserve flight efficiency and to reduce actionable conflicts to a level manageable by the self-separation capabilities (PC1, 2, 3). The capability does not require the participation of a resource or airspace manager in the organization process.

- **PC6 Self-Limiting Density/Complexity** (i.e., keeping the separation layer stable and manageable):
  This capability enables the operator to plan their entry into and through a congested or otherwise complex region to ensure adequate ability to self-separate (PC1, 2, 3) is maintained. The capability preserves adequate alerting time and flight path flexibility for resolving future potential conflicts as needed. The

capability also enables proactive decision-making to circumnavigate the highest density/complexity if needed to ensure adequate flexibility.

The Digital Flight concept did not propose any specific new capabilities associated with collision avoidance. As ICAO indicated, collision avoidance capabilities are not to be used in safety calculations and are therefore not part of the RCMP methodology explored in this paper.

3.3. RCMP Construction

Performance-Based Navigation (PBN) serves as a useful model for interpreting and basing the concept of RCMP. Its usefulness is the precedent it sets for translating operator capabilities into a safety-critical performance specification. As a performance basis, PBN is used by regulators for granting *operational approval* and by operators for deriving *operational value* from higher performance. These uses of PBN align with the two motivations for RCMP described in Section 2.2.

ICAO describes PBN as follows:

> "*PBN defines performance requirements for aircraft navigating on an [Air Traffic Service] route, on a terminal or on an approach procedure. Those routes and procedures are composed of waypoints which are expressed by [World Geodetic System 1984] coordinates rather than fixes expressed by radial/bearing and distance from ground navigation aids and permit the flexibility of point-to-point operations.*" [20]

ICAO further describes the benefits of PBN:

> "*Through the application of Area Navigation (RNAV) and Required Navigation Performance (RNP) specifications, altogether components of PBN, PBN can provide the means for flexible routes and terminal procedures, reduce aviation congestion, conserve fuel, protect the environment, reduce the impact of aircraft noise, improve safety and accessibility to challenging airports, and increase airspace capacity.*" [20]

The PBN capabilities of RNAV and RNP can be summarized as follows:

- RNAV = the capability to navigate along any path at a given precision; and
- RNP = RNAV plus additional capabilities for onboard monitoring and alerting of accuracy, integrity, continuity, and availability of the systems supporting RNP operations.

RCMP could be seen as a logical continuation of performance-based navigation into the domain of performance-based conflict management. An extension of the PBN model to conflict management could follow, thus:

- RCMP = RNP plus an appropriate set of automated conflict management capabilities:
  - PC1 = *Operator Self-Separation*, performing the separator role via automation;
  - PC2 = *Shared Separation*, sharing the separator role through implicit cooperation;
  - PC3 = *Pairwise Coordinated Separation*, tailoring separation minima through explicit coordination;
  - PC4 = *Constrained Resource Collaboration*, operating cooperatively with a resource manager;
  - PC5 = *Self-Organization*, operating efficiently without a resource manager; and
  - PC6 = *Self-Limiting Density/Complexity*, keeping the separation layer stable and manageable.

As stated earlier, in this initial stage of conceptual development, the scope of RCMP construction is focused primarily on the *tactical* separation capabilities (PC1, 2, 3), as they are closest to the collision risk being managed and their collective performance is more readily quantified. Once automated self-separation performance is established, the merits of including in RCMP construction the contributions of the in-flight *strategic* capabilities (PC4, 5, 6) to maintain automated self-separation at the intended level of performance can be considered.

3.4. System Contributions to RCMP

Establishing the performance of automated self-separation requires analyzing the technical systems involved. No single technical system unilaterally implements automated self-separation; multiple technical systems each contribute critical functionality. The following list identifies the types of technical systems involved and summarizes their role in automated self-separation:

- **Information & Connectivity Systems**: For maintaining a current digital representation of the operating environment (both current and forecasted states).
- **Surveillance Systems**: For locating and tracking cooperative and non-cooperative traffic, providing their current positions and longitudinal/lateral/vertical velocity vectors.
- **Communication Systems**: For sharing information (e.g., intent, conformance status, RCMP level) and for coordinating alerts and actions between Digital Flights.
- **Separation Automation Systems**: For hosting the algorithms that predict trajectories, detect conflicts, compute separated paths, update intent for sharing, and monitor conformance to shared intent and cooperative practices (for both ownship and traffic).
- **Command & Control (C2) Link Systems**: For remotely instructing uncrewed aircraft and communicating the selected separated path to the navigation systems.
- **Navigation Systems**: For navigating to a separated path with intended performance.

The technical systems listed above would have primary roles in collectively performing the self-separation function. The performance of each of these primary systems contributes directly to RCMP and as will be discussed, the determination of the applicable separation minima. Not listed here but also important are additional systems that could monitor the status and performance of these primary systems and monitor operator compliance to the RCMP-based separation minima. Discussed further in Section 5.7, these monitoring services, functions, and capabilities of the In-Time Safety Management System (IASMS) could help anticipate any system degradations that might require preemptive mitigation (e.g., increasing separation minima) to maintain collision risk at the intended level.

The number of primary technical systems involved in RCMP exceed the number involved in PBN, foretelling the greater complexity of constructing RCMP. For example, RNP performance depends on a Global Navigation Satellite System (GNSS) receiver to locate the aircraft, and onboard guidance, navigation, and control systems (shortened here to navigation systems) to navigate with precision along a given lateral path. For RNP, the path to fly is predetermined and fixed in space, and thus those systems are adequate for achieving RNP performance for that flight. By contrast in RCMP, the flight path is dynamic and an output of the conflict management system itself. The term *separated path* used in this paper indicates that the separation automation system has determined that, if flown accurately, it will meet the separation minima associated with the RCMP level and the analyzed encounters. RNP (flying an RNAV path accurately, with monitoring) is therefore an integral part of RCMP (determining and flying the separated path accurately, with monitoring), underscoring the merit of building RCMP as an extension to PBN.

Performance of each individual system listed above contributes to the overall performance of automated conflict management. For practicality, however, conflict management performance should be managed at an *aggregate* level, and not at the level of individual contributing systems. Just as RNP aggregates the performance contributions of GNSS receivers and navigation systems and specifies a single approved navigation precision value, RCMP should aggregate the performance contributions of all involved systems and reflect their combined performance in a single value. It is likely, though, that the performance of these systems will interact in ways that either result in just one or two systems dominating the integrated performance or result in synergistic integrated performance with the whole being greater than the sum of the parts. Either way, it is the integrated system performance that matters and that must be specified in an authorization to operate.

4. RCMP Specification

Performance requirements in PBN are identified in *navigation specifications.* The PBN Manual uses the terms *RNAV specifications* and *RNP specifications* to refer to their respective performance requirements. As justification of this performance approach, ICAO states that it permits operators to:

> "…*evaluate options presented by available technology and navigation services, which could allow the requirements to be met. An operator thereby has the opportunity to select a more cost-effective option, rather than a solution being imposed as part of the operational requirements. Technology can evolve over time without requiring the operation itself to be reviewed, as long as the expected performance is provided by the RNAV [or RNP] system*." [21]

Following the PBN model, performance requirements for automated conflict management can be similarly identified as *RCMP specifications*.

