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Assessment of Compatibility Between ACAS-Based Concepts and Small UAS Detect-and-Avoid in Low-Altitude Airspace

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Abstract

Small unmanned aircraft systems operating in low-altitude airspace are expected to share volume with crewed aviation, urban air mobility platforms, rotary-wing traffic, and dense obstacle fields while meeting regulatory constraints on collision risk and interoperability. Existing airborne collision avoidance concepts such as those derived from ACAS frameworks were originally formulated for higher-altitude, cooperative, and transponder-equipped traffic, under assumptions about surveillance performance, pilot response, separation minima, and airspace structure that do not directly hold for many low-altitude use cases. This paper examines the compatibility between ACAS-based collision avoidance concepts and detect-and-avoid architectures suitable for small unmanned aircraft in low-altitude environments, focusing on technical interactions among surveillance modalities, algorithmic decision logic, maneuverability limits, and communication constraints. The assessment considers to what extent ACAS-style advisories, state representations, and thresholding mechanisms can be consistently mapped into autonomous detect-and-avoid functions that must operate without pilot-in-the-loop and often with non-cooperative or partially cooperative traffic. The discussion covers scalability in dense operations, latency and integrity bounds, and the implications of low-cost sensors with limited performance. The analysis highlights conditions under which ACAS-based logics remain structurally compatible, conditions where direct transplantation leads to inconsistent or degraded behavior, and where tailoring of alerting thresholds, action spaces, and coordination concepts is required. The goal is to clarify the technical alignment and misalignment between these frameworks without prescribing a unique architecture, supporting reasoned integration choices for low-altitude detect-and-avoid systems.

1. Introduction

Low-altitude airspace is undergoing progressive diversification as small unmanned aircraft systems are introduced for inspection, logistics, emergency response, and data collection [1]. These vehicles tend to operate at altitudes historically dominated by rotorcraft, general aviation, and obstacle-rich urban structures, and they often rely on compact, low-power avionics. Regulatory expectations for an acceptable level of safety in this environment require credible detect-and-avoid capabilities, including both strategic conflict prevention and last-resort collision avoidance. At higher altitudes, airborne collision avoidance systems grounded in ACAS concepts have been developed to mitigate mid-air collision risk among transponder-equipped aircraft through coordinated, resolution advisory generation. The presence of a mature framework prompts the question whether such ACAS-based concepts can be directly or adaptively applied to small unmanned aircraft detect-and-avoid in low-altitude airspace.

The notion of compatibility is not limited to software reuse or parameter tuning [2]. It encompasses whether the underlying assumptions, state variables, decision structures, and

coordination mechanisms in ACAS-style systems can be consistently aligned with the operational reality of small unmanned aircraft. ACAS concepts generally presume reliable cooperative surveillance via secondary surveillance radar or ADS-B, bounded pilot response delays, prescribed vertical separation maneuvers, and relatively sparse traffic densities. In contrast, small unmanned aircraft often lack transponders, may rely on visual, acoustic, or compact radar sensing, and must function autonomously without human pilots directly executing guidance commands. Low-altitude airspace entails short time horizons to ground impact, occlusions due to terrain and infrastructure, and traffic patterns shaped by corridors or geo-fenced volumes.

Assessing compatibility between ACAS-based concepts and small unmanned aircraft detect-and-avoid therefore requires a structured analysis of several dimensions [3]. There is the algorithmic dimension, involving the mathematical form of conflict detection and resolution logic, including how advisories are synthesized from probabilistic state estimates. There is the systems dimension, covering sensor performance, communication architectures, and computational constraints, all of which influence the feasibility of running ACAS-like logic on small platforms. There is the operational dimension, where maneuverability limits, mission profiles, and environmental features determine which avoidance maneuvers are feasible, effective, and stable when commanded by onboard autonomy.

A direct transfer of existing ACAS logic into low-altitude unmanned operations could be inconsistent with these dimensions. For instance, many ACAS designs assume both aircraft will respond in a coordinated manner to resolution advisories exchanged via an air-to-air coordination channel [4]. Small unmanned aircraft operating among heterogeneous vehicles and non-cooperative obstacles cannot rely on such assumptions. Similarly, vertically biased advisories used in traditional ACAS may not be optimal or even feasible for vehicles with constrained climb performance or strict altitude limits due to airspace design. Small unmanned aircraft may need to prioritize lateral maneuvers or speed adjustments due to performance margins or regulatory constraints on altitude bands.

In parallel, small unmanned aircraft detect-and-avoid concepts are emerging that rely on strategic deconfliction layers, such as trajectory management services, and tactical avoidance layers based on onboard sensing. The interplay between these layers and ACAS-based ideas requires careful analysis of redundancy, conflict between guidance commands, and the possibility of unstable interactions if multiple avoidance logics are simultaneously active. Compatibility involves not only whether ACAS-like thresholds and logics can be numerically adjusted, but whether the structural role of an ACAS-style module remains coherent in a layered safety architecture. [5]

This paper develops a neutral, technical appraisal of this compatibility. It characterizes the salient features of ACAS-based concepts, outlines the requirements and constraints of small unmanned aircraft detect-and-avoid in low-altitude airspace, and constructs analytical models to explore how conflict detection and resolution decisions propagate through heterogeneous systems. By focusing on technical conditions rather than advocacy for a specific architecture, the paper aims to indicate where adaptation appears straightforward, where additional constructs are necessary, and where conceptual incompatibilities may persist.

2. Operational Context and Encounter Characterization for Low-Altitude Small UAS

The compatibility between ACAS-based concepts and small unmanned aircraft detect-and-avoid mechanisms depends critically on the operational and encounter context that defines

the statistical envelope of plausible conflicts. Low-altitude airspace, typically ranging from near ground level up to altitudes supporting dense rotorcraft and general aviation operations, presents geometric configurations, traffic patterns, and constraint sets that diverge from those assumed in traditional high-altitude collision avoidance design [6]. To reason about compatibility at a technical level, it is necessary to formalize the encounter space, characterize the underlying stochastic processes that generate relative motions, and identify how these distributions interact with sensing, control, and advisory structures. This section develops such a characterization, emphasizing features that materially affect whether ACAS-style logic can be meaningfully adapted or require substantive reformulation.

