Orient Academies

Integration of Onboard Detect-and-Avoid With UAS Traffic Management Services: Information Requirements and Operational Concepts

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Abstract
Uncrewed aircraft systems operating at scale in low altitude airspace require reliable means to prevent mid-air conflicts while ensuring predictable interactions with networked traffic management services. Existing detect-and-avoid capabilities and UAS Traffic Management frameworks have often been designed in partial isolation, producing gaps in information flows, inconsistent assumptions about surveillance performance, and heterogeneous responsibilities for separation assurance. These gaps become critical in dense and mixed-equipage environments where onboard automation, ground-based services, and human operators must coordinate under variable communication quality. This paper examines the integration of onboard detect-and-avoid systems with UAS Traffic Management services from the perspective of information requirements and operational concepts. The discussion characterizes how trajectory intent, surveillance data, conformance monitoring outputs, and resolution advisories may be exchanged and interpreted to support consistent conflict assessment across vehicles and services. A generic concept of operations is developed for routine, degraded, and contingency states, including the delineation of functions that remain safety-critical onboard versus those that can be delegated to network services. The paper further identifies latency, integrity, continuity, and update-rate requirements for selected information elements, considering both conservative and performance-based allocations. The analysis outlines how differing roles of strategic and tactical services can be coordinated without imposing prescriptive architectures. By formulating these requirements in a technology-neutral manner, the analysis seeks to support interoperable implementations, incremental deployment, and scalable safety assurance for beyond visual line-of-sight operations in controlled and uncontrolled airspace.

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1. Introduction

The anticipated density and diversity of uncrewed aircraft operations in low altitude airspace has motivated architectures that combine onboard automation with networked UAS Traffic Management services [1]. Onboard detect-and-avoid capabilities provide a last line of defense against mid-air collision by sensing cooperative and non-cooperative traffic and generating collision avoidance guidance within the performance limitations of onboard sensors, processing, and actuators.

In parallel, UAS Traffic Management services provide strategic and pre-tactical coordination functions, including demand-capacity balancing, airspace configuration, intent sharing, conformance monitoring, and constraint dissemination. When considered separately, each function has been studied in terms of performance requirements, algorithmic approaches, and operational deployment options. However, the safety and scalability of dense beyond visual line-of-sight operations will depend on the way these functions are combined rather than on any isolated component. This motivates a system-level analysis of information requirements and operational concepts that couple onboard detect-and-avoid and UTM services in a coherent framework.

The integration problem is complicated by several structural factors. First, detect-and-avoid logic has strict timing and integrity constraints driven by encounter geometry and vehicle performance, implying that certain decisions must reside onboard regardless of network connectivity [2]. Second, UTM services are inherently distributed, federated, and potentially heterogeneous, operated by multiple service providers with different technical implementations and service-level guarantees. Third, UAS operations occur in airspace shared with legacy crewed aviation, ground obstacles, and temporary geofenced constraints, introducing mixed equipage and incomplete data conditions. Fourth, regulatory frameworks tend to define performance objectives and roles at a high level, leaving implementers with significant flexibility and, consequently, variability in assumptions. An integrated concept must therefore remain agnostic to specific technologies yet explicit about which information is required, how it is validated, and how conflicting assessments from different entities are reconciled.

Detect-and-avoid and UTM can be viewed as complementary layers of a separation provision system, where UTM primarily manages strategic and pre-tactical separation via trajectory deconfliction, and onboard detect-and-avoid manages tactical separation in the presence of unpredicted behavior or residual uncertainty. A central question is how much the onboard system should rely on UTM-provided data, including remote tracks, intent information of other aircraft, and airspace constraint notifications, when computing conflict probabilities and resolution maneuvers. Conversely, UTM services may rely on onboard-observed state and intent to refine network-level traffic predictions and detect non-conformance [3]. Without a carefully defined interface, misaligned threat pictures can emerge, leading to conflicting advisories, duplicated responsibilities, or unsafe gaps in coverage. The present analysis focuses on these interface definitions in terms of information content, quality attributes, and timing semantics.

The objective of this paper is to propose an internally consistent set of information requirements and operational concepts for integrated onboard detect-and-avoid and UTM services that can be applied across different architectures. The scope includes beyond visual line-of-sight operations for small and medium uncrewed aircraft in uncontrolled and controlled low altitude airspace, with emphasis on cooperative surveillance and mixed-equipage scenarios. The discussion is framed to support performance-based regulation and certification arguments rather than to mandate particular technologies or vendor-specific solutions. By grounding the analysis in dynamic models, conflict risk metrics, and allocation of functional responsibilities, the paper clarifies trade-offs between onboard and ground-based functions and outlines conditions under which integrated operations can be argued to provide an acceptable level of safety.

2. System-Level Safety Objectives and Role Allocation

The integration of onboard detect-and-avoid functions with UAS Traffic Management services must be framed against explicit, system-level safety objectives that are decomposed into verifiable roles and quantitative performance criteria [4]. Without such a framework, local optimizations of individual components risk generating incompatible behaviors or unexamined dependencies that undermine overall risk control. For integrated uncrewed operations, a fundamental objective is to maintain the probability of mid-air collision per operation or per flight hour below an allocated target that is commensurate with the surrounding airspace and legacy traffic. This objective is not assigned to a single system but distributed among multiple barriers, including strategic conflict prevention, pre-tactical conformance management, tactical detect-and-avoid, and ultimate collision avoidance mechanisms. The role of integration is to ensure that each barrier is specified with clear responsibilities and assumptions regarding information availability so that combined performance remains within the target risk envelope even under degraded conditions and mixed equipage.

In a probabilistic hazard-control view, the system-level risk of collision is represented through a hierarchy of conditional probabilities. Let the overall probability of collision in a representative exposure period be denoted by a scalar P_C. Conceptually, this can be decomposed into the probability of entering a potential conflict geometry, the conditional probability that conflict is not resolved strategically or pre-tactically, and the conditional probability that onboard detect-and-avoid and residual mechanisms fail to prevent an actual collision. While different formalisms can be used, the integration problem assumes that P_C is bounded by a target P_T and that this bound is achieved through allocations to the functions implemented across onboard and UTM components. For example, a notional allocation might require

Table 1. Abstract: core themes and outcomes

Section	Core Theme	Outcome
Abstract	Integrated DAA-UTM perspective	Establishes scope, motivations, and neutral objectives
	Information-centric view	Emphasizes role of structured data exchange

Table 2. Abstract: context and integration target

Element	Description	Relevance
Operational context	Dense BVLOS in mixed-equipage airspace	Drives need for coordinated services
Integration target	Coherent, tech-neutral coupling	Supports interoperable implementations

that the contribution of failures in tactical detect-and-avoid not exceed a fraction of P_{T}, while UTM-related strategic and pre-tactical failures consume another fraction. These allocations are not merely bookkeeping; they drive concrete requirements on information integrity, latency, and coverage that each function must satisfy in order for the composition to remain acceptable across a wide range of operating conditions. [5]

Within this structure, the onboard detect-and-avoid system is assigned primary responsibility for last-resort collision avoidance whenever communication with UTM services is unavailable, untrusted, or too delayed relative to encounter dynamics. A compact representation of this responsibility is that the conditional probability of collision given the availability of functional onboard detect-and-avoid, denoted $P_{\mathrm{C|DAA}}$, must remain below a designated bound that is independent of the presence or absence of UTM support. This leads directly to minimum sensing coverage, alerting logic, and maneuverability requirements that are intrinsic to the aircraft and cannot be delegated externally. UTM services may reduce exposure to high-conflict geometries, but they are not assumed to be necessary for the basic ability of an aircraft to avoid collisions in its immediate vicinity. This asymmetry is central: integrated operations may exploit UTM-derived data to enhance performance, but the safety case is constructed so that loss or degradation of such data leads to graceful performance reduction rather than structural vulnerability.

UTM services, in contrast, are allocated responsibilities for shaping traffic flows and constraining the evolution of trajectories in ways that statistically reduce the frequency of close encounters and reduce reliance on extreme tactical maneuvers. Their strategic functions include screening submitted trajectories for predicted conflicts against other planned operations and known constraints, imposing temporal or spatial separations, and coordinating modifications when demand exceeds local capacity. Pre-tactical functions include monitoring conformance to negotiated intents and propagating notifications of deviations or new constraints [6]. The associated safety objective for UTM can be stated in terms of bounding the probability that two or more aircraft are allowed to evolve into a configuration where even correctly functioning onboard detect-and-avoid would have insufficient time or maneuver authority to prevent a collision. In abstract terms, if τ_{DAA} denotes the minimum reaction horizon required by onboard systems, UTM allocation requires that the rate at which conflicts emerge with residual time-to-conflict less than τ_{DAA} remain below a specified threshold under nominal conditions. This does not eliminate the need for robust onboard capabilities but ensures that such capabilities are not routinely stressed beyond their intended envelope.