4.1. RCMP Specification

PBN uses the nomenclature "RNAV X" or "RNP X" to designate a particular *navigation specification*. For both RNP and RNAV navigation specifications, the expression "X" (where stated) refers to the lateral navigation accuracy in nautical miles (nmi), which is expected to be achieved at least 95 percent of the flight time by the population of aircraft operating within the airspace, route, or procedure. [21]

In the RCMP concept, a similar *conflict management specification* is proposed: "RCMP X." For RCMP X, the value of "X" could nominally refer to the minimum lateral separation in nautical miles authorized to be used by that operator for that aircraft on that flight. In some applications where time is more relevant than distance, the value of "X" could instead refer to a minimum time to a collision event, or some other relevant rate-based requirement. For either approach, additional requirements such as the minimum vertical separation would be implied but not explicitly stated in the conflict management specification. For instance, for all RCMP with X greater than 1.0 (i.e., 1.0 nmi minimum lateral separation requirement) the minimum vertical separation requirement could be established by regulation to be, for example, 500 feet. All such examples in this paper are illustrative only. Such determinations would be the purview of the regulator.

It would also be logical to follow the PBN example with respect to the 95 percent qualifier. For RCMP, this would translate into an expectation that the separation minima will be achieved 95 percent of some relevant operating metric. Additional analysis would be needed to select an appropriate operating metric; but rather than flight time, it could be the number of encounters or the severity of minima violation. An aircraft may easily spend far more than 95 percent of its flight time not even encountering another aircraft.

RCMP X Authorization

An operator approved by the regulator for RCMP X operations could be interpreted as indicating the following:

- The operator (aircraft, crew, etc.) meets the requirements for RNAV and RNP.
- The operator has capabilities certified for self-separation and shared separation (PC1, PC2).
- The operator's conflict management system includes all required certified subsystems.
- The operator's subsystems all meet RCMP X baseline and application-specific requirements.
- The operator is authorized to utilize a minimum lateral separation of X (distance or time, depending on the application), where X is derived from the integrated performance of the conflict management system certified to satisfy the regulator's safety criteria (e.g., probability of separation loss or NMAC).

4.2. RCMP-Based Separation Requirements

The separation requirements derived from RCMP approval can be categorized in two general groups. The first group is for encounters between Digital Flight aircraft that are both employing automated self-separation, i.e., they both have RCMP approvals, even if they are not operating at the same performance level. Within this group, normal RCMP authorizations (described below) would apply to the majority of operations. A potential future extension to RCMP, likely requiring *special* authorization, could apply to operators seeking additional value, as discussed below. Group 1 includes both *Normal Authorization* and *Special Authorization Required*.

Group 2 is for encounters between RCMP aircraft (e.g., Digital Flights employing automated self-separation) and non-RCMP aircraft (those operating under VFR or IFR). Unique separation requirements for this second group will be needed to enable integrated operations in shared airspace. As stated earlier, approval to access integrated airspace without segregation is generally considered a significant positive attribute of airspace operating concepts.

Group 1: Normal and Special Authorization

Normal Authorization

As stated above, the RCMP specification (e.g., RCMP 1.0) would identify the *minimum* approved separation value for an operator's aircraft on a given flight. However, it would not necessarily be the *actual* separation minima to be applied in every encounter. The separation minima for a particular encounter must also consider the capabilities and performance of *the other aircraft* involved in the encounter.

Given this pairwise relationship, the RCMP concept proposes that the two RCMP levels together (assuming they both have one) would determine the separation minima to be applied in that specific encounter using a largest-value derivation.

For example, the other aircraft (also a Digital Flight) may have a lower-performing set of self-separation capabilities as a result of, say, a less frequent update rate for sharing their operational intent, or newly degraded performance of one of their technical systems supplying their self-separation capability. As a result, that operator may have a larger RCMP value and therefore larger separation minima, e.g., RCMP 2.0. Because that operator is only authorized for 2.0 nmi separation, its encounter with an RCMP 1.0 aircraft must respect the larger of the two values. Therefore, both aircraft would apply 2.0 nmi as the minimum separation for this encounter.

This conservative approach of using the larger of the two RCMP values is appropriate for aircraft that are cooperating but not directly coordinating. In the Digital Flight context of distributed, automated conflict management, a cooperating aircraft is one that conforms to the cooperative practices which includes publishing their operational intent broadly. Broad intent dissemination (i.e., shared situation awareness) and adherence to cooperative practices are forms of *implicit cooperation*. It is possible, however, to go further and leverage *explicit coordination* between flights to derive additional operational value. This level of performance may require special authorization, described next.

Future Extension: Special Authorization Required

In a future evolution of the RCMP concept, RCMP-capable aircraft could optionally equip with additional systems that enable the capability for *peer-to-peer coordination* (i.e., Digital Flight PC3) and could therefore qualify for special authorization to use even smaller separation minima in their encounters than provided by normal authorization. The PBN analogy would be 'RNP Authorization Required' (i.e., RNP AR), in which additional requirements are applied to operators wishing to gain additional operational value (e.g., greater airspace access is granted today based on the ability to fly RNP AR approach and departure procedures).

In RCMP, the special authorization might require automatic peer-to-peer sharing of conflict alerts and explicit coordination of actions during an encounter through a dedicated digital communication link. This peer-to-peer sharing would allow two *RCMP AR* aircraft to both receive real-time alerts from both of their conflict management systems. It also would allow the two aircraft to directly coordinate their maneuvers through a dedicated communication channel (machine-to-machine). As a result of this extra information sharing and maneuver coordination, the target collision risk could be maintained with even smaller separation minima. This assumes that position uncertainty was not the determining factor of the two aircraft's RCMP values.

In practice, this encounter might work as follows. When two RCMP AR aircraft with peer-to-peer separation coordination capability (PC3) detect an upcoming encounter between them, they establish a peer-to-peer link and begin automatically exchanging conflict information. If the aircraft special authorizations are RCMP AR 0.1 and RCMP AR 0.5, for example, their ability to directly coordinate with each other may support a regulator authorization to assign separation minima based on a best-of-values determination, in this case 0.1 nmi separation (the smaller value of 0.1 and 0.5 nmi). This could allow for significantly smaller separation between pairs of RCMP AR (i.e., PC3 capable) aircraft, which some operators may value enough in their use case to warrant equipping and seeking the additional authorization (and the associated extra certification burden). Operators would not be required to equip at this level, just as RNP operators can opt not to pursue RNP AR approval if they do not need it. It is, however, a valid conceptual extension to the RCMP concept and should be reserved for consideration in a future evolution of RCMP.

Group 2: Separating from Non-RCMP Aircraft

Some flights (VFR and IFR) may not have an RCMP designation, and so other factors besides RCMP level must be considered for RCMP aircraft (Digital Flights) separating from non-RCMP aircraft (VFR and IFR). Because encounters with non-RCMP aircraft depend on neither cooperation (PC2) nor coordination (PC3), the Digital Flight operator would be the sole separator (PC1). While authorized to normally use the "X" value for separation (given their RCMP X operational approval), the human-centered conflict management methods of the non-RCMP traffic aircraft would likely preempt this approach. Instead, the following principles for establishing the separation minima in encounters with non-RCMP aircraft may have merit:

- For encounters with VFR aircraft, the separation minima could be selected to be compatible with the DAA "well clear" minima.
- For encounters with IFR aircraft, the separation minima could be the appropriate IFR separation values used by ATC for the airspace in which the encounter occurs.
- For encounters with aircraft of unknown operating mode, VFR may serve as a model to authorize the use of well-clear minima for all such encounters, though perhaps with additional buffers added based on observed operating behavior.

