

Advances in UAV Visual Navigation for Low-Altitude Air Traffic Safety: An Integrated Perspective on Perception, Decision-Making, and Traffic Management

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Abstract: As applications such as logistics delivery, urban air mobility, emergency response, and infrastructure inspection expand, low-altitude UAV operations are shifting from dispersed, low-density flights toward large-scale, high-density operations. Visual navigation, owing to its low weight, low cost, and limited dependence on external infrastructure, has become a key enabling technology for autonomous localization, environmental perception, and obstacle avoidance when global navigation satellite system signals are degraded or unavailable. From the perspective of low-altitude air traffic safety, however, improvements in the performance of individual vision algorithms do not automatically translate into safe system-level operations. Visual observations must be converted into conflict assessments, safety-critical decisions, exchangeable information, and operationally manageable states before a closed safety loop can be established. This review examines UAV visual navigation through three interrelated dimensions: perception capability, decision safety, and compatibility with traffic management. It synthesizes research on visual simultaneous localization and mapping and visual-inertial odometry, object detection and tracking, depth estimation, conflict detection, autonomous avoidance, low-altitude traffic management, operational risk assessment, and safety assurance. Particular attention is given to the propagation of visual-perception uncertainty into safety-critical decisions, the transformation of onboard visual outputs into information that can be used by low-altitude traffic management systems, and the assurance of learning-based vision systems. The review indicates that the main bottlenecks are shifting from the accuracy of individual algorithms to cross-layer metric alignment, standardization of visual safety information, interoperability among heterogeneous systems, and certification of learning-based perception. Future research should therefore extend beyond algorithmic optimization toward operational risk management and regulatory oversight by developing safety-consequence-oriented metrics, standardized information interfaces, runtime assurance mechanisms, and digital-twin-based validation integrated with flight testing.

Keywords: Visual navigation; Detect and avoid; Conflict detection and resolution; Operational risk assessment.

1. Introduction

The scope of low-altitude UAV applications is expanding rapidly. Logistics delivery, urban air mobility (UAM), emergency search and rescue, and infrastructure inspection are moving low-altitude operations from isolated trials toward routine and increasingly large-scale deployment. As the number of aircraft and mission types grows, interactions among operators, flight trajectories, and limited airspace resources become more complex. Safe autonomous operations therefore require more than accurate localization and path planning; they must also address non-cooperative traffic, dynamic obstacles, traffic conflicts, and ground risk, thereby creating new demands for low-altitude air traffic safety management.

Visual navigation is a fundamental capability for autonomous UAV operation. Compared with navigation architectures that rely primarily on global navigation satellite systems (GNSS) and inertial measurement units (IMUs), vision sensors are relatively inexpensive and lightweight, provide passive sensing, and depend less on external infrastructure. These characteristics make them particularly valuable in urban canyons, indoor environments, and situations in which GNSS signals are degraded, denied, or interfered with. Recent advances in visual simultaneous localization and mapping (SLAM), object detection and tracking, depth estimation, and scene understanding have substantially improved the environmental awareness of UAVs.

From a low-altitude air traffic safety perspective, however, technical performance and operational safety are not equivalent. Higher visual-SLAM accuracy does not necessarily guarantee position integrity, and better object-detection accuracy does not by itself demonstrate an acceptably low probability of missed conflicts. Visual observations must pass through target-state estimation, conflict prediction, path planning, and avoidance decision-making before they can be translated into aircraft maneuvers. Once UAVs operate within a scaled low-altitude traffic environment, the resulting safety-critical information must also be exchanged with and validated by ground-based traffic management systems. Consequently, research on UAV visual navigation is moving beyond stand-alone algorithmic performance toward perception reliability, decision safety, and cross-system coordination.

At the traffic-management level, the U.S. Unmanned Aircraft System Traffic Management (UTM) framework, the European U-space framework, and China's low-altitude operational management framework represent different organizational and regulatory approaches. Bauranov and Rakas [1] reviewed airspace design concepts for UAM; Hamissi and Dhraief [2] surveyed the functional architecture and operational mechanisms of UTM; and Yang et al. [3] focused on UAM airspace design and risk assessment. These studies provide an important foundation for understanding low-altitude traffic organization and risk control. Nevertheless, existing reviews generally address visual

navigation, collision avoidance, or traffic management as separate topics. Less attention has been paid to how onboard visual capabilities can be translated into safety-relevant information that supports traffic-level decision-making and management.

Accordingly, this review organizes the literature around three interrelated dimensions: perception capability, decision safety, and management compatibility. The perception dimension concerns the reliability of localization, target detection, and range estimation; the decision dimension examines how visual uncertainty affects conflict detection, risk assessment, and avoidance strategies; and the management dimension considers information exchange, interoperability, and safety validation across UTM, U-space, and other low-altitude operational frameworks. This structure extends visual navigation from a single-vehicle technical problem to a broader issue of operational safety, technology management, and regulatory oversight in low-altitude airspace.