The allocation of roles must explicitly consider mixed equipage, where some aircraft may rely heavily on UTM services and others may operate with strong onboard detect-and-avoid but limited connectivity. To maintain neutrality in such environments, the integrated concept defines obligations in terms of observable behaviors rather than specific technologies. Aircraft that declare limited onboard detect-and-avoid capability may be restricted by UTM to more conservative trajectories or lower-density regions, thereby consuming a larger share of the strategic safety budget. Conversely, aircraft with capable onboard systems may be granted more flexibility, provided their behavior remains within declared performance bounds and is transparent enough for UTM predictions to remain valid. Importantly, these allocations are asymmetric but not preferential: no category is assumed to be intrinsically safe without verification, and each is required to expose sufficient status and capability information to support consistent risk assessment at the system level. [7]

A critical facet of role allocation concerns the management of inconsistent or conflicting information from onboard and UTM sources. Integrated systems cannot assume that all actors share an identical traffic picture

Table 3. Introduction: main themes

Section	Core Theme	Outcome
Introduction	Joint role of strategic and tactical layers	Frames DAA and UTM as complementary barriers
	Heterogeneous environment	Highlights regulatory, performance, and equipage diversity

Table 4. Introduction: framing and scope

Element	Description	Relevance
Problem framing	Misaligned assumptions and gaps	Motivates precise interface definitions
Scope	Low-altitude BVLOS operations	Focuses analysis on scalable use cases

or that all surveillance and communication channels are fault-free. Instead, they must specify precedence rules and reconciliation mechanisms. One principle, consistent with safety-critical design in other domains, is that for immediate collision avoidance decisions, local sensor and integrity-checked data onboard have precedence over remote advisories when discrepancies exceed defined tolerances. In mathematical terms, if an onboard estimate of an intruder state lies outside an admissible consistency region relative to the corresponding UTM-supplied state, the onboard detect-and-avoid system is required to treat the network data as degraded and rely on local observations when calculating avoidance maneuvers. A simple scalar indicator can represent this consistency check, for instance a residual e between fused and remote estimates that must remain below a threshold for normal reliance. When e exceeds the threshold, role allocation dictates a deterministic shift toward conservative onboard-led behavior, avoiding ambiguous shared control. [8]

Another aspect involves the temporal layering of roles across different look-ahead horizons. UTM services predominantly operate at longer horizons where their access to aggregated data and computational resources can be leveraged to anticipate potential conflicts and allocate airspace. Onboard detect-and-avoid operates at shorter horizons where rapid response is possible and required. The integration must avoid both gaps and overlaps. A gap would arise if UTM assumes that onboard systems can handle conflicts with very small time-to-loss-of-separation, while onboard designs assume that UTM will never allow such situations to occur. An overlap arises if both layers attempt to manage the same conflict geometry with incompatible objectives, producing oscillatory advisories or excessive maneuvering. To mitigate these outcomes, the integrated concept defines explicit transition regions in time-to-conflict or risk space at which authority shifts from primarily UTM-driven interventions to primarily onboard-driven interventions [9]. These transition regions are expressed through threshold values that are stable, documented, and reflected symmetrically in both UTM and onboard design requirements, so that each component can predict when the other is expected to act.

Functional role allocation also extends to the treatment of non-cooperative or partially cooperative traffic. UTM services have limited direct influence over aircraft that do not participate in intent sharing or that lack compatible communication equipment. Onboard detect-and-avoid, by contrast, is expected to manage collision risk with such traffic using whatever sensing modalities are available, including passive detection. In these situations, UTM cannot credibly claim responsibility for tactical separation involving non-participating entities, though it may disseminate known constraints or surveillance data derived from legacy systems. Consequently, the safety objective for integrated operations must recognize that certain classes of encounters are handled almost exclusively by onboard systems, and that UTM contributions are auxiliary. The architecture should, however, ensure that when UTM-derived estimates of non-cooperative traffic are available, they are incorporated in a manner that does not degrade the integrity of onboard sensing, for instance through bounded fusion algorithms that do not allow unverified remote tracks to override high-confidence local measurements. [10]

The definition of roles must be accompanied by measurable indicators of performance and health, since safety cases and operational approvals depend on demonstrating that allocations are satisfied in practice. For each major function, such as onboard conflict detection, trajectory conformance monitoring, or UTM strategic deconfliction, one can define empirical performance measures including detection probability, false alert rates, latency distributions, and coverage metrics. Integration implies that these measures are not interpreted in isolation but in relation to their impact on the combined barrier structure. For instance, a modest increase in

Table 5. System-level objectives: themes

Section	Core Theme	Outcome
System-Level Safety Objectives and Role Allocation	Decomposition of collision risk	Links system-level targets to functional layers
	Role clarity	Distinguishes strategic UTM and tactical onboard duties

Table 6. mechanisms

Element	Description	Relevance
Risk allocation	Conditional probabilities over barriers	Guides requirement setting for each function
Precedence rules	Onboard data vs. UTM advisories	Avoids ambiguous authority in conflicts

false strategic alerts from UTM may be acceptable if onboard logic is able to discriminate and filter advisories without excessive maneuvering, whereas high latency in UTM notifications that coincide with tight onboard reaction margins may be unacceptable. The role allocation framework must therefore support joint evaluation, where performance degradations at one layer are tested against the compensating capabilities of others, rather than enforcing rigid specifications that ignore cross-layer resilience.

The neutrality of the integration concept is preserved by avoiding prescriptive hierarchy among specific implementations while maintaining clear authority structures over decision types. For example, UTM services may be operated by different providers using heterogeneous algorithms for demand-capacity balancing, but all must conform to a common set of obligations regarding the semantics of their outputs and their interaction with onboard systems [11]. These obligations include the requirement that when a UTM advisory is labeled as mandatory within a given airspace construct, it must be accompanied by sufficient quality indicators for onboard detect-and-avoid to independently verify that compliance does not violate tactical safety thresholds. If verification fails, onboard systems are authorized to deviate while communicating their rationale. Similarly, onboard manufacturers may implement distinct detect-and-avoid algorithms, but these algorithms must expose behavior envelopes and health states that enable UTM to model their likely responses. In this sense, integration is enforced not at the level of specific algorithms but at the level of declared behaviors and guarantees that link roles to safety objectives.

Finally, system-level safety objectives and role allocations must remain compatible with evolutionary development and partial deployment. In early stages of UAS Traffic Management implementation, coverage may be limited geographically or functionally, and only some operators may possess advanced onboard detect-and-avoid systems. The integration framework should define conditions under which operations can proceed with reduced functionality without invalidating risk assumptions [12]. This implies that allocations are expressed in terms of conditional obligations: when UTM services of a specified class are available and authenticated, certain strategic responsibilities apply; when they are absent, onboard systems and procedural mitigations assume a larger share of the safety burden. Likewise, when aircraft advertise particular detect-and-avoid capabilities, they are expected to meet associated performance criteria; if such capabilities are not present, UTM and operational rules adapt by constraining exposure. By expressing roles as explicit, conditional contributions to a shared risk budget, the integrated concept supports gradual introduction of services and technologies while maintaining a coherent mapping from system-level objectives to the behavior of individual components and actors.

3. Background and Problem Setting

The integration of onboard detect-and-avoid with UAS Traffic Management services is situated in a layered assurance context in which separation provision relies on a combination of strategic planning, conformance monitoring, and tactical intervention. For the purposes of this analysis, a generic operating environment is assumed in which multiple uncrewed aircraft, each with its own flight management system, automation stack, and detect-and-avoid capability, operate under network-coordinated constraints and services. The UAS Traffic Management layer is treated as a logical ensemble of service providers responsible for processing intent submissions, propagating airspace constraints, and issuing notifications related to predicted conflicts or conformance deviations. The detect-and-avoid layer is treated as a set of onboard functions that transform sensor and data-link inputs into

Table 7. environment summary

Section	Core Theme	Outcome
Background and Problem Setting	Multi-actor airspace model	Defines participants, services, and constraints
	Imperfect information	Emphasizes asymmetric and delayed traffic views

Table 8. modeling constructs

Element	Description	Relevance
Dynamic states	Common-frame 6D state vectors	Basis for relative motion reasoning
Protected volume	Rectangular separation region	Formalizes minimum separation condition

collision risk assessments and potential resolution advisories [13]. The problem is to specify the bidirectional information flows and decision responsibilities such that these layers form a coherent, non-contradictory whole across a spectrum of operational conditions.