Ultimately the VFR, IFR, and ATC communities will need to concur with the separation minima used by Digital Flight operators for encounters with non-Digital Flight aircraft, as well as consider the additional training implications.

5. RCMP Contributing Systems

As noted earlier, no technology singlehandedly performs all the functions of automated conflict management. Rather, multiple technical systems perform various contributing functions that together constitute the functioning of a complete conflict management system. For RCMP development, each contributing system will require a quantitative assessment of its own performance as a contribution to the integrated performance of automated self-separation capabilities and their outcomes. This section presents an initial qualitative discussion of each system's potential impact on RCMP. A more detailed analysis and a quantitative assessment are beyond the scope of this concept paper. Following the discussion of each system, the section highlights the synergistic relationship between the In-Time Safety Management System (IASMS) concept and RCMP.

The systems contributing to automated self-separation, first introduced in Section 3.4 along with their respective roles and illustrated in Figure 3, are diverse: *information/connectivity systems* enable digital modeling of the operating environment; *surveillance systems* locate and track relevant traffic within that environment; *communication systems* share intent and enable coordination; *separation automation systems* predict trajectories, detect and resolve conflicts, and monitor conformance; *C2 systems* transmit flight path changes to the aircraft, and *navigation systems* execute the flight path change with intended precision. Each system will be discussed in turn in the sections below.

The initial qualitative discussion here will work backwards from the desired outcome of the integrated system: *separation from traffic and hazards is maintained at a performance level associated with a specified acceptable risk of NMAC*. The acceptable risk of NMAC is considered an input to this process, not an output, and might be specified in either absolute terms (i.e., TLS, e.g., 10^{-x} NMAC per flight hour) or a risk ratio relative to the NMAC rate of current

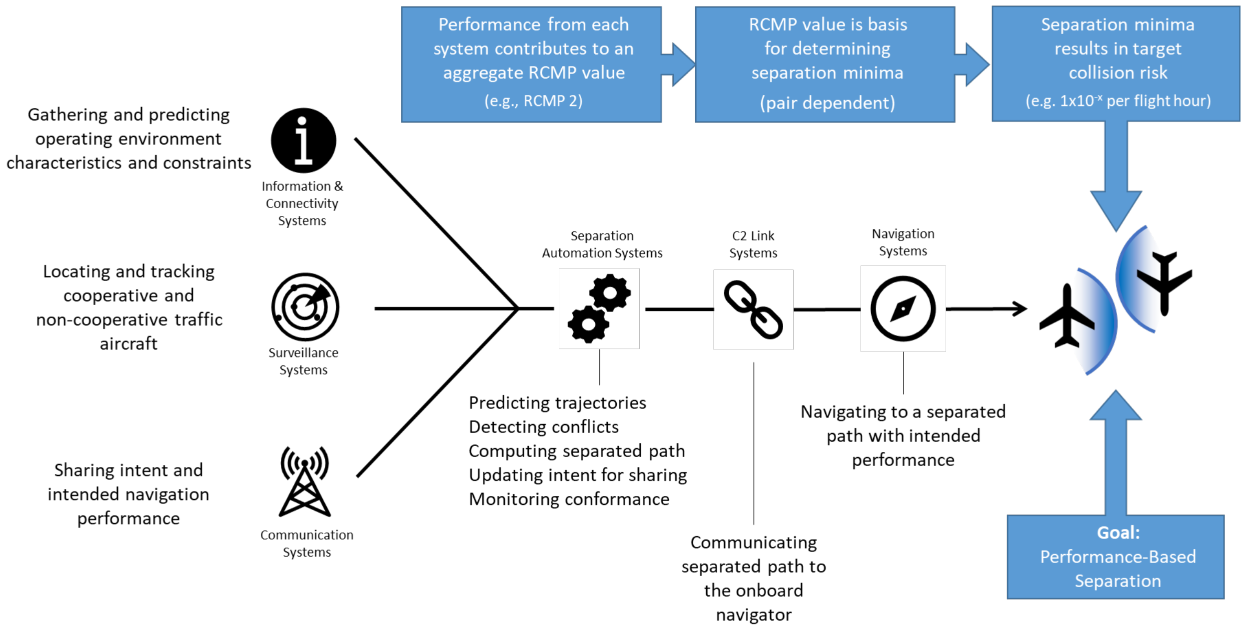

Figure 31. Systems contributing to automated self-separation. Performance from each system contributes to an aggregate RCMP value that determines the minimum separation and achieves the separation goal at a specified collision risk.

human-centered conflict management operations. The regulator working with the community at large would need to establish the level of acceptable risk and its quantification method.

Performance indicators cross cutting all systems involved in automated conflict management include the attributes of *accuracy, availability, continuity, integrity, and latency*. Accuracy is how well a measured or estimated system value conforms with its true value. Availability refers to the percentage of time the system is available for its function. Continuity is the ability of the system to continue to perform its function during the operation. Integrity is the trustworthiness of the system, so that function unreliability is alerted in timely fashion. Latency refers to the overall timeliness of system functionality. [22] RCMP would need to establish monitoring/alerting requirements and benchmarks for each of these attributes to ensure automated self-separation remains functional throughout the applicable portion of the flight.

5.1. Navigation System

In automated self-separation, the role of the navigation system (a shorthand used here for the aircraft's integrated guidance, navigation, and control systems) is to conform the aircraft to a separated path within the bounds of intended performance. As stated earlier, *separated path* here refers to a four-dimensional (4D) flight path with lateral, vertical, and along-track performance bounds that the separation automation system has predetermined will meet the separation minima associated with the analyzed upcoming encounters with traffic and hazards within the conflict horizon. This discussion assumes that all preceding functions by the other contributing systems (left of navigation in Figure 3) have performed adequately, and that achieving 4D flight path conformance is the primary remaining requirement assigned to the navigation system.

The main factor in navigation affecting RCMP is the performance bound. Because infinitely precise navigation is impractical, the computed flight path for self-separation must account for imprecise navigation when locating the path to be flown relative to the predicted locations of traffic and hazards. RNAV and RNP address this issue by bounding in the navigation specification the Total System Error (TSE), comprising three contributing components: path definition error, flight technical error, and navigation system error. The net effect of RNAV/RNP navigation specifications is to bound or "contain" the TSE distribution. See the left diagram of Figure 4. For example, in conventional application of navigating to a charted (fixed) path, RNP 1.0 requires TSE to remain within one nautical mile of the desired path for at least 95 percent (%) of the flight time for that operation. A similar RNP performance requirement applies in the along-track dimension (i.e., longitudinally) though is not operationally used today and would need revisiting for its ability to adequately contain the along-track future positions. Additionally, RNP on-board performance monitoring provides the pilot with an alert when the probability of TSE exceeding 2x RNP is greater than 10^{-5} (i.e., TSE is bounded within the navigation specification value for 99.999% of the flight time). [23]