Low-altitude operations of small unmanned aircraft are often structured by local mission objectives and geographically constrained volumes. Typical patterns involve route following along predefined corridors, loitering over points of interest, or repeated traversals of narrow airspace between fixed locations. Crewed rotorcraft and general aviation aircraft intersect these regions episodically, sometimes with significant speed differentials and limited predictability of intent from the perspective of unmanned vehicles [7]. To formalize this environment, consider an airspace region represented as a bounded domain in three-dimensional position space, with embedded subregions for obstacles, no-fly zones, and protected infrastructure. Each aircraft trajectory within this domain may be modeled as a stochastic process influenced by waypoints, wind, tracking errors, and tactical decisions. The encounter process between any two vehicles can then be described by a relative state process defined on this domain, whose distribution depends on traffic intensity, routing policies, equipage, and external constraints.

Let a small unmanned aircraft be denoted by an index and a potential intruder by another index. Define a relative position vector and relative velocity vector in a fixed inertial frame aligned such that horizontal axes span the ground plane and the vertical axis corresponds to altitude. The encounter state at time can be represented as a vector combining relative position and velocity [8]. For many detect-and-avoid analyses, a lower-dimensional representation focusing on separation along the line of sight and along the vertical axis is convenient, but in low-altitude environments lateral structure, terrain, and obstacles introduce anisotropy that complicates such reductions. A more appropriate representation for compatibility assessment retains horizontal components to capture corridor alignment and cross-track deviations, since these fundamentally affect feasible conflict resolution directions.

The time evolution of the encounter state can be modeled at a high level by a stochastic differential or difference equation of the form

$$x_{k+1} = f(x_k, u_k, v_k) + w_k$$

where the argument aggregates relative kinematics at step, the symbol denotes control actions applied by the ownship and intruder, and the term denotes environmental and modeling disturbances. In an ACAS-style context, this evolution is often simplified by assuming constant intruder velocity and focusing on ownship advisory-induced changes [9]. For small unmanned aircraft at low altitude, both participants may perform frequent course and speed adjustments driven by mission logic or obstacle avoidance, yielding a richer set of possible accelerations. Compatibility with ACAS-based concepts requires examining whether the simplified encounter dynamics underlying existing decision regions remain conservative and representative under these conditions, or whether they misclassify large portions of realistic state space.

Encounter characterization in low-altitude airspace must account for heterogeneous classes of intruders, including equipped small unmanned aircraft, unequipped small unmanned aircraft,

rotorcraft, general aviation aircraft, and potentially other cooperative vehicles. Each class exhibits distinct kinematic and operational characteristics. For instance, multirotor vehicles may maintain low ground speeds and high maneuver agility, fixed-wing unmanned aircraft may require minimum speeds and bank angle limits, while helicopters may execute rapid vertical transitions or hover in proximity to structures [10]. Let a class index label each traffic type, each associated with a feasible velocity set and admissible control set. The overall encounter process becomes a mixture of class-conditioned processes, with mixture weights determined by traffic composition. For ACAS-based compatibility, the policy space should ideally be robust with respect to this mixture. If the original policy assumes specific climb rates or minimum airspeeds inconsistent with small unmanned aircraft capabilities, the resulting advisories may not be executable or may be unnecessarily restrictive.

The spatial distribution of encounters is shaped by imposed route structures and altitude stratification. In many proposed low-altitude concepts, altitude layers may be allocated by direction of travel or vehicle category to reduce head-on or crossing conflicts [11]. However, enforcement may be imperfect, and local deviations around obstacles and weather can perturb trajectories. From a modeling standpoint, the joint distribution of relative headings and vertical offsets is not uniform, and correlations with obstacle density and geofenced areas are expected. Let the random variables representing initial relative bearing and relative altitude difference have density functions conditional on location and time. Accurate characterization of these densities is critical for evaluating ACAS-derived alerting thresholds, which often depend on assumptions about typical approach geometries. If, for example, low-altitude encounters are predominantly lateral with constrained vertical maneuverability, ACAS concepts heavily biased toward vertical resolutions may provide limited benefit unless rebalanced. [12]

A key aspect of encounter modeling for detect-and-avoid is the temporal horizon over which conflicts can be detected and resolved. At low altitude, limited vertical room and proximity to structures reduce available maneuver space and shorten warning times. Let the time-to-loss-of-separation be defined as the minimum over time of when predicted separation reaches the protection boundary under current velocities. In higher-altitude ACAS analysis, typical thresholds for issuing advisories are tuned such that the ratio of time-to-go to the required maneuver response time remains comfortably large across encounter sets. In small unmanned aircraft operations, slower cruise speeds can increase raw time-to-go for some conflicts, but sudden accelerations or turns near obstacles and corridors can reduce effective reaction windows [13]. Modeling this distribution requires integrating kinematic constraints with environmental layouts. Compatibility is improved when ACAS-based trigger conditions can be reparameterized to maintain an adequate ratio of advisory lead time to autonomous actuator response, but only if the structural dependence on time-to-go remains valid under the new conditions.

The presence of static and dynamic obstacles other than aircraft significantly modifies the notion of a protection volume. In ACAS-based frameworks, the protection volume is usually symmetric and defined solely by relative aircraft separation. For low-altitude small unmanned aircraft, the safe set is instead the intersection of aircraft-to-aircraft separation constraints, terrain and structure clearance constraints, and geofencing constraints around sensitive areas. Let the admissible configuration set be defined as the set of states where horizontal and vertical distances to all obstacles and protected regions exceed respective minima and where relative distances to all aircraft exceed specified separation thresholds [14]. A conflict event corresponds to the state leaving this admissible set. The geometry of this set is highly nonconvex in realistic urban scenarios. As a result, avoidance maneuvers that would be acceptable from an ACAS perspective may drive the system closer to terrain or geofence

boundaries, altering risk trade-offs. Encounter characterization must therefore represent not only relative positions between aircraft but also relative positions to the environment, and compatibility requires that advisory logic be interpretable and tunable in this augmented state space.