A minimal analytical representation of this environment considers each aircraft i as a controlled dynamical system with state vector

$$x_i(t) = \begin{bmatrix} p_{ix}(t) \\ p_{iy}(t) \\ p_{iz}(t) \\ v_{ix}(t) \\ v_{iy}(t) \\ v_{iz}(t) \end{bmatrix},$$

where position and velocity components are expressed in a common local frame consistent with the UTM service domain. The evolution of the state is governed by dynamics of the form

$$\dot{x}_i(t) = f_i\big(x_i(t), u_i(t), w_i(t)\big),$$

where u$_i(t) denotestheappliedcontrolinputandw_i(t) captureswindandmodeluncertainty.TheUTMservicesaggregatesharedstatesandintent$
$\{x_i(t), \gamma_i(t)\}_{i=1}^{N}$,

where each trajectory intent representation $\gamma_i(t)$ encodes planned position as a function of time and optional bounds on uncertainty. The detect-and-avoid system onboard aircraft i has direct access to local sensory measurements and to a filtered subset of $\Xi(t)$ delivered via communication links, subject to latency and integrity constraints.

From a separation assurance perspective, conflict risk is associated with the relative states between aircraft. For any pair (i,j), define the relative position and velocity vectors

$$r_{ij}(t) = p_j(t) - p_i(t),$$

$$u_{ij}(t) = v_j(t) - v_i(t).$$

A protected volume $\mathscr{P}$ surrounding each aircraft is specified to represent a region within which the probability of simultaneous occupancy must remain acceptably low. One simple parameterization is

$$\mathscr{P} = \left\{ r \in \mathbb{R}^3 : |r_x| \le d_h, [15] |r_y| \le d_h, |r_z| \le d_v \right\},$$

with horizontal and vertical separation parameters d$_h andd_v determined$
$basedcriteria.Thedetect-and-avoidfunctionevaluatesestimatesofr_{ij}(t)$
over a look-ahead horizon, while the UTM service evaluates predicted intersections of $\gamma_i(t)$ and $\gamma_j(t)$ at coarser resolution.

The problem setting is characterized by imperfect and asymmetric information. Onboard sensors observe nearby traffic within a limited field of view and with noise characteristics that depend on cooperative or non-cooperative equipage. UTM services observe intent submissions, historical conformance data, and any surveillance feeds they are authorized to use, but they may not have immediate access to all local measurements available onboard. Communication channels introduce latency, loss, and possible degradation, implying that $\Xi(t)$ as seen by a UTM service differs from the set of states estimated onboard each vehicle [16]. As a result, conflict assessments derived from onboard detect-and-avoid and from UTM services may diverge both in magnitude and timing. The central challenge is not to remove these divergences entirely, which would be unrealistic, but to constrain and structure them so that the combination of functions reliably enforces minimum separation and produces predictable behaviors at the system level.

This background motivates the need for explicit modeling of roles and information requirements. For each category of safety-relevant decision, it is necessary to identify which entity is primarily responsible, which supporting information it must have, what level of quality is required, and how discrepancies between sources should be handled. The subsequent sections treat these questions by first outlining an integrated operational concept, then formulating quantitative information requirements and conflict detection models consistent with that

Table 9. Operational concept: states and roles

Section	Core Theme	Outcome
Integrated Operational Concept for Onboard DAA and UTM	Tiered nominal-degraded-contingency logic	Structures behavior across connectivity states
	Authority partitioning	Keeps last-resort avoidance onboard

Table 10. phases and fallback

Element	Description	Relevance
Phased operations	Pre-flight, en route, terminal phases	Aligns UTM and DAA roles over time
Fallback behaviors	Holds, RTL, protected volumes	Enables predictable responses to failures

concept, and finally examining architectural and human integration considerations that arise in practical deployment.

A key dimension of the problem setting is regulatory and policy heterogeneity across regions. While some regions may provide prescriptive minima for separation, communication reliability, or equipage, others emphasize performance-based objectives without detailed allocation of functions [17]. This variability implies that integration concepts should not embed assumptions that only hold in a specific jurisdiction, such as ubiquitous cooperative surveillance or uniform spectrum availability. Instead, they must accommodate a spectrum of UTM deployment models, ranging from centralized platforms to federated ecosystems, and from government-operated services to private providers. In each case, the coupling with onboard detect-and-avoid must be robust against differences in service quality and must tolerate partial participation while still maintaining consistent safety logic for aircraft that rely primarily on onboard capabilities.

Another dimension arises from diversity in vehicle performance and autonomy levels. Small multirotor aircraft, fixed-wing platforms, and larger cargo vehicles exhibit distinct kinematic envelopes, climb and descent capabilities, and reaction times. Some may host advanced sensors and computational resources, while others are limited to minimal cooperative transceivers. The integrated system must function in mixed-equipage airspace where certain vehicles implement full detect-and-avoid and UTM connectivity, others depend primarily on UTM-based separation, and some legacy aircraft may be visible only intermittently. These differences shape the feasible detection horizons, maneuver options, and reliance on strategic planning versus tactical response [18]. Modeling the problem setting therefore involves not only dynamic equations for motion but also classifications of capability levels and the design of integration rules that remain valid when individual assumptions are violated by particular participants.

4. Integrated Operational Concept for Onboard DAA and UTM

An integrated operational concept for detect-and-avoid and UAS Traffic Management must define how strategic, pre-tactical, and tactical functions are distributed between onboard systems and network services under varying conditions of connectivity and equipage. In the nominal state, each operator submits trajectory intent to a UTM service prior to flight, including planned four-dimensional paths, performance envelopes, and operational constraints. The UTM service evaluates compatibility of submitted intents with airspace structure, applicable constraints, and other trajectories, and may propose modifications or allocate temporal and spatial access segments. Once accepted, this negotiated intent becomes the reference against which conformance is monitored by both the UTM service and the onboard systems. Onboard detect-and-avoid, in this state, monitors local traffic and compares observed behavior with expected behavior derived from shared intents and surveillance updates, but does not routinely command aggressive maneuvers when UTM-level strategic separation is preserved.

When deviations from planned behavior occur, either due to tracking uncertainty, modeling error, or intentional maneuvers, the UTM service detects loss of conformance by comparing observed or reported states with the submitted intent [19]. Notifications of nonconformance are disseminated to affected parties, including other UTM service suppliers and operators, using agreed interfaces. The onboard detect-and-avoid system incorporates such notifications as context for its own assessment but retains responsibility for immediate collision risk estimation based on sensed and received traffic data. In encounters where UTM predicts future conflicts beyond a specified time threshold, UTM may

Table 11. Information requirements

Section	Core Theme	Outcome
Information Requirements and Data Modeling	Explicit data elements and qualities	Defines latency, integrity, continuity needs
	Consistent semantic views	Aligns onboard and UTM representations

Table 12. Information requirements

Element	Description	Relevance
Trajectory intent	Harmonized paths with tolerance	Supports shared conflict prediction
Constraint sets	Onboard-conservative airspace models	Prevents resolution violating restrictions

issue proposed trajectory adjustments intended to restore strategic separation. These adjustments are evaluated by each aircraft automation stack for feasibility and compliance with onboard safety constraints. Acceptance and execution of UTM-proposed adjustments are conditional on detect-and-avoid verification that the proposed path does not introduce unacceptable near-term collision risks.

In a degraded connectivity state, where an aircraft maintains only partial or intermittent access to UTM services, the operational concept allocates greater autonomy to onboard detect-and-avoid for both conflict detection and resolution. Strategic separation planning may become stale or unavailable, and the aircraft relies on onboard surveillance, pre-briefed constraints, and conservative models of traffic density [20]. In such conditions, detect-and-avoid logic can revert to policies that favor robust self-separation with minimal reliance on remote intent data, for example by enforcing speed and heading adjustments that maintain buffers relative to last-known traffic positions and by respecting geofenced airspace regions that are cached onboard. When connectivity is restored, the aircraft publishes its current state and updated intent, enabling UTM to re-integrate it into the network-level traffic picture without abrupt transitions or conflicting advisories.

A contingency state is defined for conditions where either onboard detect-and-avoid performance or UTM service quality falls below defined thresholds. Examples include sensor failures, corrupted data-link messages, or systemic UTM outages. In these cases, predefined fallback behaviors are invoked. Onboard systems may command the aircraft to enter predefined contingency volumes, execute holding patterns at safe altitudes, or transition to return-to-launch or land-at-nearest procedures, while maintaining passive detect-and-avoid capabilities to the extent possible. UTM services, upon detecting widespread degradation or loss of visibility, may restrict new operations, reconfigure airspace, or escalate notifications to supervisory authorities [21]. In all cases, the concept maintains that last-resort collision avoidance actions remain onboard, driven by locally available information and simple, verifiable rules that do not depend critically on complex coordination protocols.