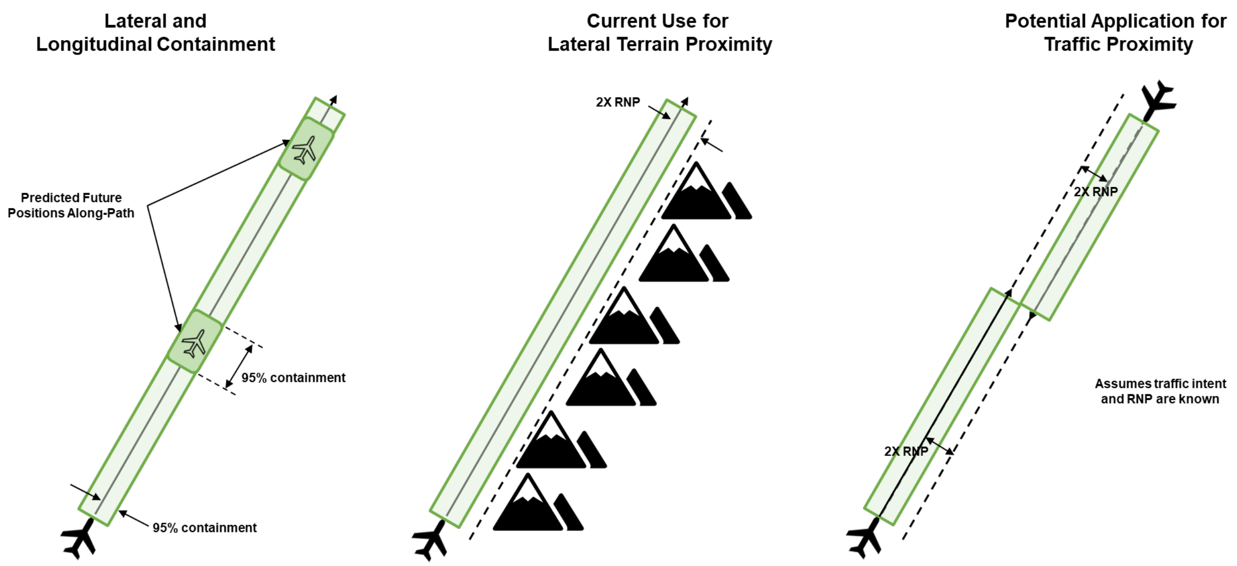

Figure 42. RNP provides containment in lateral and along-path dimensions. Currently used for protecting terrain proximity, the potential applicability to traffic proximity is envisioned in RCMP.

For lateral protection, RNP as currently defined by the regulator for navigation performance should be directly suitable for use in the RCMP construct. In the design of RNP AR procedures for instrument approaches near mountainous terrain, the lateral protection for terrain proximity is 2x RNP with no additional buffer, as illustrated in the center diagram of Figure 4. [24] In other words, an aircraft on an RNP AR procedure flying in IMC to within 2x RNP of a canyon wall is considered acceptable risk. For RCMP, the application of RNP tolerances for traffic separation could potentially take the same approach by applying 2x RNP for lateral protection between the ownship path and the projected path of an encountered aircraft, as shown in the right diagram of Figure 4. Since the encountered aircraft may be operating with a different RNP, a conservative approach would be to apply the larger of the two aircraft's RNP values, as suggested in Section 4.2. The purpose of this discussion is not to define the final quantitative approach, but to suggest that the current RNP construct may be suitable for use in self-separation between RCMP-compliant aircraft. Extensive analysis will be required to determine if 2x RNP lateral protection between two aircraft intended path centerlines is sufficient to meet the safety target.

Lateral containment alone is insufficient for automated self-separation, which must account for all possible conflict geometries in 4D space. Along-track (longitudinal) and vertical containment will also be important, especially for crossing conflicts in which the 3D paths nearly intersect in space and the aircraft crossing times at the closest point of approach must produce at least the required separation. As stated in reference [23], most RNP applications require that both lateral and along-track error be contained within the RNP navigation specification for at least 95% of the flight time for that operation. This requirement should carry into RCMP to accommodate crossing conflict geometries. Alternatively, new concepts for specifying and communicating the complete bounding of 4D trajectories simultaneously in lateral, vertical, and along-track dimensions can be considered, such as the Trajectory Specification Language by Paielli [25]. The cited work has the advantage of having been designed specifically for traffic separation.

A potential shortcoming of RNP as currently defined is the limited number of approved specifications (i.e., TSE bounding values), the smallest of which is RNP 0.1 (equivalent to 607.6 feet). For small UAS operating in proximity, for example, this may be insufficient. Smaller RNP values may be needed in RCMP, and the acceptable risk of NMAC may need tailoring to the application (e.g., the greater risk tolerance of operations not over people). Another factor to consider is wake vortex avoidance which for larger aircraft may require additional longitudinal and vertical separation.

5.2. C2 System

If the separation automation system is onboard the aircraft, delivery of the separated path to the navigation system would be through onboard networks with negligible performance impact on conflict management. However, for architectures in which the separation automation is not hosted onboard the aircraft, a command-and-control (C2) or similar communications link becomes an integral and critical part of the automated self-separation system. A C2 link failure would be analogous to an IFR aircraft losing communication with ATC (their separator) and unable to receive instructions. Even partially degraded link performance could impact self-separation. Among the performance factors to consider are link availability at the time of transmission, and message reception probability due to transmit power, line-of-sight geometry, signal interference, and receiver sensitivity. While intermittent link performance issues can be mitigated with multiple transmissions of the separated path message until confirmation is received, the impact of message reception latency may depend on messaging proximity to critical time horizons.

Time horizons are typically used by separation automation systems to limit the impacts of trajectory prediction uncertainty on the accuracy of conflict detection by not searching too far in the future. They also may use minimum time horizons to ensure that conflicts are detected and resolutions computed with adequate time remaining for the aircraft to maneuver and maintain separation. The critical period is between these maximum and minimum time horizons, during which the C2 link must have adequate performance to transmit the separated path to the navigation system as soon as it is computed. Any probability of messaging delay will likely require advancing the time horizons enough to ensure the Digital Flight complies with the cooperative practice to “take timely action.” [6]

A C2 link can nominally perform well (i.e., meet minimum RCMP standards) but experience degraded performance during periods of a particular flight. Provided this degraded state can be detected quickly (e.g., through delayed confirmation of message receipt), the operator could be required by the regulator to switch temporarily to a larger RCMP value – and therefore larger separation minima – until link performance is restored.

The concept of “Required C2 Performance” (RLP, where “L” stands for Link) has been proposed to resolve confusion with Required Communication Performance (RCP) that was designed to support ATM functions. [26] The concept defines an “RLP type” that specifies performance in terms of four parameters:

- **Communication transaction time**: The maximum time for the completion of the operational communication transaction after which the initiator should <u>revert to an alternative procedure</u>. (Emphasis added – see discussion below.)
- **Continuity**: Probability that a transaction can be completed within the communication transaction time given that the service was available at the start of the transaction.
- **Availability**: The probability that an operational communication transaction can be initiated when needed.
- **Integrity**: The probability of one or more undetected errors in a completed communication transaction. [26]

The key phrase in communication transaction time (first item in the above list; see underlined text) relevant to automated self-separation is “revert to an alternative procedure.” A self-separating aircraft that nominally receives alerts and separated paths from an off-board system (either hosted at the operator’s ground control station or a third-party service provider) may need to host an additional separation automation system onboard the aircraft to maintain RCMP authorization during degraded RLP conditions. Also needed would be onboard cooperative surveillance and (depending on flight location) non-cooperative surveillance (e.g., a DAA system).