Traffic intensity and spatial correlation play a direct role in the multiplicity of simultaneous encounters [15]. In many low-altitude operational concepts, vehicles may aggregate along preferred paths, forming effectively one-dimensional flows with localized crossflows at intersections or merging points. This concentration inflates the probability of multi-intruder scenarios where ownship must consider more than one potential conflict within overlapping time horizons. Let the average traffic intensity be described by a spatially varying rate function. The expected number of intruders within a conflict horizon can be approximated by integrating this rate over an ownship-centric safety volume. When this expectation exceeds values that justify purely pairwise reasoning, detect-and-avoid policies must resolve priority among conflicting advisories [16]. ACAS-based concepts, which historically focus on pairwise coordination with an assumed small number of nearby equipped aircraft, may not directly handle such multiplicities without additional prioritization rules. Compatibility in dense low-altitude operations thus depends on whether ACAS-inspired decision regions can be generalized to multi-threat contexts without causing advisory instability or excessive conservatism.

An additional feature of low-altitude encounter characterization is the variability in equipage with cooperative surveillance and communication systems. Some small unmanned aircraft may broadcast position information, others may rely solely on onboard sensing, and many potential intruders of concern, such as legacy general aviation aircraft or non-cooperative drones, may not provide standardized messages. Let an equipage indicator represent whether an intruder is cooperative or non-cooperative from the perspective of the ownship [17]. The joint encounter model must treat cooperative and non-cooperative cases differently, assigning distinct measurement likelihoods and detection probabilities. In ACAS-based frameworks, cooperative surveillance is fundamental to accurate tracking and coordination. When translated into a mixed-equipage low-altitude environment, the policy design must accommodate structural uncertainty about intruder type and its compliance with advisories. Encounter characterization should therefore embed a probabilistic model for equipage conditioned on airspace class, altitude band, and mission type, which in turn informs whether ACAS-style assumptions about mutual coordination are statistically justified in a given context.

To incorporate sensing characteristics into encounter modeling, one may treat the detect-and-avoid system as operating on a belief state that encodes probability distributions over relative configurations. Let the belief at time be denoted by a distribution over the encounter state, updated according to motion models and observation models corresponding to specific sensors such as ADS-B, radar, or vision [18]. The observation models encode detection probabilities, false alarm probabilities, and estimation error distributions as functions of range, line-of-sight conditions, and clutter. In low-altitude environments, occlusions from buildings and terrain, multipath interference, and non-stationary clutter introduce strong dependencies that differ from those in the open airspace assumed by ACAS. Thus, even if the underlying dynamic model of encounters remains conceptually similar, the evolution of the belief state and the confidence intervals used in advisory translation differ substantially. Compatibility conditions for ACAS-based logic then require that decision thresholds, which are often functions of nominal separations and closure rates, be recalibrated with respect to these modified belief dynamics.

The formal encounter model for compatibility analysis can be cast as a stochastic hybrid

system, where discrete modes represent different interaction regimes and continuous states represent relative positions and velocities [19]. For example, one mode could represent both vehicles being cooperative with a functional communication channel, another mode could represent unilateral cooperation, and additional modes could represent purely non-cooperative sensing-based detection. Transitions between modes capture communication losses, sensor failures, or changes in equipage exposure as aircraft move between coverage areas. Let the hybrid state be defined as a pair combining discrete and continuous components. The detect-and-avoid policy, whether ACAS-based or otherwise, must be designed to handle all reachable modes under realistic disturbance and failure conditions. If original ACAS concepts are tied to a single mode with full coordination and cooperative surveillance, then the presence of multiple modes in low-altitude operations indicates that structural extensions are necessary [20]. Encounter characterization that explicitly features these modes creates a rigorous basis to judge whether such extensions remain aligned with or diverge from the ACAS design philosophy.

Temporal correlation in trajectories also plays a role. Many small unmanned aircraft missions involve repetitive operations along similar routes, inducing statistical dependencies in encounter patterns over time. This can alter the long-run distribution of closest approach events relative to a memoryless assumption often implicit in generalized encounter models. Let an underlying route set define typical paths and their scheduling distributions. The resulting encounter process may exhibit clustering of conflicts at specific spatial-temporal junctions such as corridor intersections or launch and recovery sites [21]. Detect-and-avoid logic tuned without regard to such clustering might either underreact in congested nodes or overreact in sparse regions. For compatibility, ACAS-inspired systems intended for low-altitude application would need adaptation of alerting thresholds or context-aware tuning that acknowledges location-dependent encounter statistics.

Finally, encounter characterization must integrate ground risk perspectives relevant for low-altitude operations. While ACAS frameworks primarily target mid-air collision risk between aircraft, small unmanned aircraft detect-and-avoid systems operate under additional objectives related to overflight of people and critical infrastructure. The expected consequences of a deviation maneuver depend not only on the probability of collision avoidance success but also on how that maneuver redistributes risk over the ground [22]. Let a spatial risk density represent the expected impact or consequence measure at each ground location. A resolution maneuver that significantly shifts trajectory toward regions of higher risk density, even if it increases aircraft separation, may not be acceptable. Incorporating this into encounter modeling adds another dimension to the cost structure underlying advisory logic. In such settings, compatibility of ACAS-derived policies hinges on whether they can accommodate additional weighting of ground risk without undermining their core collision avoidance behavior, and whether their decision maps can be parameterized to account for heterogeneous risk densities common in low-altitude environments.

In summary, a technically grounded compatibility assessment demands that low-altitude small unmanned aircraft encounters be modeled with attention to bounded and structured airspace, heterogeneous vehicle classes, mixed equipage, multi-intruder interactions, belief-based sensing effects, mode switching in communication and cooperation, and spatially varying air and ground risk [23]. Within this framework, ACAS-based concepts can be viewed as specific policy constructions derived for a narrower subset of assumptions. The degree to which they can be transplanted or adapted for small unmanned aircraft detect-and-avoid depends on how these expanded encounter characteristics are incorporated into policy generation and whether resulting advisories remain feasible, interpretable, and aligned with low-altitude safety objec-

tives.