The integrated operational concept thus relies on a tiered allocation of responsibilities. UTM focuses on ensuring compatibility of planned trajectories and managing information about constraints and conformance at horizons where communication delays and processing times are acceptable. Onboard detect-and-avoid focuses on short-horizon collision risk under uncertain and possibly inconsistent data. Information flows are structured so that onboard systems can exploit UTM products when available, but can also function with reduced reliance on them without abrupt change in behavior. Conversely, UTM services treat onboard-generated status, health, and maneuver decisions as authoritative for local behavior, using them to update predictions and, where necessary, to revise advisories to other participants. This concept provides a foundation upon which quantitative information and performance requirements can be specified without prescribing particular system implementations. [22]

To clarify temporal interactions, the integrated concept may distinguish between phases of operation. Prior to departure, operators submit intended trajectories and receive strategic acceptance or alternative proposals from UTM services. During climb and en route phases, routine conformance monitoring compares actual positions and planned paths using tolerance bands that reflect navigation accuracy and expected maneuvering. As long as deviations remain within bands, no additional action is required. If deviations approach thresholds, UTM may label the operation as marginal and alert both the operator and potentially affected neighbors, while onboard detect-and-avoid continues to treat nearby aircraft according to their broadcast positions and intents. In the descent and landing phases, especially in dense

Table 13. Conflict modeling: themes

Section	Core Theme	Outcome
Conflict Detection, Risk Metrics, and Resolution Modeling	Unified risk-based detection	Links probabilistic DAA alerts and UTM margins
	Resolution as constrained control	Embeds advisories in feasibility checks

Table 14. Conflict modeling: key constructs

Element	Description	Relevance
Risk metric	Probability of protected volume entry	Triggers tactical responses
Authority check	UTM proposals screened onboard	Prevents unsafe externally driven maneuvers

terminal areas, greater emphasis is placed on rapid updates and possibly localized UTM or corridor services, but the underlying principle remains: UTM shapes flows and constraints, while onboard systems manage immediate separation given whatever information is available.

Within this phased view, the integration must avoid ambiguous authority transitions [23]. For example, when UTM proposes a reroute to avoid a congestion hotspot, it is essential that aircraft automation treat this proposal as a candidate plan subject to detect-and-avoid screening, rather than as an unconditional command. Likewise, when onboard detect-and-avoid selects a maneuver that temporarily diverges from the negotiated path to resolve a conflict, UTM services should interpret this as a safety-driven deviation, not as arbitrary non-compliance. This can be achieved through explicit message semantics where maneuvers are labeled with reasons such as conflict resolution or contingency, allowing UTM to distinguish between anomalies and intentional protective actions. Such semantics reduce the risk that well-intentioned interventions at one layer are misclassified as violations at another, which could otherwise trigger unnecessary secondary responses.

5. Information Requirements and Data Modeling

Formalizing the interaction between onboard detect-and-avoid and UTM services requires explicit definitions of the information elements exchanged and of their associated quality attributes. Each information element is modeled as a random variable or stochastic process with specified bounds on latency, integrity, continuity, availability, and resolution. Let $I_k(t)$ denote the k-th information element available to a given function at time t, where examples include ownship state estimate, remote aircraft state estimate, declared intent trajectories, airspace constraint sets, conformance status flags, and system health indicators [24]. For each $\mathrm{I}_k(t), anassociatedtuple \mathrm{Q}_k(t) =$

$$\big(\tau_k(t), \varepsilon_k(t), \eta_k(t), \alpha_k(t)\big)$$

represents effective latency τ_k, maximum bias or integrity risk ε_k, continuity status η_k, and availability indicator α_k [25]. These attributes may evolve over time as channel conditions, sensor health, or service-level performance change. The detect-and-avoid and UTM logic must be designed to account for $\mathrm{Q}_k(t) intheirdecisionrules, ratherthanassumingid$

Trajectory intent is modeled as a function $\gamma_i(t)$ that maps time into a nominal state with associated uncertainty bounds. For planning horizons of interest, $\gamma_i(t)$ may be represented by a sequence of waypoints with timestamps and speed constraints, or by parameterized curves. For the purpose of integration, the key requirement is that trajectory intents shared with UTM and those used onboard to predict ownship motion are consistent up to a bounded divergence. Let $\hat{\gamma}_i^{\mathrm{UTM}}(t)$ denote the intent representation stored by UTM and $\hat{\gamma}_i^{\mathrm{OB}}(t)$ the corresponding onboard representation. A consistency requirement can be stated as

$$\sup_{t\in[0,T]} \left\| [26] \hat{\gamma}_i^{\mathrm{UTM}}(t) - \hat{\gamma}_i^{\mathrm{OB}}(t) \right\| \leq \Delta_\gamma,$$

for some tolerance Δ_γ derived from navigation and communication performance. When this bound is exceeded, either due to unreported maneuvers or data loss, the system transitions to a non-conformance regime in which UTM and neighboring aircraft treat the trajectory as uncertain and adjust conflict assessment thresholds accordingly.

Remote traffic information is derived from cooperative surveillance, non-cooperative sensors, and UTM-mediated track services. Let $z_{ij}(t)$ denote the measurement of aircraft j as seen by aircraft i, and let $\hat{x}_j^{\mathrm{UTM}}(t)$ be the state estimate provided by UTM. The onboard detect-and-avoid system forms a fused estimate $\tilde{x}_j(t)$ according to rules that account for the reliability of each

Table 15. Architecture and roles: summary

Section	Core Theme	Outcome
System Architecture, Human Roles, and Implementation Considerations	Functional partitioning	Maps services to avionics, ground, and UTM
	Human oversight model	Positions operators as supervisors, not manual resolvers

Table 16. Architecture and roles: enablers

Element	Description	Relevance
Interfaces	Standardized messages and health flags	Enables certification and interoperability
Resilience	Fallback modes and cyber safeguards	Limits impact of failures or attacks

source. In abstract form,

$$\tilde{x}_j(t) = F\left(z_{ij}(t), \hat{x}_j^{\mathrm{UTM}}(t), Q_z(t), Q_{\mathrm{UTM}}(t)\right),$$

where F is a fusion operator that down-weights or discards inconsistent inputs when integrity indicators suggest possible faults [27]. The information requirement imposed on UTM in this context is not that it provide exact truth, but that it provide track estimates whose residual errors and fault probabilities are bounded in a manner compatible with onboard integrity monitoring. Similarly, UTM requires that aircraft share minimal status indicators, such as health of detect-and-avoid capability and adherence to negotiated intent, to maintain an accurate network picture.

Airspace constraint information includes static structures, temporary restrictions, and dynamic hazard volumes. These constraints are treated as sets in the state space, denoted $\mathscr{A}_m(t)$ for the m-th constraint. For integration, it is necessary that any constraint used by UTM for strategic planning be made available in compatible form onboard so that detect-and-avoid and trajectory generation do not inadvertently violate restrictions while resolving conflicts. A consistency condition of the form

$$\mathscr{A}_m^{\mathrm{OB}}(t) \supseteq \mathscr{A}_m^{\mathrm{UTM}}(t)$$

may be imposed to ensure that onboard representations are at least as conservative as those used by UTM, reducing the risk that onboard maneuvers driven by detect-and-avoid logic encroach into airspace that UTM treats as protected. [28]

Information requirements can be further expressed in terms of timing semantics. For each critical function, such as short-horizon conflict detection, there exists a maximum tolerable end-to-end delay between the generation of a relevant event and the availability of sufficient information to react. Denote this delay bound by $\tau_{\max}$ for the function. The integrated design must ensure that the combined latencies of sensing, communication, processing, and actuation do not exceed $\tau_{\max}$ with probability above a specified risk threshold. This leads to inequalities of the form

$$\Pr\left(\tau_{\text{sense}} + \tau_{\text{comm}} + \tau_{\text{proc}} + \tau_{\text{act}} > \tau_{\max}\right) \leq \rho,$$

where ρ is a small allocation of allowable exceedance probability. Mapping such probabilistic timing constraints into specifications for UTM services and onboard components provides a systematic means to align their performances without overconstraining implementations. [29]

The specification of semantics for each shared information element is as important as its numerical accuracy. For instance, a conformance status flag may encode distinct states such as conforming, marginal, nonconforming, or unknown, each with associated expectations for subsequent behavior. When an aircraft is labeled marginal, UTM may increase surveillance priority or adjust predicted uncertainty bounds, while onboard detect-and-avoid may treat that aircraft with slightly more conservative thresholds. If labeled non-conforming or unknown, stronger assumptions about possible maneuvers are applied, potentially triggering earlier or more pronounced avoidance actions. These semantic layers operate on top of the quantitative models Q$_k(t)$*andensurethatdifferenc*

Health information about detect-and-avoid capability itself also forms part of the integration. Let H$_i(t)$*representadiscrete*
valuedindicatorofthehealthstateofdetect − and − avoidonaircrafti, takin
and − avoidcapability, UTMmayimposeincreasedseparationbuffersarou
and − avoidthresholdswhenencounteringit.