5.3. Separation Automation System

As the hub of automated self-separation decision-making, the separation automation system hosts the algorithms that assure the aircraft's flight path remains appropriately separated from traffic and hazards. It builds and continually refreshes a digital model of the aircraft's current and forecast operating environment (using inputs from information systems, discussed below) and it further populates the model with traffic positions and intent (received from surveillance and communication systems, also discussed below). The following are among the key functions of a separation automation system:

- Predicting trajectories of ownship and traffic
- Selecting appropriate separation minima for each encounter (using RCMP values)
- Detecting conflicts (i.e., predicted loss of separation)
- Determining the ownship's separator role for each encounter
- Computing one or more separated paths for selection and execution
- Updating the ownship's shared intent, based on the selected separated path
- Monitoring ownship and traffic conformance to shared intent and cooperative practices.

Reference [13] describes a system concept for "dynamic path planning" (DPP) automation that aligns with this paper's description of the separation automation system. The goal of a DPP automation system is to ensure that a "*safe and operationally acceptable flight path is available to the users and the flight path execution system throughout the flight.*" [13] Its objectives are to construct and maintain a flight path to have five desired qualities: feasible, deconflicted, harmonized, flexible, and optimal. DPP system tasks are to create the flight path; to monitor the flight path and the factors which may impact it; to evaluate ongoing acceptability of the flight path and proposed changes; to revise the flight path as needed to sustain the desired qualities; and to coordinate the flight path with other airspace users and service providers.[13] Of primary interest to the RCMP concept is the system's performance in deconfliction (i.e., separation), though all five qualities are relevant to automated conflict management.

Whereas industry-developed performance constructs already exist for communication (RCP), navigation (RNP), surveillance (RSP), and C2 link (RLP) systems, separation automation systems do not yet have an established construct specifying required system performance; one is therefore needed for RCMP. An analysis of DPP system architecture research offers some insights into potential quantitative measures of effectiveness for separation automation systems.

- Probability of successful completion of task (e.g., detect conflict, compute separated path)
- Probability of providing a successful result within a specified time
- Probability of timely alerting of task failure
- Probability of missed detection (different from late detection)
- Probability of false detection.[27]

Specification of thresholds in these and potentially other areas would provide the system designer the guidance and flexibility needed to select suitable algorithms capable of these thresholds and therefore contributing to the total separation automation system performance. For instance, in conflict detection, different algorithms may vary in search granularity. The same holds true for conflict resolution in evaluating multiple candidate solutions. (See Figure 5.) Systems that do not meet strict requirements for accuracy and timeliness may have to rely more frequently on alternative systems like DAA and may not be approved for the highest levels of RCMP. If approved at lower levels (i.e., its lower performance is still adequate for self-separation), the operational effect would be the requirement to apply larger separation minima. Extensive modeling and simulation would be needed to determine the sensitivity and therefore extra separation required beyond that determined by RNP and RLP.

Timing criteria that must be considered in RCMP is for the system to produce a separated path with adequate time remaining for the aircraft to maneuver and achieve the required separation. Aircraft with less maneuverability may require more time to maneuver, which may put greater demands on other systems such as surveillance. This issue illustrates the complex interdependency between systems and their integrated performance for automated self-separation.

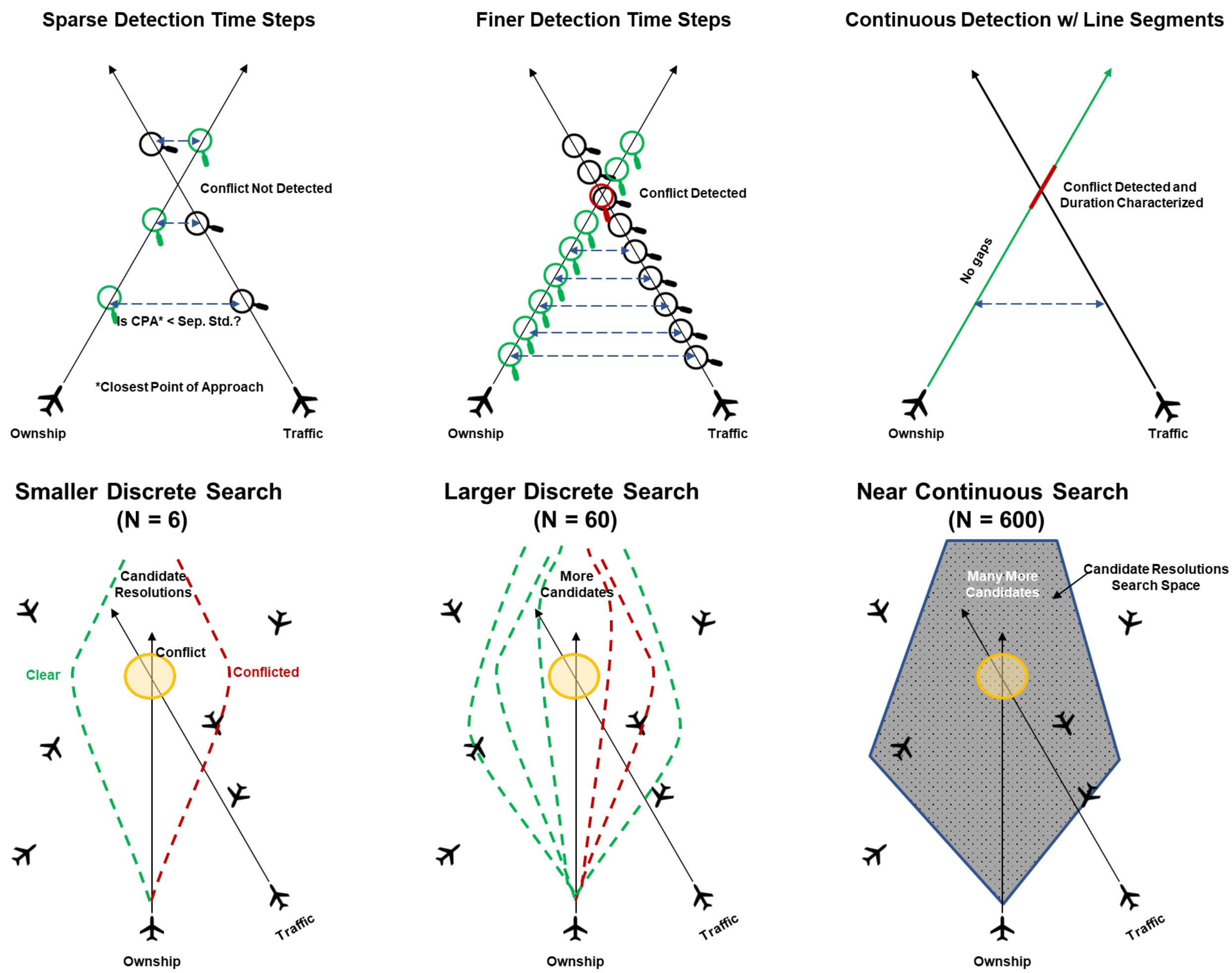

Figure 5. Separation automation systems may vary in their algorithms for conflict detection (top row) and conflict resolution (bottom row) resulting in varying performance. RCMP may need to establish minimum requirements or account for this variability.