3. ACAS-Based Collision Avoidance Concepts

ACAS-based collision avoidance concepts are built on the definition of a surveillance-driven encounter state, transition dynamics, and a decision policy that emits resolution advisories when assessed collision risk exceeds acceptable thresholds. A typical formulation represents the encounter between two aircraft by a relative state, where horizontal separation, vertical separation, and relative velocities evolve according to kinematic equations and uncertainties in state estimation. Resolution advisories are constructed to reduce the probability of near mid-air collisions under a wide range of trajectories, while controlling nuisance alerts and respecting maneuver constraints.

Table 1. Representative low-altitude operational contexts relevant for detect-and-avoid compatibility assessment.

Operational context	Airspace structure	Traffic mix	Key constraint
Urban delivery routes	Corridor-based paths	Small unmanned aircraft, rotorcraft	Dense obstacles
Suburban inspection	Loosely defined volumes	Small unmanned aircraft, general aviation	Intermittent visibility
Rural survey	Wide open blocks	Small unmanned aircraft, agricultural aviation	Long ranges to intruders
Critical infrastructure	Restricted envelopes	Security helicopters, small unmanned aircraft	Tight geofencing
Port and coastal	Layered coastal corridors	Helicopters, unmanned surveillance	Maritime interference
Emergency response	Dynamic ad hoc zones	Manned responders, mixed unmanned aircraft	Rapid reconfiguration
Industrial sites	Localized shells	Multirotor fleets	Electromagnetic clutter
Recreational zones	Shared low-level areas	Light sport aircraft, hobby unmanned aircraft	Unpredictable behavior

Table 2. High-level comparison of ACAS-based concepts and small unmanned aircraft detect-and-avoid roles.

Aspect	Traditional ACAS concepts	Small unmanned aircraft detect-and-avoid	Compatibility remark
Primary role	Last-resort collision mitigation	Integrated tactical avoidance	Conceptual alignment
Surveillance basis	Cooperative beacons	Mixed cooperative and non-cooperative sensing	Requires reformulation
Executor of advisories	Human pilot	Onboard autonomy	Structural shift
Preferred maneuver axis	Vertical bias	Often lateral or combined	Requires retuning
Coordination mechanism	Symmetric message exchange	Often absent or partial	Limited direct reuse
Equipage assumptions	Highly standardized	Heterogeneous capabilities	Fragmented assumptions
Alert semantics	Pilot-oriented phrases	Machine-executable commands	Translation required
Integration layer	Above separation services	Embedded with multiple layers	Needs interface design

At the core of many ACAS-like systems is a probabilistic model of encounter evolution [24].

Table 3. Surveillance modalities considered in low-altitude detect-and-avoid architectures.

Sensor modality	Coverage characteristics	Principal strengths	Principal limitations
ADS-B or transponder reception	Line-of-sight cooperative tracks	Standardized state reports	Incomplete equipage
Compact primary radar	Azimuth sectors around ownship	Range and range-rate observability	Clutter in urban terrain
Electro-optical vision	Directional fields	High angular resolution	Sensitivity to lighting
Infrared imaging	Directional fields	Performance in reduced visibility	Lower detail on small targets
Lidar systems	Narrow beams or scanning patterns	Precise range to structures	Limited range to small aircraft
Acoustic arrays	Local hemispherical	Detection of nearby propeller signatures	Ambient noise contamination
Network-based feeds	Airspace-wide logical coverage	Aggregated cooperative tracks	Latency and availability

Table 4. Representative avoidance maneuver classes for small unmanned aircraft relative to ACAS-style advisories.

Maneuver type	Typical realization for small unmanned aircraft	Main enabling factors	Principal constraints
Lateral deviation	Heading change around threat or obstacle	High agility of multirotor platforms	Corridor boundary adherence
Vertical change	Climb or descent bands	Available altitude margins	Terrain and airspace limits
Speed adjustment	Throttle or pitch modification	Flexible mission timing	Stall envelopes and traffic flows
Combined maneuver	Coupled lateral and vertical action	Rich control authority	Complexity of verification
Hold or loiter	Orbit near safe point	Stable hover capability	Local congestion risk
Abort to safe site	Directed path to preplanned location	Predefined recovery points	Site availability and occupancy

The system observes sensor data, generates a track for each intruder, propagates the state forward under simplified motion models, and evaluates whether projected separations violate predefined safety volumes. If the belief over future states indicates a collision risk beyond a defined threshold, an advisory is generated. Traditional designs often prefer vertical separation maneuvers to minimize interactions with air traffic control procedures and lateral route structures. Coordination logic ensures that advisories issued to each aircraft are mutually compatible.

The structure of these concepts can be abstracted into a mapping from a state estimate to a discrete advisory set [25]. Consider a nominal relative state vector with horizontal separation component, vertical separation component, and their respective rates. The collision avoidance logic defines regions in this state space where different advisories are optimal or required according to the cost structure embedded in the system design. These regions are typically computed offline and encoded into compact tables or policy maps for real-time execution. The emphasis is on conservative coverage of rare collision scenarios while maintaining an operationally acceptable alert rate.

Decision making in ACAS-based systems is linked to explicit performance requirements, such as upper bounds on collision probability conditional on system equipage, and constraints on vertical rate, acceleration, and alert duration [26]. Advisory sequences are constrained in

Table 5. Key encounter geometries influencing detect-and-avoid policy design in low-altitude airspace.