Structuring information requirements in this explicit manner enables systematic traceability from high-level safety objectives to concrete interface specifications. Instead of relying solely on informal language about reliable connectivity or adequate surveillance, system designers can allocate risk budgets to particular informa-

Table 17. Simulation assessment: themes

Section	Core Theme	Outcome
Simulation-Based Assessment of Integrated DAA-UTM Concepts	Scenario-driven evaluation	Quantifies safety and efficiency under variability
	Stress testing integration	Examines impact of delays, outages, mixed equipage

Table 18. Simulation assessment: tools

Element	Description	Relevance
Monte Carlo models	Randomized encounters and flows	Estimates collision and alert statistics
Sensitivity studies	Vary information quality and logic	Supports refinement of requirements

tion flows, define measurable indicators of compliance, and support verification through simulation and testing. The resulting model does not assume that all information is always available at high quality; rather, it prescribes how detect-and-avoid and UTM functions should adapt their behaviors as quality indicators Q$_k(t)andhealthstatesH_k(t)evolveovertime.$[31]

6. Conflict Detection, Risk Metrics, and Resolution Modeling

The detect-and-avoid and UTM layers implement related but distinct conflict detection and resolution processes. A consistent integration requires that, while their algorithms may differ, they operate on compatible abstractions and risk metrics. Consider again an encounter between aircraft i and j. The relative state is described by r$_{ij}(t)andu_{ij}(t),andtheprotectedvolume\mathscr{P}$. The onboard detect-and-avoid system estimates a probability distribution over r$_{ij}(t)conditionedonallavailabledata.Letthisdistributionatpredictiontimetwithhorizon\Delta$ be $f_{ij}(r;t,\Delta)$. A basic risk metric is the probability that the protected volume is violated within the look-ahead horizon:

$$P_{ij}(t,\Delta) = \int_{\mathscr{P}} f_{ij}(r;t,\Delta)\,\mathrm{d}r.$$

Resolution thresholds are defined by comparing $P_{ij}(t,\Delta)$ with predefined alert levels. In the integrated setting, these thresholds should be harmonized with UTM-level triggers for strategic advisories, such that UTM does not frequently recommend maneuvers in situations where onboard logic considers risk negligible, and vice versa.

UTM conflict detection operates primarily on predicted trajectories $\gamma_i(t)$ and $\gamma_j(t)$. Let $d_{ij}(t)$ denote the predicted separation between these nominal trajectories. UTM may define a deterministic separation margin function $s(t)$ and flag a strategic conflict when $d_{ij}(t) < s(t)$ for some t within its planning horizon. To align with probabilistic onboard metrics, the separation margin should be interpretable as an envelope that, together with uncertainty models, implies an approximate bound on $P_{ij}(t,\Delta)$. One approach is to choose s(t) such that, for nominal uncertainty covariances, the probability of penetration of $\mathscr{P}$ during adherence to γ_i and γ_j remains below a design value. This requires that UTM and onboard systems share at least coarse assumptions about navigation performance and maneuvering behavior, even if their detailed models differ. [32]

Resolution modeling in the integrated context is framed as a constrained optimal control problem in which candidate maneuvers must satisfy both onboard safety constraints and compatibility with UTM-managed airspace. For aircraft i, define a control policy $u_i(t)$ over a near-term horizon that influences its trajectory. A generic formulation is

$$\min_{u_i(\cdot)} \int_{t_0}^{t_0+T} L\big(x_i(t),u_i(t)\big)\,\mathrm{d}t,$$

subject to dynamics $\dot{x}_i(t) = f_i(x_i(t),u_i(t),w_i(t))$, bounds on inputs and states, satisfaction of airspace constraints, and maintenance of collision risk below alert thresholds. Integration with UTM introduces additional constraints representing adherence to or controlled deviations from negotiated intent. For example, a compact condition may require that the deviation between actual and negotiated trajectory, denoted $\delta_i(t)$, remains within a tolerance envelope unless a conflict resolution requires temporary excursion:

$$\|\delta_i(t)\|[33] \le \Delta_{\mathrm{nom}},$$

for nominal operations, and a relaxed bound for explicit resolution segments coordinated with UTM.

In scenarios where UTM issues a resolution advisory based on network-level optimization, the onboard detect-and-avoid system evaluates this advisory as one candidate control policy among many. Formally, if UTM proposes a control profile $u_i^{\mathrm{UTM}}(t)$ or an equivalent path

Section	Core Theme	Outcome
System Architecture, Human Roles, and Implementation Considerations	Functional partitioning	Maps services to avionics, ground, UTM
	Human oversight model	Positions operators as supervisors, not manual resolvers

Element	Description	Relevance
Interfaces	Standardized messages and health flags	Enables certification and interoperability
Resilience	Fallback modes and cyber safeguards	Limits impact of failures or attacks

adjustment, onboard logic computes the resulting risk metric $P_{ij}^{\mathrm{UTM}}(t,\Delta)$ for all relevant j and accepts the advisory only if

$$P_{ij}^{\mathrm{UTM}}(t,\Delta) \le P_{\max}$$

for all encounter partners, where $P_{\max}$ is the onboard tactical threshold. If the proposed advisory does not satisfy this condition, onboard systems may modify or override it while informing UTM of the adopted maneuver, enabling UTM to update its predictions and generate consistent advisories for others. This mechanism ensures that tactical safety constraints are enforced locally while preserving as much alignment as possible with network-level coordination.

An additional integration aspect concerns mutual predictability of resolution logics. If each aircraft independently applies detect-and-avoid rules that are opaque to UTM and to each other, coordinated behavior may be difficult to guarantee, especially in dense airspace. To mitigate this, the operational concept may include the publication of abstract behavior models or maneuvering policies, such as preferred avoidance directions or speed-change patterns, that UTM and neighboring aircraft can assume in their predictions. Mathematically, these policies can be represented as admissible sets of control actions $\mathscr{U}_i(t)$ conditioned on observed conflicts, with UTM-level planning assuming that aircraft will choose controls within $\mathscr{U}_i(t)$. The detect-and-avoid and UTM functions are integrated when these assumed sets are consistent with actual onboard implementations, thereby reducing the risk of incompatible expectations without revealing proprietary algorithmic details. [34]

More detailed modeling of conflict evolution can be obtained by linearizing relative motion under constant-velocity or constant-acceleration assumptions. For example, under a constant-velocity model, future relative position over a look-ahead interval Δ is approximated by

$$r_{ij}(t+\Delta) = r_{ij}(t) + u_{ij}(t)\,\Delta.$$

Within this simplification, conditions for predicted penetration of $\mathscr{P}$ reduce to checks on scalar projections of u$_{ij}(t) along r_{ij}(t), enabling closed-form expressions for approximate intru$ $velocity case illustrates how onboard and UTM assessments can be related:$ $UTM might operate with coarser-granularity approximations of similar fo$ $rate measurements and nonlinear models.$

Incorporating uncertainties more explicitly, suppose the relative state at time t is modeled as a Gaussian random vector with mean $\mu_{ij}(t)$ and covariance matrix $\Sigma_{ij}(t)$. Under linear dynamics and Gaussian process noise, the predicted distribution at horizon Δ remains Gaussian with updated moments. An approximate closed-form for the probability of entering $\mathscr{P}$ can then be derived using standard techniques for computing probabilities over hyper-rectangular regions. While exact computation may be intensive, upper bounds can be expressed in terms of one-dimensional tail probabilities of normalized components of $\mu_{ij}(t)$. These approximations motivate risk-based alerting criteria that can be tuned consistently across different implementations. The critical integration requirement is that UTM-level thresholds on predicted separation and onboard-level thresholds on probabilistic risk are calibrated so that they do not lead to contradictory categorizations of the same situation.

Another modeling aspect addresses multi-intruder scenarios in which an aircraft faces simultaneous or sequential conflicts with multiple neighbors [35]. Let $\mathscr{N}_i(t)$ denote the set of relevant intruders for aircraft i at time t, defined through screening thresholds on range and relative geometry. A composite risk metric may be defined as

$$P_i(t) = 1 - \prod_{j \in \mathscr{N}_i(t)} \big(1 - P_{ij}(t,\Delta)\big),$$

representing the probability of at least one protected volume violation within the horizon under independence assumptions. Onboard detect-and-avoid may use such a metric to prioritize resolution against the most critical intruders while ensuring that overall risk remains bounded. UTM services, observing a broader set of

Section	Core Theme	Outcome
Simulation-Based Assessment of Integrated DAA-UTM Concepts	Scenario-driven evaluation	Quantifies safety and efficiency under variability
	Stress testing integration	Examines impact of delays, outages, mixed equipage

Element	Description	Relevance
Monte Carlo models	Randomized encounters and flows	Estimates collision and alert statistics
Sensitivity studies	Vary information quality and logic	Supports refinement of requirements

trajectories, may apply analogous metrics at the network level to identify hotspots where multiple potential conflicts interact. The integration challenge is to ensure that local decision rules based on $\mathrm{P}_i(t)$ and network-level interventions based on aggregate metrics do not interfere destructively [36]. [illegible]