5.4. Information and Connectivity Systems

Conducting flight by reference to digital information (as envisioned in Digital Flight, but relevant to any application of automated self-separation) requires the aircraft operator to build and maintain a comprehensive digital model of the current and forecast operating environment for that aircraft. As illustrated in Figure 6, broad categories of information would be included in the model, such as atmospheric and weather data, aerodrome and airspace data, terrain and obstacle data, constrained resource status, C2 and GNSS constellation status, and other relevant information on airspace system infrastructure and procedures. The model would also be infused with traffic information provided from surveillance and communication systems (discussed next), thereby providing the complete operating context for the aircraft in machine-readable format. In conflict management, the separation automation system applies its algorithms to this ever-evolving digital model as its only source of timely information on the operating environment. *Information quality* in the model is therefore paramount to the performance of automated self-separation.

Information quality is challenged by the vast diversity of data elements contained in the model and the many disparate data sources used. For instance, each data element may have its own time of applicability and update rate. Different granularities or spatial resolutions may be used, and there may be inconsistencies among related data elements acquired from different sources at different times. The potential also exists for some data to become stale or expired, or for there to be gaps in the vicinity of the ownship. These factors and more will drive the need for extensive integrity monitoring on the data and for alerting of detected or predicted degradation.

Like with separation automation systems, there currently is no performance construct for information systems that could be incorporated into an RCMP construct, and therefore the need for one must be determined. Extensive analysis, modeling, and simulation could determine the impacts of various information quality attributes on conflict management and the associated minimum performance requirements on an element-by-element basis (where some elements may have no RCMP impact). Incorporation into RCMP, however, will likely require an aggregate roll-up into an overall information system performance impact.

Adjunct to the information system, the connectivity system also plays a critical role in supplying the operating environment information to the separation automation system (which may be hosted onboard, on the ground, or in the cloud). A connectivity system is actually just a communication system, but its performance requirements may differ significantly from other communication applications in automated conflict management (e.g., coordinating separation maneuvers requiring rapid exchange). In its role as an information supplier, a connectivity system may be able to supply model updates asynchronously and at varying rates based on the data it is updating. For example, convective weather polygons may be available on a five-minute cycle, while wind forecasts may update only hourly. Traffic position data may be updating continuously, whereas traffic intent changes may be sporadic but still time critical.

The performance requirements of information connectivity relative to conflict management may therefore depend on what data it transmits and the tolerance for brief or extended interruptions. Ground-to-ground connectivity is unlikely to experience significant disruptions, while ground-to-aircraft connectivity may be vulnerable to them. Ensuring that the digital model resides with the separation automation system and can "coast" during disruptions would be an important mitigation, as coasted or extrapolated data are superior to their complete absence.

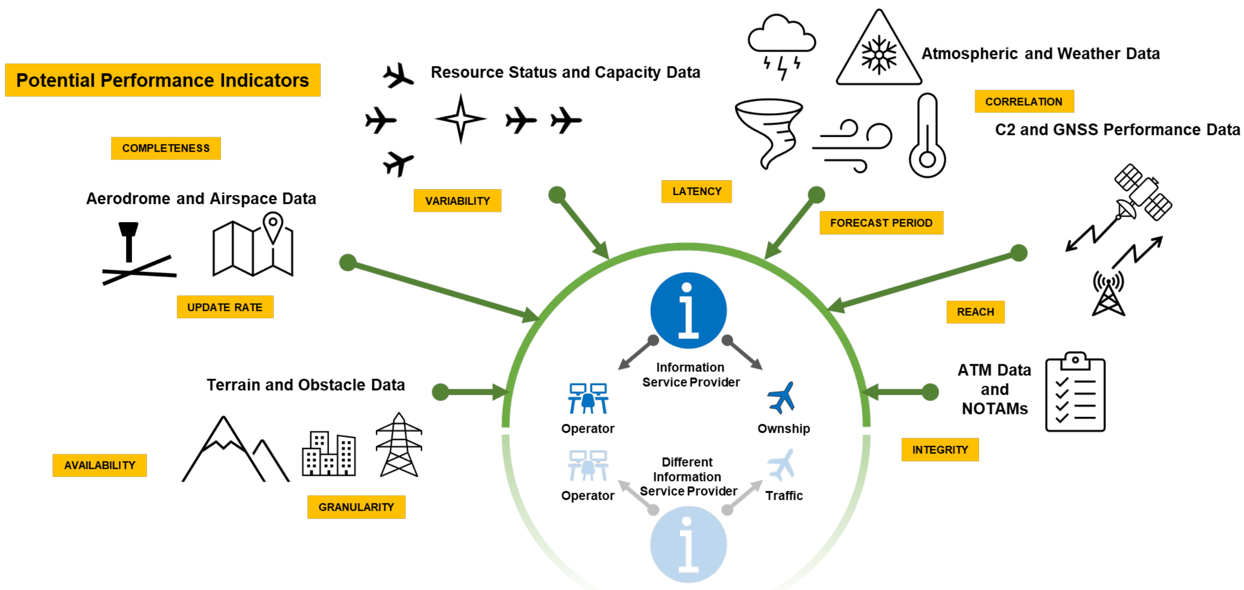

Figure 6. Connected information systems provide access to broad categories of information for use in building and maintaining a digital model of the aircraft's operating environment, an essential element of automated conflict management.

5.5. Surveillance System

Unsurprisingly, surveillance systems are fundamental to automated self-separation in that they provide information on nearby traffic to the separation automation system. Warranting their separate discussion here, surveillance systems play a more critical role relative to the information systems discussed earlier, such that dedicated systems for surveillance information are likely needed to ensure adequate self-separation performance. To that end, RCMP must consider two categories of traffic aircraft: those participating in *cooperative* surveillance and those that are *non-cooperative*. The two categories are illustrated in Figure 7, along with potential performance indicators.

In the *cooperative* category (left side of Figure 7), electronic conspicuity is present, and aircraft state information is supplied by the traffic aircraft's operator, either through broadcast mechanisms (receivable both airborne and on the ground) or through a ground-based relay service if unequipped to broadcast at sufficient range. Cooperative surveillance is akin to VFR's mantra to "see and be seen" and is the basis for digitally enabled cooperative operations in which operators proactively contribute to airspace safety by sharing their aircraft's surveillance information directly. Indeed, the regulator has already mandated cooperative surveillance in certain airspace regions.

The *non-cooperative* category (right side of Figure 7) accommodates aircraft unable, unwilling, or otherwise not required to be electronically conspicuous. For digital operations in airspace regions that may have non-cooperative aircraft present, some form of non-cooperative surveillance capability would be necessary for the Digital Flight operator *if the regulator holds them accountable for separation from non-cooperative traffic*. This policy question has significant implications to RCMP regarding the requirement for non-cooperative sensors or services, their performance implications on self-separation, and potentially the airspace where self-separation can be permitted. For instance, the performance of non-cooperative sensors for DAA systems can be significantly impeded by atmospheric conditions and ground clutter, depending on their type (e.g., radar, optical, acoustic). Short detection ranges can make it difficult to detect threats at a sufficient distance to avoid collisions, much less maintain separation. These factors must be considered in RCMP, because the mitigation method of increasing separation minima may not be feasible due to the performance limitations of non-cooperative surveillance systems.