Encounter geometry	Relative motion pattern	Typical sources	Modeling implication
Head-on corridor conflict	Opposing paths along shared route	Bidirectional logistics flows	Short warning times
Overtaking in corridor	Faster follower approaching slower leader	Mixed fixed-wing and multirotor	Prolonged proximity
Crossing at node	Intersecting paths at junction	Networked urban routes	Multi-threat interactions
Vertical merge near structure	One aircraft climbing or descending near obstacle	Rotorcraft and unmanned aircraft mix	Limited vertical margin
Random nearby transit	Unconstrained pass-by	Legacy general aviation	High variance in headings
Stationary hover versus transit	Fixed point inspection versus passing traffic	Infrastructure survey	Persistent conflict cone

Table 6. Information and decision timescales relevant for integrating ACAS-based ideas with small unmanned aircraft detect-and-avoid.

Timescale layer	Representative functions	Information sources	Constraints
Strategic planning	Route and altitude selection	Offboard services, maps	Limited fidelity of forecasts
Pre-tactical updates	Local adjustments before launch	Recent traffic patterns	Sparse historical data
Tactical detect-and-avoid	Real-time conflict decisions	Onboard sensing, cooperative tracks	Computational limits
Last-resort maneuvering	Immediate collision mitigation	Minimal state estimates	Tight dynamic margins
Post-flight analysis	Performance assessment	Logged flight data	Scenario coverage

their temporal evolution to reduce oscillatory behavior and avoid destabilizing pilot responses. Surveillance assumptions typically involve cooperative transponder or ADS-B signals that provide range, bearing, altitude, and occasionally velocity information with relatively high integrity and bounded latency. The alerting logic is evaluated at a regular cycle, using updated tracks and filtered state estimates.

A key element of ACAS-based concepts is that the system is assumed to be supplementary to pilot see-and-avoid and to ground-based separation services. The human pilot executes advisories, and system design anticipates human reaction times, compliance probabilities, and possible deviations. The role of ACAS is last-resort collision mitigation, not comprehensive traffic management [27]. This limited but clearly defined role simplifies some aspects of modeling, such as assuming that maneuvers will be applied approximately as commanded within a delay window and that coordination messages will be reliably exchanged when both aircraft are equipped.

These characteristics strongly influence compatibility with small unmanned aircraft detect-and-avoid. Autonomy replaces the human pilot, surveillance sources diversify beyond cooperative beacons, and low-altitude operations see different geometry distributions and maneuver capabilities. Any assessment of compatibility must examine whether ACAS-based decision logics can be reinterpreted under changed assumptions about who or what executes advisories, how states are estimated, and what performance metrics govern acceptability.

Table 7. Core safety assessment components for evaluating ACAS-inspired detect-and-avoid implementations.

Assessment element	Technique	Targeted property	Relevance to compatibility
Encounter modeling	Stochastic traffic generation	Representativeness of conflicts	Basis for policy tuning
Logic verification	Formal methods and model checking	Correctness of decision rules	Ensures safe adaptations
Monte Carlo simulation	Large-scale scenario runs	Emergent behavior patterns	Identifies misalignments
Flight testing	Controlled experiments	Real-world integration effects	Confirms feasibility
Hazard analysis	Structured risk decomposition	Critical failure modes	Informs policy constraints
Configuration control	Traceable implementation baselines	Consistency of deployed logic	Supports mixed equipage

4. Small UAS Detect-and-Avoid Architectures in Low-Altitude Airspace

Detect-and-avoid architectures for small unmanned aircraft in low-altitude airspace generally integrate onboard sensing, communication links where available, and decision logic that may include both strategic and tactical components [28]. Strategic elements can involve offboard services providing route deconfliction or conformance monitoring, while tactical components must respond to imminent conflicts using local sensor data when communication or cooperative information is incomplete. The architectures must function within the size, weight, and power constraints inherent to small platforms and must accommodate environmental complexity such as buildings, terrain, and dynamic obstacles.

Onboard sensing for small unmanned aircraft may involve combinations of ADS-B receivers, compact primary radar, optical or infrared cameras, lidar, or acoustic sensors. Each modality presents specific angular coverage, range, field-of-view, and false alarm characteristics, with performance strongly influenced by clutter and occlusion. Unlike the cooperative, largely line-of-sight assumptions underpinning traditional ACAS surveillance, low-altitude unmanned environments often exhibit intermittent detection and tracking performance [29]. Detect-and-avoid logic must therefore operate on state estimates with higher and more variable uncertainty, while still delivering timely maneuvers within short time-to-impact horizons.

In many small unmanned aircraft applications, control is fully autonomous with no direct pilot stick input at the timescale relevant for collision avoidance. The detect-and-avoid function issues trajectory modifications directly to the flight control system, typically as changes in path, speed, or attitude commands. This eliminates uncertainty associated with human reaction time but introduces a requirement for verified stability and compatibility between collision avoidance outputs and underlying autopilot behavior. The detect-and-avoid architecture must be integrated into flight management such that guidance commands are feasible given aerodynamic and propulsion limits and do not invalidate safety margins with respect to terrain or no-fly volumes.

The operational density of low-altitude unmanned traffic can be high, particularly in urban or logistics scenarios [30]. Small unmanned aircraft may follow structured corridors, constrained altitude layers, or ad hoc routes around local obstacles. The geometry of typical encounters can deviate significantly from the high-altitude environment for which ACAS concepts were tuned. Conflicts involving slow-moving multirotor vehicles, fast fixed-wing unmanned aircraft, helicopters, and general aviation in mixed equipage scenarios introduce a broader spectrum of

relative velocities, climb capabilities, and permissible avoidance directions. Detect-and-avoid architectures must be robust to such heterogeneity, which in turn influences the viability of direct application of ACAS-style advisories.

Low-altitude operations also require consideration of ground risk and non-participant exposure [31]. Collision avoidance maneuvers that are acceptable at higher altitudes might be constrained near the ground to limit increases in kinetic energy directed toward populated areas or critical infrastructure. The detect-and-avoid system for a small unmanned aircraft therefore operates within multiple constraints: avoiding other aircraft and obstacles, respecting geofencing, and controlling ground risk. This multi-constraint context may necessitate cost functions and decision criteria that depart from traditional ACAS formulations.