7. System Architecture, Human Roles, and Implementation Considerations

Realizing the integrated concept in practice involves architectural decisions concerning the partitioning of functions between onboard processors, ground control stations, and distributed UTM services, as well as the allocation of oversight roles among human operators and supervisory authorities. An abstract architecture can be described in which each aircraft hosts an integrated avionics stack combining navigation, flight control, detect-and-avoid processing, and communication functions. This stack interfaces with one or more remote pilot stations or fleet management centers and with UTM service providers through standardized data-link protocols. Onboard detect-and-avoid modules access local sensors, such as cooperative transceivers and electro-optical or radar systems, and receive network-distributed tracks and constraints. UTM services aggregate flight intents, track feeds, conformance assessments, and airspace configuration data, providing summarized advisories to relevant participants. The architecture is constrained by the principle that safety-critical decision loops for immediate collision avoidance do not depend on a single external service. [37]

From an implementation perspective, the interfaces between detect-and-avoid and UTM are central to certification and interoperability. These interfaces specify message types, timing requirements, and error handling behaviors rather than internal algorithms. For example, an onboard system might be required to publish health indicators of its detect-and-avoid capability, including validity of sensor inputs and availability of key processing functions. UTM services may use these indicators to adjust the confidence placed in trajectory predictions and to decide whether additional separation buffers are necessary. Similarly, UTM-originated advisories are labeled with quality metrics indicating the assumptions, horizon, and residual uncertainties under which they were generated, enabling onboard logic to evaluate them in light of its own risk estimates. This modular approach supports implementations by multiple vendors, provided each adheres to the common semantics and performance envelopes implied by the information requirements.

Human operators remain responsible within this architecture but interact with the integrated system primarily through higher-level supervisory functions [38]. Remote pilots or fleet managers monitor mission progress, system status, and alerts generated by both onboard detect-and-avoid and UTM services. Their role is to validate or refine strategic decisions, such as rerouting around evolving constraints or modifying mission objectives, rather than to manually execute time-critical collision avoidance maneuvers. For such a role allocation to be credible, alerts and advisories must be presented in a manner that is consistent across systems and that reveals the underlying rationale at an appropriate level of abstraction. This suggests that both onboard and UTM components should expose harmonized human-machine interface concepts, such as common alert levels, standardized phrasing for recommended actions, and clear indication of whether an advisory is mandatory, suggested, or informational.

Implementation considerations also include resilience to partial failures and cyber-physical threats. Because integration introduces dependencies between onboard and networked elements, failure of one component has the potential to propagate. To contain such effects, the architecture can enforce structural constraints where onboard detect-and-avoid always retains a conservative fallback policy that assumes worst-case behavior of traffic in the absence of trustworthy UTM data [39]. UTM services, in turn, should be designed so that unresponsive or misbehaving nodes are isolated based on conformance and health data, preventing their anomalies from undermining network-level planning. These behaviors can be represented as state machines with explicit transitions triggered by threshold crossings in quality metrics $Q_k(t), ensuringthatresponsestodegradationaredeterministicandanalyzable$

The integration of autonomy with human oversight raises additional design questions. Automated resolution decisions must be explainable to the extent required for post-event analysis and for the calibration of operator trust. This can be supported by logging a compact set of variables, such as the evaluated risk metrics, candidate maneuvers considered, selected action, and relevant information quality indicators at each decision point. Representing these logs in a standardized format across onboard detect-and-avoid and UTM services facilitates safety assessment and investigation processes without imposing particular algorithm structures. Overall, architectural and human integration considerations influence how the abstract concepts and mathematical models can be realized in systems that are certifiable, maintainable, and adaptable to evolving regulatory and technological contexts. [40]

Practical deployment also raises questions of scalability and lifecycle management. As the number of participating aircraft and service providers grows, the architecture must prevent centralized bottlenecks and allow incremental introduction of new capabilities. One approach is to define the detect-and-avoid and UTM interface as a set of minimal mandatory messages common to all participants, with optional extensions for enhanced performance. This permits early systems with limited functionality to interoperate safely alongside more advanced platforms. Over time, performance-based requirements can incentivize migration toward richer capabilities without invalidating earlier deployments. Careful versioning and backward compatibility mechanisms are necessary to ensure that updates to message schemas or interpretation rules do not create latent inconsistencies in safety-critical behavior.

Cybersecurity considerations are inherent in any architecture relying on distributed digital communication [41]. Integrity of messages carrying trajectory intents, health statuses, and advisories is essential, since manipulated data could induce unsafe maneuvers or erode trust in the system. The integration concept therefore assumes cryptographic protection and authentication of safety-relevant messages, but it must also be resilient when such protections fail or when anomalies are detected. For example, if onboard systems detect inconsistencies between locally sensed traffic and UTM-provided tracks beyond plausible error bounds, they may downgrade the trust level assigned to network data and revert to conservative policies relying on onboard sensing. UTM services, similarly, may flag anomalous behavior by particular nodes and adjust their influence on network-level planning. These defensive reactions can be formalized through thresholds on residuals between fused estimates and individual sources, promoting predictable fallback behaviors.

Finally, the role of human oversight within the integrated architecture should be aligned with realistic cognitive capabilities. Operators supervising multiple vehicles cannot be expected to interpret complex, rapidly changing conflict geometries in real time [42]. Instead, systems should present synthesized information about risk trends, rule-based justifications for automatic maneuvers, and clear indications when operator input is required for higher-level decisions. Training and procedures can then focus on understanding the logic of integration, the meaning of health and conformance indicators, and the appropriate responses to alerts, rather than on ad hoc strategies for individual conflicts. This perspective treats human operators and automated systems as complementary elements in a single control loop, where automation handles fast timescales under defined rules and humans provide oversight, exception handling, and long-horizon judgment.

8. Simulation-Based Assessment of Integrated DAA-UTM Concepts

Assessing whether a proposed integration of onboard detect-and-avoid with UTM services supports acceptable risk levels and operational efficiency requires systematic simulation and analysis. While the precise configuration of such assessments depends on local use cases, a generic framework can be described in which encounter models, traffic demand scenarios, and performance models of sensing and communication are combined into Monte Carlo experiments. These experiments are used to estimate metrics such as probability of protected volume violation, rate of unnecessary maneuvering, trajectory deviation magnitudes, and sensitivity to degradation in information quality.

Let $\boldsymbol{\theta}$ denote a vector of scenario parameters describing traffic density, equipage mix, communication performance, and environmental conditions [43]. For a given integration concept and a fixed $\boldsymbol{\theta}$, define a random variable $Z(\boldsymbol{\theta})$ representing an outcome metric, such as the minimum separation achieved in an encounter or the number of conflict resolution maneuvers initiated per flight hour. The simulation framework approximates the distribution of $Z(\boldsymbol{\theta})$ by repeated sampling over stochastic elements including initial conditions, sensor noise, and decision logic variability. For each outcome metric, one may estimate its expectation and selected quantiles. For example, let $J(\boldsymbol{\theta})$ denote the estimated probability of a protected volume violation in a representative operation under scenario $\boldsymbol{\theta}$. Formally,

$$J(\boldsymbol{\theta}) = \Pr\left([44]\exists t : r_{ij}(t) \in \mathscr{P} \,\middle|\, \boldsymbol{\theta}\right),$$

where the probability is taken over the ensemble of simulated encounters and uncertainties. The integration concept is considered compatible with specified safety objectives if $J(\boldsymbol{\theta})$ remains below allocated thresholds across the relevant scenario envelope.

An important feature of simulation-based assessment in this context is the explicit modeling of information inconsistencies between onboard systems and UTM services. This includes time-varying latency in sharing trajectory updates, intermittent loss of advisories, and discrepancies between onboard and UTM estimates of traffic states [45]. By parameterizing these effects in $\boldsymbol{\theta}$, one can evaluate how sensitive conflict detection and resolution performance is to deviations from ideal assumptions. For instance, an analysis may examine the change in $J(\boldsymbol{\theta})$ as a function of increased latency in UTM-provided tracks while onboard detect-and-avoid continues to operate on local sensing. Similar experiments can probe the consequences of overconfident or underconfident integrity flags on shared information elements, identifying regimes in which the integrated system becomes either overly conservative or insufficiently responsive.

Another dimension of assessment concerns interactions among multiple aircraft executing coordinated or independent resolution maneuvers. Integrated concepts that rely heavily on UTM-mediated deconfliction might, in principle, reduce the likelihood of conflicting avoidance maneuvers in multi-vehicle encounters. However, if connectivity is degraded or if response times differ, independent onboard decisions may dominate. Simulation campaigns can quantify the rate of such interactions and assess whether the combination of onboard and UTM policies leads to stable behavior, meaning that conflicts are typically resolved with bounded maneuver complexity and without oscillatory or indecisive patterns [46]. This is particularly relevant in dense corridors and urban environments, where aircraft may face overlapping advisories and where consistency between onboard and UTM assumptions about right-of-way or preferred maneuvering spaces is critical.