A performance construct exists for required surveillance performance (RSP) and was developed for operational IFR use in airspace where procedural separation is applied, ensuring the air traffic controller has timely, accurate, and dependable surveillance. [28] While RSP specifications for procedural separation (e.g., surveillance delivery times measured in 100s of seconds) were intended for use in Automatic Dependent Surveillance Contract (ADS-C) and Controller Pilot Data Link Communications (CPDLC) and are too large for general use in the RCMP construct for domestic self-separation operations envisioned in this paper, the construct may still serve as a useful foundation. For more appropriate performance requirements, one can look to regulations for Automatic Dependent Surveillance Broadcast (ADS-B) for guidance. [29]

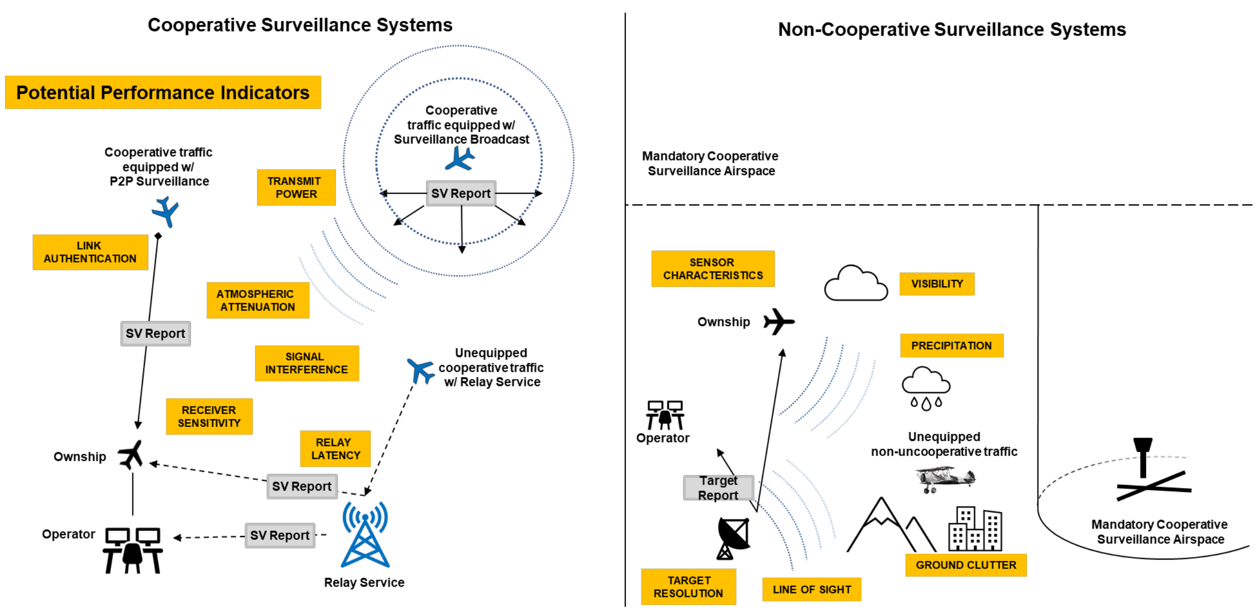

Figure 7. Cooperative and non-cooperative surveillance systems are fundamental to automated self-separation. They each have multiple performance factors that need consideration in RCMP development. SV = State Vector.

Factors affecting cooperative surveillance system performance may include waveform, antenna location, transmit power, signal interference, terrain, atmospheric attenuation, and receiver sensitivity. For non-cooperative sensors, factors may include sensor type, atmospheric conditions, signal interference, target resolution, ground clutter, line of sight, and perception and tracking algorithms. Performance indicators for both systems could include reception/detection probability, accuracy, latency, update rate, and operational volume. Minimum specifications may be needed in RCMP to ensure that surveillance is not the limiting factor in separation performance, or if it is, then to apply appropriately larger separation minima to account for the limitations.

5.6. Communication System

In digitally enabled cooperative operations, operational intent and related information would be shared among operators to promote a common operating picture (discussed in the companion paper [10]) and to increase efficiency in automated conflict management. Operational intent can include both *tactical* and *strategic* elements.

Tactical intent would typically be augmentations of the ownship's current state vector, to include target states if the aircraft is currently maneuvering either laterally or vertically, and/or one or more 4D trajectory change points for upcoming maneuvers. Sharing this information has direct value to the separation automation systems of other Digital Flight operators by enabling more accurate conflict detection and in computing separated paths that account for the shared intent within the separation time horizon. Similarly, the ownship operator benefits by receiving tactical intent information from their counterparts, resulting in earlier and more robust separation decision-making and better flight efficiency in the self-separation process.

Strategic intent can vary in type but generally would identify airspace resources the Digital Flight operator is intending to use. It may be a volume of airspace in which the aircraft will loiter while conducting a mission, a series of waypoints, or it may be a destination airport or arrival fix and the estimated time of arrival. The general purpose of strategic intent would be to enable resource managers and Digital Flight operators to anticipate resource demand and to plan accordingly through strategic conflict management processes such as demand/capacity balancing.

The communication system is the mechanism by which operational intent is shared. While strategic intent may be stable enough to tolerate variability in communication performance, tactical intent may change more frequently as the ownship's trajectory adjusts in response to conflicts and other dynamic factors. In addition, Digital Flight operators would share their current RCMP level as part of their operational intent message, indicating their minimum authorized separation based on their current RCMP. Timely and accurate exchange of this information through the communication system would be central to the performance of automated self-separation.

Factors affecting communication system performance and therefore RCMP would be similar to those affecting the cooperative surveillance system, which is itself effectively a communication system. Given that shared intent is an augmentation of the state vector supplied separately by cooperative surveillance, the safety criticality of not receiving tactical intent may be tempered but is still important as it underlies the efficiency benefits of cooperative operations.

From a separation perspective, the primary impact on RCMP of reduced or missing traffic intent, either due to communication system performance or operators just not sharing intent, would be the need to add a buffer to the minimum separation value to preserve additional time to react to the encountered aircraft potentially blundering inadvertently into the ownship's path.

Figure 8 illustrates from left to right the reduced buffer needed as higher-value intent is shared, with the preferred type being trajectory intent. Research has shown that sharing even just minimal trajectory intent can reduce conflict alerts and short-notice tactical maneuvering. [30]

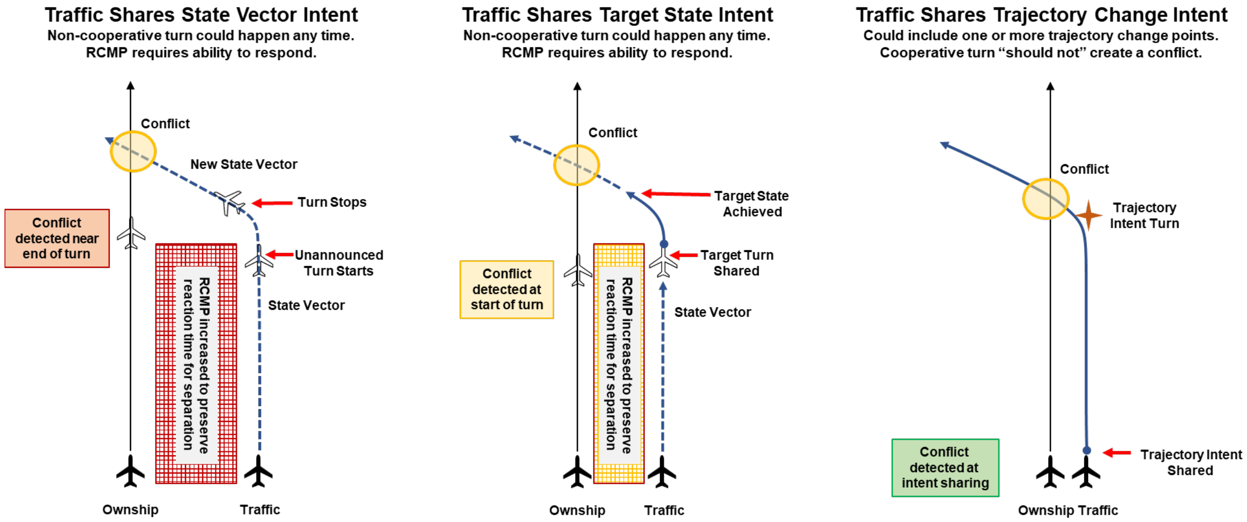

Figure 8. Communication systems are used for sharing operational intent. Receiving reduced or no tactical intent may require RCMP separation values to be increased with buffers to preserve reaction time for separation.