Communication constraints further shape detect-and-avoid architectures. Reliance on continuous, low-latency communication with ground services cannot be assumed in all environments, and coordination with other vehicles via explicit air-to-air links may be intermittent or absent [32]. Hence, detect-and-avoid systems must function with degraded or purely local information, and their compatibility with ACAS-based coordination assumptions becomes conditional. Any ACAS-derived logic used within a small unmanned aircraft must be evaluated under these communication constraints to ensure that its decisions remain meaningful and do not depend critically on unavailable coordination messages.

5. Surveillance and Communication Compatibility Constraints

Compatibility between ACAS-based concepts and small unmanned aircraft detect-and-avoid is significantly influenced by the surveillance and communication environment in low-altitude operations. Traditional ACAS frameworks assume cooperative surveillance with standardized message formats, relatively homogeneous equipage, and air-to-air coordination channels that support synchronized advisory selection. In contrast, small unmanned aircraft may operate with partial equipage, intermittent communication, and diverse sensing modalities whose outputs do not align directly with cooperative state reports. [33]

For small unmanned aircraft equipped with ADS-B or transponder receivers, there exists a partial alignment with ACAS assumptions, as cooperative intruders can be tracked with reasonable accuracy. However, equipage rates among small platforms and low-altitude legacy traffic can be limited, and the presence of obstacles and urban canyons can compromise reception. Non-cooperative intruders must be detected using onboard sensors with different error characteristics than cooperative surveillance. As a consequence, any ACAS-derived decision table or logic that presumes a certain minimum surveillance quality must be reassessed or reconstructed using the statistics of low-altitude sensor performance.

Communication channels for coordination among collision avoidance systems present further compatibility challenges. ACAS concepts generally include coordination messages exchanged between aircraft to ensure that advisories are complementary rather than conflicting [34]. In heterogeneous small unmanned aircraft environments, not all vehicles will implement compatible protocols, nor will all conflicts involve equipped participants. The absence of reliable, universal coordination undermines ACAS-style symmetric advisory generation. A small unmanned aircraft may need to operate under unilateral assumptions, selecting maneuvers that are safe regardless of whether the other party follows an analogous advisory.

Latency and integrity constraints in communication links also affect compatibility. In low-altitude environments relying on cellular or ad hoc networks, delay and packet loss statistics can differ from the assumptions made for dedicated ACAS coordination channels [35].

Attempting to apply coordination rules without guaranteed timely delivery can introduce inconsistent advisory states and potential oscillations. For compatibility, ACAS-based concepts would require either robustification against missed or delayed messages or confinement to purely local decision-making that does not depend on strict synchronization.

Another factor is the granularity and semantics of state information. ACAS-based systems are tuned to use specific state variables, such as altitude reported in standardized units and encoded with known quantization properties. Small unmanned aircraft sensors may provide different observables or resolutions, for example visual detections with angular bearings and range estimates subject to environment-dependent biases [36]. Achieving compatibility may require translating such heterogeneous measurements into a state space that is suitable for ACAS-inspired logic, while accounting for increased uncertainty and possible non-Gaussian errors.

Overall, surveillance and communication constraints indicate that direct reuse of ACAS coordination mechanisms and surveillance-driven thresholds is limited. Instead, compatibility is more plausible at the conceptual level, where conflict detection relies on probabilistic prediction of relative motion and decision policies map state estimates to maneuvers. To preserve coherent behavior in low-altitude environments, ACAS-based ideas must be reformulated under sensing models and communication patterns consistent with small unmanned aircraft operations, ensuring that advisory stability, false alert rates, and risk metrics remain controlled.

6. Mathematical Conflict Modeling and Resolution Logics

Assessing compatibility requires formal conflict models capturing the dynamics and uncertainties relevant to both ACAS-based and small unmanned aircraft detect-and-avoid systems. Let a relative encounter state be represented by a vector with horizontal and vertical components [37]. For illustration, define a relative position and rate pair along axes aligned with the line of sight and altitude difference. The evolution of this state is governed by kinematics subject to control inputs, environmental disturbances, and estimation errors. Both ACAS-style and unmanned detect-and-avoid logics implement mappings from such states to advisories that influence control inputs.

Consider a simplified continuous-time relative dynamics model. Let a scalar represent along-track relative distance and another represent its rate, while a separate scalar represents vertical separation and its rate [38]. Under constant relative velocities in the absence of maneuvers, the state evolves linearly. Collision is associated with the state entering a protection zone defined by minimum horizontal and vertical separations. A collision probability over a time horizon can be expressed as an integral of the encounter density over the unsafe region. In a compact form, for an encounter density function over time and state, one can write a collision probability as

$$P_{\mathrm{c}} = \int_{0}^{T} \lambda(t)\, dt$$

where the integrand represents an instantaneous hazard rate derived from the predicted distribution of separation [39]. Within ACAS-based concepts, advisory logic is tuned such that this probability remains below specified thresholds across representative encounter sets.

In small unmanned aircraft detect-and-avoid, autonomy executes maneuvers directly based on advisory outputs. Conflict modeling must therefore incorporate the closed-loop behavior of the autopilot and the detect-and-avoid logic. A discrete-time formulation with sampling

period can be adopted, with state updates given by a function that maps the current state and control to the next state, including disturbances. Let the control input be selected from a finite action set representing feasible lateral or vertical maneuvers. A hazard functional can be defined as the probability that the state enters the protection zone at any step over a prediction horizon, conditioned on the action sequence. [40]

To connect ACAS-based concepts and unmanned detect-and-avoid, one can view both as instances of stochastic control problems where a policy maps state estimates to actions to reduce collision risk and manage alerting behavior. A generic cost function can be defined that includes collision penalties and penalties for maneuvers considered undesirable, such as high accelerations or proximity to ground or no-fly volumes. For a state and action, with discount factor less than one, a value function can be defined as

$$J(x) = \min_{u} \mathbb{E}\big[\, c(x, u) + \gamma J(f(x, u, w)) \big]$$

where the expectation is taken over disturbance and estimation error. ACAS-based systems approximate such solutions through offline optimization and encode them as decision tables [41]. Small unmanned aircraft detect-and-avoid algorithms can employ similar constructions, but with modified cost structures and dynamics to represent autonomous response and low-altitude constraints.