The outputs of such assessments inform refinement of the information requirements and operational concepts. If, for a given allocation of responsibilities and quality attributes $Q_k(t)$, *simulationsindicatethatrisktargetsarenotmetforcertaintrafficdensities,theintegrationdesigncanbeadjustedbytighteningl*
and−avoidandUTMintegrationtoquantitativeoutcomemetricsprovidesausefulbasisforregulatoryevaluationandforcomparingalternativ

Developing such simulation frameworks requires careful abstraction choices. The models must be rich enough to capture key dependencies introduced by integration, such as the coupling between information latency and detect-and-avoid decision timing, yet computationally tractable for large-scale experimentation [47]. One strategy is to separate fast-time encounter simulation from slower-time network evolution. Fast-time modules simulate individual conflicts using detailed kinematic and sensor models, while slow-time modules generate traffic patterns, UTM advisories, and constraint updates at coarser resolution. Interfaces between these modules exchange aggregated statistics or parameterized response surfaces rather than raw trajectories, enabling exploration of broad parameter spaces without prohibitive cost. Within this structure, integrated detect-and-avoid and UTM logic can be instantiated with varying fidelity, from high-level policy emulations to code-level prototypes.

A further consideration is validation of the simulation environment itself. Since regulatory and operational decisions may rely on its outputs, the models of detect-and-avoid and UTM behavior should be traceable to documented requirements and, where available, empirical measurements. Sensitivity analyses can identify which assumptions about sensing, communication, or pilot response most strongly influence estimated risk metrics, guiding data collection efforts [48]. Scenario design should reflect realistic distributions of mission types, including point-to-point logistics, inspection flights, and ad hoc operations, as well as a spectrum of equipage levels and compliance rates. Only by exercising the integrated concept under such diverse conditions can stakeholders gain a balanced view of its implications.

Although simulation cannot substitute for operational experience, it enables structured exploration of rare events that would be difficult to observe directly. Integrated detect-and-avoid and UTM concepts can thus be stress-tested against extreme but plausible combinations of delays, outages, and unexpected maneuvers. When discrepancies emerge between intended and observed behavior within the simulations, they can be traced back to specific assumptions in the information requirements or operational rules, prompting targeted refinements. This iterative loop between concept definition and simulation-based evaluation contributes to a gradual convergence toward integration strategies that are analytically justified and practically implementable within heterogeneous operational environments.

9. Conclusion

The integration of onboard detect-and-avoid systems with UAS Traffic Management services is a structural requirement for the scalable use of uncrewed aircraft in low altitude airspace, yet it raises questions about the allocation of responsibilities, the quality and semantics of shared information, and the compatibility of independent decision-making processes [49]. This paper has outlined an operational concept in which UTM services manage strategic and pre-tactical separation through intent coordination and constraint dissemination, while onboard detect-and-avoid manages tactical collision risk in the presence of uncertainties and connectivity limitations. Information requirements have been expressed using explicit models for latency, integrity, continuity, and availability, together with consistency conditions between onboard and UTM representations of trajectories, constraints, and system health.

By introducing probabilistic risk metrics for conflict detection and framing resolution maneuvers as constrained optimal control problems, the analysis provides a means to reason about how onboard and network-level decisions interact. Short-horizon collision avoidance thresholds and long-horizon separation margins can be related through shared assumptions about navigation and maneuver capabilities, enabling UTM advisories to be evaluated onboard and onboard maneuvers to be anticipated by UTM services. Architectural and human integration considerations highlight the need for interfaces that are precise in semantics yet flexible in implementation, allowing multiple vendors and service providers to interoperate without exposing proprietary internal algorithms.

Simulation-based assessment was discussed as a mechanism to evaluate candidate integration concepts against safety and efficiency metrics under varying conditions of traffic density, equipage, and information quality. Such assessments do not offer definitive guarantees but help identify parameter regimes where integrated operations maintain acceptable collision risk while avoiding excessive conservatism. Overall, the results indicate that coherent definitions of information requirements, risk metrics, and fallback behaviors can support integration paths in which onboard detect-and-avoid remains responsible for last-resort safety, UTM services contribute structured coordination, and the combined system exhibits predictable behavior across nominal, degraded, and contingency conditions. [50]

References

[1] M. Klenka, "Major incidents that shaped aviation security," Journal of Transportation Security, vol. 12, pp. 39–56, 2 2019.

[2] U. Seidaliyeva, D. Akhmetov, L. Ilipbayeva, and E. T. Matson, "Real-time and accurate drone detection in a video with a static background.," Sensors (Basel, Switzerland), vol. 20, pp. 3856–, 7 2020.

[3] E. A. Yfantis and S. L. Harris, "An autonomous uas with ai for forest fire prevention, detection, and real time advice and communication to and among firefighters," Journal of Computer Science Applications and Information Technology, vol. 2, pp. 1–5, 10 2017.

[4] A. T. Mozas-Calvache, J. L. Pérez-García, and T. F. del Castillo, "Monitoring of landslide displacements using uas and control methods based on lines," Landslides, vol. 14, pp. 2115–2128, 5 2017.

[5] S. Dorafshan and M. Maguire, "Bridge inspection: human performance, unmanned aerial systems and automation," Journal of Civil Structural Health Monitoring, vol. 8, pp. 443–476, 5 2018.

[6] A. J. Werth, M. M. Kosma, E. M. Chenoweth, and J. M. Straley, "New views of humpback whale flow dynamics and oral morphology during prey engulfment.," Marine Mammal Science, vol. 35, pp. 1556–1578, 5 2019.

[7] S. Guan, Z. Zhu, and G. Wang, "A review on uav-based remote sensing technologies for construction and civil applications," Drones, vol. 6, pp. 117–117, 5 2022.

[8] A. Udovic, H. de Jong, and J. Vielhauer, "Validation of unmanned aircraft systems' integration into the airspace (vusil i and ii)," SAE International Journal of Aerospace, vol. 4, pp. 1216–1227, 10 2011.

[9] J. R. M. de Dios, L. Merino, F. Caballero, and A. Ollero, "Automatic forest-fire measuring using ground stations and unmanned aerial systems," Sensors (Basel, Switzerland), vol. 11, pp. 6328–6353, 6 2011.

[10] A. C. Canolla, M. B. Jamoom, and B. Pervan, "Unmanned aircraft systems detect and avoid sensor hybrid estimation error analysis," in 17th AIAA Aviation Technology, Integration, and Operations Conference, p. 4384, 2017.

[11] S. C. Hassler and F. Baysal-Gurel, "Unmanned aircraft system (uas) technology and applications in agriculture," Agronomy, vol. 9, pp. 618–, 10 2019.

[12] S. C. Britch, K. J. Linthicum, R. L. Aldridge, F. V. Golden, and T. W. Walker, "Visualizing efficacy of pesticides against disease vector mosquitoes in the field.," Journal of visualized experiments : JoVE, 3 2019.

[13] G. Iannace, G. Ciaburro, and A. Trematerra, "Fault diagnosis for uav blades using artificial neural network," Robotics, vol. 8, pp. 59–, 7 2019.

[14] P. Koutalakis, O. Tzoraki, G. I. Prazioutis, G. T. Gkiatas, and G. N. Zaimes, "Can drones map earth cracks? landslide measurements in north greece using uav photogrammetry for nature-based solutions," Sustainability, vol. 13, pp. 4697–, 4 2021.

[15] T. Fernández, J. M. Gómez-López, J. L. Pérez-García, J. Cardenal, J. Delgado, E. M. Mata, M. Sánchez-Gómez, J. Calero, J. Tovar-Pescador, and F. Moya, "Analysis of gully erosion in a catchment area in olive groves using uas photogrammetry techniques," The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLIII-B2-2020, pp. 1057–1064, 8 2020.

[16] J. M. Boehmler, S. M. Loría-Salazar, C. Stevens, J. D. Long, A. C. Watts, H. A. Holmes, J. C. Barnard, and W. P. Arnott, "Development of a

multispectral albedometer and deployment on an unmanned aircraft for evaluating satellite retrieved surface reflectance over nevada's black rock desert.," Sensors (Basel, Switzerland), vol. 18, pp. 3504–, 10 2018.

[17] F. A. Chicaiza, E. Slawiñski, L. R. Salinas, and V. A. Mut, "Evaluation of path planning with force feedback for bilateral teleoperation of unmanned rotorcraft systems," Journal of Intelligent & Robotic Systems, vol. 105, 5 2022.

[18] K. Iizuka, T. Yonehara, M. Itoh, and Y. Kosugi, "Estimating tree height and diameter at breast height (dbh) from digital surface models and orthophotos obtained with an unmanned aerial system for a japanese cypress (chamaecyparis obtusa) forest," Remote Sensing, vol. 10, pp. 13–, 12 2017.