5.7. In-Time Safety Management System (IASMS)

The concept of In-Time Safety Management Systems (IASMS) is well aligned with the concept of RCMP and vice versa. IASMS is envisioned to include services, functions, and capabilities to monitor data, make assessments, and perform or inform safety assurance actions. [31] In the context of RCMP, IASMS could serve a crucial role as a prognostic performance monitor of the technical systems that comprise the automated self-separation functionality, especially information systems. In the context of IASMS, RCMP could be the mechanism by which the operator takes safety assurance action in response to an IASMS alert. For example, with sufficient notice of degrading information sources provided by IASMS, the Digital Flight separation automation system – as a client of IASMS data systems monitoring services – could automatically apply safety buffers to the separation minima to mitigate potential adverse effects of the degraded data.

Since many data elements in the information system's model of the operating environment are peripheral to traffic separation, this RCMP-based mitigation approach probably only need apply to certain specific data elements that directly affect the accuracy of predictions required for self-separation. An example might be the modeling of atmospheric winds, temperature, and pressure that impact aircraft performance and trajectory predictions. Errors, or rather differences, in these models between two operators whose Digital Flights encounter each other may lead to differences in how their respective separation automation systems view the conflict (or even if it is detected). The risk is mitigated if they use the same information service provider, but it is potentially exasperated if using different providers that are themselves supplied data from different data sources (see Figure 6). Industry standardization of information elements of key importance to automated conflict management may mitigate this risk.

6. RCMP Phased Implementation

Phased implementation of RCMP can provide an opportunity for technical maturation and the collection of operational data to address regulator uncertainty. Gradual implementation of operational changes is a time-honored mechanism in aviation. Complementing a rigorous design assurance process, a phased approach to implementation permits operations in a low-risk environment, where the approved minimum separation is large enough to provide the necessary safety buffer while RCMP systems are demonstrated, evaluated, and validated.

Emerging industries centered on increasingly autonomous operations are expected to operate within a continuous improvement technology cycle. RCMP can evolve alongside it as technological performance is demonstrated. For example, in high altitude airspace above Flight Level 600, stratospheric balloons demonstrated the capability to provide telecommunications services from upper Class E airspace. This model was deployed effectively in emergency response situations. Approvals were based not only on the emergency nature of the situation but were also enabled by the absence of a prescribed separation standard for unmanned free balloons. In order to provide similar services using fixed wing or other maneuverable high-altitude aircraft, the separation question must be resolved. RCMP provides a path to approve such operations in upper Class E airspace, where demand is low and encounters with manned aviation are unlikely.

Other remote airspace may also provide an opportunity for phased implementation and validation. Data gathered from these low-risk missions can serve to feed a safety case for operations in increasingly complex controlled airspace, with each operation providing the opportunity for analysis of system design, performance, and integrity that can lead to newly approved, smaller RCMP values based on improved conflict management systems. In many ways the initial operational implementation of UTM in North Texas could be viewed as an early step towards RCMP. [14] For operators seeking early access over populated areas with uncrewed aircraft capable of transporting humans, the safety pilot approach can provide risk mitigation and accountability until confidence in separation automation is achieved.

7. Summary: Requiring Conflict Management Performance

RCMP is a performance-based construct which could provide an accountability basis for operators to gain operational approval to use automated conflict management. In fact, any concept employing automated conflict management, including provider-centric concepts, could leverage RCMP. In this paper, the term RCMP is used in two ways: it is the means by which an operator demonstrates the adequacy of their automated conflict management system to the regulator for operational approval, and it is the value of the minimum separation that may be applied between a Digital Flight and another aircraft. Described qualitatively in this paper, RCMP would provide a quantitative link between conflict management system performance and an approved safety outcome (i.e., a target level of safety for collision risk). Higher performing conflict management systems would qualify for reduced separation values, unlocking significant efficiency and capacity benefits for their operators.

A phased implementation of RCMP, complemented by rigorous design assurance, could support early operations that rely on larger separation values to build regulator trust in automated conflict management through safe gathering of operational evidence and acceptance of residual risk. As higher levels of RCMP performance and reduced separation are approved, diverse operations with different performance capabilities and operational needs could be enabled while still being unified under a single performance-based construct. In this way, the diverse industry advances together.

The RCMP concept expands on PBN’s principles of RNAV and RNP with three additional specific capabilities of automated conflict management proposed in the Digital Flight framework: Operator Self-Separation, Shared Separation, and Pairwise Coordinated Separation. Enabling these capabilities are six separate technical systems that together comprise an integrated conflict management system, the performance of which is the subject of RCMP and which establishes the safety outcome. The higher the performance of the integrated system, the smaller the minimum separation values that could be authorized for the same safety outcome. IASMS could complement RCMP with independent performance monitoring and alerting.

The six technical systems contributing to automated self-separation are diverse: information/connectivity systems enable digital modeling of the operating environment; surveillance systems locate relevant traffic within that modeled environment; communication systems share intent and enable coordination; separation automation systems predict trajectories, detect and resolve conflicts, and monitor conformance; C2 systems transmit flight path changes to the aircraft; and navigation systems execute the flight path change with intended precision. Each of these systems are qualitatively reviewed in this paper for attributes that may contribute to or impact the performance of the integrated conflict management system. An argument is made for extending RNP, which can protect aircraft from terrain on fixed routes, to dynamically computed flight paths that separate aircraft from encountered aircraft. Each of the remaining systems are explored for their performance roles in informing, defining, transmitting, or executing this separated path.

Following the PBN model, RCMP X is proposed as a conflict management specification, where the value of "X" is the minimum separation value (in time or distance, as appropriate) approved for that flight. For basic encounters between two Digital Flights of different RCMP levels, the separation to be applied would be based on the more conservative of the two RCMP levels (i.e., the larger of the two values of "X" becomes the requirement for both flights). In a future RCMP evolution, peer-to-peer active coordination during an encounter could enable even closer separation. For encounters with VFR or IFR aircraft, separation minima appropriate to those operations would be used (e.g., "well clear" values for VFR encounters and airspace-appropriate values for IFR encounters).

Realizing the vision of Digital Flight, or any other concept of operator-centric, automated conflict management will ultimately require regulatory approval. To be successful, any proposal for a new operating mode must establish *explicit* operator accountability to the regulator for automated self-separation, clarify *implicit* operator accountability, and offer a measurable performance construct establishing for what the operator will be held accountable (e.g., RCMP). These components would significantly enhance the viability of a new operating mode in the eyes of the regulator and thus accelerate its authorization. This paper and its companion paper are intended to provide a foundation from which these issues can be explored further towards implementation.

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