Compatibility assessments can then be framed around the alignment of these underlying control problems. If the state space, dynamics, and cost structures assumed in ACAS-based designs differ substantially from those relevant to small unmanned aircraft, direct reuse of policies becomes inconsistent. For example, if the ACAS concept penalizes lateral maneuvers heavily relative to vertical ones due to air traffic control considerations, but small unmanned aircraft have limited vertical authority and flexible lateral paths, then the original cost structure is misaligned. Applying such a policy unchanged may yield maneuvers that are infeasible or suboptimal in low-altitude unmanned contexts. [42]

A more detailed conflict model for small unmanned aircraft must incorporate environmental constraints. Let a configuration describe not only relative separation to intruders but also margins to terrain and airspace boundaries. Feasible controls must maintain these margins above minimum values. The admissible action set thus depends on the current configuration, and the detect-and-avoid policy must select actions that remain in this set. A resolution logic derived from ACAS that assumes an action set independent of terrain may not satisfy these constraints without modification.

Additionally, the uncertainty model differs [43]. ACAS-based frameworks often assume relatively well-characterized cooperative surveillance with bounded errors. Small unmanned aircraft rely on sensors whose detection probabilities and false alarm rates are environment dependent. The conflict model can represent measurement as a noisy observation of the true state, with noise distribution that may be non-Gaussian and dependent on geometry. The resulting belief state over relative separation evolves stochastically. An optimal policy in this context emerges from a partially observable stochastic control formulation, where decisions depend on the belief state rather than a precise estimate [44]. ACAS-inspired policies that rely on crisp thresholds on nominal separations may not be robust to such uncertainty structures unless adapted.

A practical compatibility condition can be articulated in terms of monotonicity and dominance properties of advisories. If, for a given encounter class, an ACAS-like policy and an unmanned detect-and-avoid policy both ensure that collision risk remains below a target bound under their respective dynamics and uncertainty models, and if the unmanned policy's feasible

action set is a superset of the maneuvers allowed under the ACAS concept, then it is possible to embed ACAS-like logic as a subset of the unmanned policy. Conversely, if the unmanned constraints exclude key ACAS maneuvers or expose significantly different uncertainty, then compatibility is limited and more extensive redesign is required.

7. Scalability, Interoperability, and Algorithmic Complexity

In dense low-altitude operations, detect-and-avoid systems must handle simultaneous encounters with multiple intruders, possible coupling among conflicts, and real-time constraints on computation [45]. ACAS-based concepts were not originally designed for extreme densities of small vehicles operating with low-cost avionics and partial equipage. Compatibility assessments must examine how ACAS-style decision mechanisms scale when integrated into architectures supporting large numbers of small unmanned aircraft.

Scalability can be considered through the growth of required state dimension and computation with the number of intruders. A straightforward extension of pairwise ACAS logic to many intruders can become complex if advisories must ensure consistency across multiple simultaneous conflicts. Small unmanned aircraft detect-and-avoid systems may adopt hierarchical or prioritized strategies, selecting a dominant threat based on risk metrics while monitoring others [46]. ACAS-based regional partitions of the state space can, in principle, be extended to handle multiple intruders by conservative superposition rules, but doing so without excessive conservatism or oscillatory behavior requires careful design. Compatibility is improved when the underlying ACAS concepts are formulated in a way that remains composable under additional intruder dimensions.

Interoperability with other safety layers is also central. Low-altitude airspace concepts frequently include strategic deconfliction provided by external services. A small unmanned aircraft may receive a planned trajectory designed to reduce conflict likelihood. The onboard detect-and-avoid then acts as a tactical backup [47]. ACAS-based concepts, originally defined as independent of ground-based separation assurance, enter this layered structure as one of several mechanisms. Compatible integration requires ensuring that ACAS-style advisories do not conflict systematically with strategic trajectories or with other onboard collision avoidance algorithms, and that their activation criteria are harmonized.

Algorithmic complexity considerations arise from the computational resources available on small unmanned aircraft. Sophisticated stochastic optimization or high-dimensional policy tables may exceed feasible memory or processing budgets. ACAS-based designs that rely on precomputed tables are appealing because of their predictable execution cost [48]. However, their compatibility depends on whether the tables remain valid when re-parameterized for low-altitude operations and different vehicle performance characteristics. Recomputing policies for new encounter models and cost structures may produce tables of increased dimensionality, challenging compact implementations.

One way to examine complexity is to consider the size of the discrete state grid needed to represent relevant encounter geometries, velocities, and environmental constraints. For small unmanned aircraft, the range of possible speeds and climb rates, as well as the importance of terrain and obstacles, may necessitate finer discretization in certain dimensions or additional state variables. The growth in table size can be approximated as the product of discretization levels across dimensions [49]. If this growth leads to memory demands incompatible with small avionics, direct adaptation of ACAS-like table-driven approaches becomes less practical.

A further compatibility concern involves the determinism and predictability of advisories. In

environments where many small unmanned aircraft implement different or partially compatible detect-and-avoid logics, predictable interaction patterns become important. ACAS-based concepts offer predictable coordination behavior when both sides are similarly equipped. In heterogeneous unmanned environments, such symmetry is not guaranteed. Therefore, detect-and-avoid algorithms inspired by ACAS must be designed in a way that retains coherent behavior when interacting with vehicles that either do not follow the same logic or follow only a subset of its rules [50]. This requirement for robustness under heterogeneous interaction is more stringent than in the traditional ACAS design space.

8. Safety Assessment, Verification, and Validation Framework

Compatibility between ACAS-based concepts and small unmanned aircraft detect-and-avoid must also be analyzed under a safety assessment framework. Such a framework typically includes hazard identification, fault tree or event tree analysis, Monte Carlo encounter simulations, and formal verification techniques applied to decision logic. The aim is to characterize whether the integrated system satisfies collision risk objectives across representative operational scenarios and failure modes.