[19] F. Sanfilippo, J. Azpiazu, G. Marafioti, A. A. Transeth, Øyvind Stavdahl, and P. Liljeback, "Perception-driven obstacle-aided locomotion for snake robots: The state of the art, challenges and possibilities †," Applied Sciences, vol. 7, pp. 336–, 3 2017.

[20] R. Day and J. L. Salmon, "A framework for multi-uav persistent search and retrieval with stochastic target appearance in a continuous space," Journal of Intelligent & Robotic Systems, vol. 103, pp. 1–17, 11 2021.

[21] C. I. Justino, A. C. Duarte, and T. Rocha-Santos, "Recent progress in biosensors for environmental monitoring: A review.," Sensors (Basel, Switzerland), vol. 17, pp. 2918–, 12 2017.

[22] S. S. Ateş, M. Uzgör, and K. Yüksek, "Uav tracking module proposal based on a regulative comparison between manned and unmanned aviation," Journal of Airline and Airport Management, vol. 12, pp. 29–29, 7 2022.

[23] A. la Cour-Harbo and H. Schiøler, "Probability of low altitude midair collision between general aviation and unmanned aircraft," Risk analysis : an official publication of the Society for Risk Analysis, vol. 39, pp. 2499–2513, 7 2019.

[24] M. Finke and S. Lorenz, "Segmented standard taxi routes—a new way to integrate remotely piloted aircraft into airport surface traffic," Aerospace, vol. 7, pp. 83–, 6 2020.

[25] F. Corraro, G. Corraro, G. Cuciniello, and L. Garbarino, "Unmanned aircraft collision detection and avoidance for dealing with multiple hazards," Aerospace, vol. 9, pp. 190–190, 4 2022.

[26] A. Qadir, W. H. Semke, and J. Neubert, "Vision based neuro-fuzzy controller for a two axes gimbal system with small uav," Journal of Intelligent & Robotic Systems, vol. 74, pp. 1029–1047, 8 2013.

[27] W.-L. Chuang and S.-M. Lin, "A piv-based algorithm for simultaneous determination of multiple velocity fields from stratified crossflows in single field of view," Water, vol. 14, pp. 1877–1877, 6 2022.

[28] P. B. Chilson, T. M. Bell, K. Brewster, G. B. H. de Azevedo, F. H. Carr, K. Carson, W. Doyle, C. A. Fiebrich, B. R. Greene, J. L. Grimsley, S. T. Kanneganti, J. J. Martin, A. D. Moore, R. D. Palmer, E. A. Pillar-Little, J. L. Salazar-Cerreno, A. R. Segales, M. E. Weber, M. Yeary, and K. K. Droegemeier, "Moving towards a network of autonomous uas atmospheric profiling stations for observations in the earth's lower atmosphere: The 3d mesonet concept.," Sensors (Basel, Switzerland), vol. 19, pp. 2720–, 6 2019.

[29] L. Pádua, J. Hruška, J. Bessa, T. Adão, L. Martins, J. A. Gonçalves, E. Peres, A. Sousa, J. P. Castro, and J. J. Sousa, "Multi-temporal analysis of forestry and coastal environments using uass," Remote Sensing, vol. 10, pp. 24–, 12 2017.

[30] Y. Akbari, N. Almaadeed, S. Al-Maadeed, and O. Elharrouss, "Applications, databases and open computer vision research from drone videos and images: a survey," Artificial Intelligence Review, vol. 54, pp. 3887–3938, 2 2021.

[31] F. Benassi, E. Dall'Asta, F. Diotri, G. Forlani, U. M. di Cella, R. Roncella, and M. Santise, "Testing accuracy and repeatability of uav blocks oriented with gnss-supported aerial triangulation," Remote Sensing, vol. 9, pp. 172–, 2 2017.

[32] A. Canolla, M. B. Jamoom, and B. Pervan, "Interactive multiple model sensor analysis for unmanned aircraft systems (uas) detect and avoid (daa)," in 2018 IEEE/ION Position, Location and Navigation Symposium (PLANS), pp. 757–766, IEEE, 2018.

[33] O. Alvear, C. T. Calafate, N. R. Zema, E. Natalizio, E. Hernández-Orallo, J.-C. Cano, and P. Manzoni, "a discretized approach to air pollution monitoring using uav-based sensing," Mobile Networks and Applications, vol. 23, pp. 1693–1702, 5 2018.

[34] C. S. Kulkarni and K. Goebel, "Joint special issue on phm for aerospace systems," International Journal of Prognostics and Health Management, vol. 12, 3 2021.

[35] F. Friedman-Berg, J. Rein, and N. Racine, "Minimum visual information requirements for detect and avoid in unmanned aircraft systems," Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 58, pp. 54–58, 10 2014.

[36] A. Alvino and S. Marino, "Remote sensing for irrigation of horticultural crops," Horticulturae, vol. 3, pp. 40–, 6 2017.

[37] T. Ostermann, C. L. Ben, and I. Martin, “Larus: an unmanned aircraft for the support of maritime rescue missions under heavy weather conditions,” CEAS Aeronautical Journal, vol. 11, pp. 633–649, 3 2020.

[38] A. Lampert, B. Altstädter, K. Bärfuss, L. Bretschneider, J. Sandgaard, J. Michaelis, L. Lobitz, M. Asmussen, E. Damm, R. Käthner, T. Krüger, C. Lüpkes, S. Nowak, A. Peuker, T. Rausch, F. Reiser, A. Scholtz, D. S. Zakharov, D. Gaus, S. Bansmer, B. Wehner, and F. Pätzold, “Unmanned aerial systems for investigating the polar atmospheric boundary layer—technical challenges and examples of applications,” Atmosphere, vol. 11, pp. 416–, 4 2020.

[39] J. A. Pérez-Castán, F. G. Comendador, A. B. Cardenas-Soria, D. Janisch, and R. M. A. Valdés, “Identification, categorisation and gaps of safety indicators for u-space,” Energies, vol. 13, pp. 608–, 1 2020.

[40] A. J. Wirsing, A. N. Johnston, and J. J. Kiszka, “Foreword to the special issue on ’the rapidly expanding role of drones as a tool for wildlife research’,” Wildlife Research, vol. 49, pp. i–v, 2 2022.

[41] Y. Naidoo, R. Stopforth, and G. Bright, “Quad-rotor unmanned aerial vehicle helicopter modelling & control,” International Journal of Advanced Robotic Systems, vol. 8, pp. 45–, 1 2011.

[42] C. Brenner, M. Zeeman, M. Bernhardt, and K. Schulz, “Estimation of evapotranspiration of temperate grassland based on high-resolution thermal and visible range imagery from unmanned aerial systems,” International journal of remote sensing, vol. 39, pp. 5141–5174, 5 2018.

[43] J. S. Forbey, G. L. Patricelli, D. Delparte, A. H. Krakauer, P. J. Olsoy, M. Fremgen, J. D. Nobler, L. P. Spaete, L. A. Shipley, J. L. Rachlow, A. K. Dirksen, A. C. Perry, B. A. Richardson, and N. F. Glenn, “Emerging technology to measure habitat quality and behavior of grouse: Examples from studies of greater sage-grouse,” Wildlife Biology, vol. 2017, 6 2017.

[44] J. Saunders, S. Saeedi, and W. Li, “Autonomous aerial robotics for package delivery: A technical review,” Journal of Field Robotics, vol. 41, pp. 3–49, 7 2023.

[45] W. K. New, C. Y. Leow, K. Navaie, Y. Sun, and Z. Ding, “Application of noma for cellular-connected uavs: opportunities and challenges,” Science China Information Sciences, vol. 64, pp. 1–14, 3 2021.

[46] A. Michez, S. Broset, and P. Lejeune, “Ears in the sky: Potential of drones for the bioacoustic monitoring of birds and bats,” Drones, vol. 5, pp. 9–, 1 2021.

[47] V. R and K. K. Shaw, “Design and development of heavy drone for fire fighting operation,” International Journal of Engineering Research and, vol. 9, 6 2020.

[48] S. Oh, D.-Y. Lee, C. Gongora-Canul, A. Ashapure, J. Carpenter, A. P. Cruz, M. Fernández-Campos, B. Lane, D. E. P. Telenko, J. Jung, and C. D. Cruz, “Tar spot disease quantification using unmanned aircraft systems (uas) data,” Remote Sensing, vol. 13, pp. 2567–, 6 2021.

[49] M. Khalaf-Allah, “Novel solutions to the three-anchor toa-based three-dimensional positioning problem.,” Sensors (Basel, Switzerland), vol. 21, pp. 7325–, 11 2021.

[50] T.-H. Tran and D.-D. Nguyen, “Management and regulation of drone operation in urban environment: A case study,” Social Sciences, vol. 11, pp. 474–474, 10 2022.