For ACAS-based systems, risk analyses have historically relied on traffic encounter models tailored to cooperative, higher-altitude operations and have used structured evaluation scenarios [51]. When these concepts are considered for small unmanned aircraft in low-altitude environments, encounter models need to reflect traffic composition, equipage variability, environmental features, and maneuverability constraints specific to these operations. The statistical properties of conflicts, including relative altitude distributions, heading distributions, closure rates, and obstacle proximity, can differ substantially. Without updated encounter models, conclusions about performance may not transfer.

Verification of detect-and-avoid logic for autonomous aircraft involves checking both functional correctness and robustness against uncertainties. In formal terms, one can express safety requirements as invariants or temporal logic properties over the trajectories of the closed-loop system [52]. For example, a property may state that, with high probability, the separation between any pair of aircraft remains above a minimum threshold given specified classes of disturbances and sensor errors. Model checking or theorem proving techniques can, in principle, be applied to simplified models of the detect-and-avoid algorithm to assess whether such properties hold or to identify counterexamples.

ACAS-based policies implemented as finite lookup tables lend themselves to certain verification approaches, since the mapping from discrete encounter states to advisories is explicit. However, when adapting these policies for small unmanned aircraft, additional dimensions and constraints introduce complexity. Verification must ensure that, for all reachable states in the discretized model including low-altitude constraints and environmental bounds, the recommended action sequences do not lead to violations of safety properties. If achieving this requires substantial restructuring of the original policy space, compatibility at the implementation level is reduced, even if the conceptual approach remains similar. [53]

Validation through simulation is essential to characterize practical performance. High-fidelity simulations incorporating sensor models, communication effects, and autopilot dynamics can provide empirical distributions of minimum separation under various architectures. To compare ACAS-based and unmanned detect-and-avoid approaches, one may define metrics such as collision probability, near miss rates, alert frequency, and maneuver severity distributions. If an adapted ACAS-inspired policy is to be considered compatible, its performance under relevant traffic and environment models should be at least comparable to dedicated unmanned

detect-and-avoid designs given equivalent information, without introducing systematic patterns of undesirable behavior.

The safety assessment framework also needs to consider failure conditions [54]. Small unmanned aircraft detect-and-avoid systems must remain robust under sensor outages, partial communication loss, or degraded navigation performance. ACAS-based concepts typically include certain assumptions on system availability and integrity. When those assumptions do not hold at low altitude, policies may require modification such that default or degraded modes maintain acceptable risk. The extent of such modification is a measure of compatibility: extensive redesign for degraded operations suggests limited direct applicability of original ACAS constructs.

Finally, the verification and validation of autonomous detect-and-avoid systems may involve demonstrating explainability or traceability of advisories [55]. Even if human pilots are not in the loop, system developers and regulators may require that advisory sequences can be related to comprehensible state transitions. ACAS-like table-based approaches possess inherent traceability. Preserving this characteristic while adapting to the complexities of small unmanned aircraft and low-altitude environments can be valuable but may conflict with the need for richer state representations and learning-based components. Decisions about incorporating learning elements versus preserving structured ACAS-style logic affect both compatibility and the feasibility of rigorous safety arguments.

9. Conclusion

The assessment of compatibility between ACAS-based collision avoidance concepts and small unmanned aircraft detect-and-avoid in low-altitude airspace indicates that alignment exists primarily at the level of underlying principles rather than direct transfer of implementations. Both frameworks are grounded in the prediction of relative motion, evaluation of collision risk, and synthesis of maneuvers intended to maintain separation under uncertainty [56]. However, the specific assumptions embedded in traditional ACAS designs concerning surveillance quality, human pilot response, maneuver preferences, and equipage homogeneity differ from those applicable to autonomous small unmanned aircraft operations near the ground.

Surveillance and communication characteristics in low-altitude environments present a distinct challenge. Partial equipage, non-cooperative intruders, and occlusion-prone sensing mean that ACAS-style coordination and thresholding cannot be adopted without rederivation under new performance models. Mathematical conflict modeling for small unmanned aircraft must capture different uncertainty structures and tighter coupling with terrain and airspace constraints. Within such models, ACAS-inspired policies can serve as a reference, but compatibility requires modifications to state representations, admissible action sets, and cost functions used in policy design. [57]

Scalability and interoperability considerations further constrain direct application. Dense low-altitude traffic with mixed logic implementations and layered safety architectures requires detect-and-avoid algorithms that exhibit stable interaction properties without relying on uniform protocol adherence. ACAS-based concepts can inform design of such algorithms, particularly through their emphasis on structured, table-driven decision policies and coordination principles, yet the absence of guaranteed symmetry among participants limits unaltered reuse. Implementations targeting small unmanned aircraft must reflect available computational resources, the need for integration with autopilots, and evolving external services for strategic deconfliction.

From a safety assessment viewpoint, the transition of ACAS-based ideas into small unmanned aircraft detect-and-avoid calls for new encounter models, updated risk analyses, and verification methods that address autonomous behavior and environmental complexity [58]. Where ACAS-derived logic is retained, it must be shown to satisfy low-altitude safety objectives under realistic sensing and communication assumptions. Where substantial adaptation is necessary, it is more appropriate to regard the resulting system as a distinct detect-and-avoid design influenced by ACAS principles, rather than a straightforward instance of the original concept.

Overall, the compatibility between ACAS-based concepts and small unmanned aircraft detect-and-avoid in low-altitude airspace is conditional and context-dependent. Conceptual elements such as probabilistic conflict assessment, structured policy representation, and conservative advisory construction remain relevant. At the same time, differences in vehicle characteristics, operational constraints, and surveillance infrastructures necessitate careful reformulation rather than direct transplantation. A measured approach that selectively adopts and adapts ACAS-inspired mechanisms, while explicitly modeling low-altitude unmanned conditions, provides a technically coherent path for integrating these frameworks without overstating their alignment. [59]

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