2. UAV Visual Perception and Its Operational Safety Constraints

2.1. Visual Localization and Position Integrity

Visual SLAM and visual-inertial odometry (VIO) are widely used to maintain autonomous localization when GNSS is unavailable or unreliable. Feature-based, direct, and learning-based SLAM approaches have all been deployed on UAV platforms. In their review of UAV visual SLAM, Zhuang et al. [4] noted that fusing visual and inertial information can reduce the accumulated drift associated with vision-only localization and improve stability under complex vehicle motion.

For safety-critical low-altitude operations, however, a low average localization error is insufficient. It is also necessary to determine whether the localization error remains within predictable and operationally manageable bounds. Poor texture, rapid maneuvers, dynamic occlusion, and abrupt illumination changes may cause sudden degradation in visual localization, while accumulated drift and scale uncertainty can propagate to downstream target-position estimation and conflict prediction. Koukiou and Anastassopoulos [5] proposed autonomous integrity monitoring for UAV sensors, in which sensor-output quality is continuously assessed and alerts or degraded modes are triggered when confidence falls. This line of work suggests that safety-oriented visual localization should report not only position estimates but also uncertainty, integrity status, and abnormal operating conditions so that subsequent functions can adapt their control or management strategy to the current localization quality.

2.2. Object Detection, Tracking, and Range Estimation

Object detection and continuous tracking determine whether a UAV can identify other aircraft and dynamic obstacles in sufficient time to respond. Tang et al. [6] reported that YOLO-based detectors offer a favorable balance between accuracy and computational speed for UAV vision, but small targets, motion blur, rapid viewpoint changes, and occlusion remain important performance limitations. Butt et al. [7] further showed that complex illumination and long-range sensing can substantially reduce the detection capability of a single vision sensor for non-cooperative targets.

After a target is detected, its range and motion state must

also be estimated. Padhy et al. [8] investigated monocular RGB-based depth estimation for UAV navigation and demonstrated the potential of combining visual geometry with learning-based methods for low-cost ranging, while also highlighting the persistent scale ambiguity of monocular vision. From an operational safety standpoint, different perception failures lead to different consequences: missed detections reduce target-detection probability and warning time; track loss degrades velocity and trajectory prediction; and range-estimation errors distort time-to-collision estimates and required separation. Perception systems should therefore be evaluated not only by accuracy, recall, or depth error, but also by the operational risks associated with changes in these metrics.

Table 1. Relationship between visual-perception performance and operational safety

Perception function	Major technical limitation	Operational safety impact	Management-relevant metric
Visual SLAM/VIO	Drift, scale uncertainty, degradation in dynamic environments	Distorted ownship position state	Position integrity; confidence
Object detection	Small targets, occlusion, long-range missed detection	Reduced conflict-warning time	Detection probability; missed-alert rate
Object tracking	Motion blur; track loss	Increased trajectory-prediction error	Tracking continuity; state-estimation error
Depth estimation	Monocular scale ambiguity; weak-texture error	Biased safety-distance assessment	Range error; safety margin

2.3. From Algorithmic Performance to Safety Consequences

A substantial gap remains between perception metrics and operational safety metrics. Vision algorithms are usually assessed at the pixel, object, or trajectory level, whereas traffic management must determine whether the system is likely to miss a conflict, erode minimum separation, or fail to execute a safe avoidance maneuver. Chandran et al. [9] noted that vision sensors are particularly useful for short-range detection of non-cooperative targets, but long-range motion estimation remains vulnerable to the lack of direct depth information. Fasano and Opromolla [10] further related sensing parameters such as detection range, field of view, and update rate to detect-and-avoid requirements.

Operational use therefore requires a cross-layer mapping from algorithmic metrics to safety consequences. Localization error, for example, must be related to uncertainty in predicted conflict position; missed-detection rates should be translated into the probability of missed conflict alerts; and depth-estimation error should be linked to uncertainty in required separation. Only when this mapping is established can visual-perception performance become a meaningful input to operational risk assessment and safety-critical decision-making.

3. Conflict Risk and Autonomous Decision-Making Driven by Visual Perception

3.1. Conflict Detection and Risk Quantification

Conflict detection determines whether predicted aircraft states will violate a required separation threshold. Under ideal observation conditions, velocity-obstacle methods, collision cones, and other geometric approaches can identify conflicts efficiently. When visual measurements contain noise, delay, or missed detections, however, fixed deterministic thresholds may increase both false alerts and missed alerts.

Estevez et al. [11] developed a low-cost vision system for online reciprocal collision avoidance and validated its feasibility in close-range flight experiments. As traffic density increases, however, the interaction between visual uncertainty and multi-aircraft dynamics makes deterministic safety thresholds progressively less representative of actual operational risk. Fitrikananda et al. [12] used multi-parameter quantification and Monte Carlo simulation to map detection probability, false-alarm rate, and tracking accuracy to mid-air collision risk, thereby establishing a quantitative connection between perception performance and safety outcomes. Jenie et al. [13] classified conflict detection and resolution methods according to surveillance type, coordination mode, maneuver strategy, and level of autonomy, further illustrating that different operating concepts impose different risk-control requirements.

For low-altitude operations in which visual uncertainty is significant, conflict management should therefore evolve from purely deterministic thresholding toward risk-driven decision-making that explicitly incorporates perception uncertainty into conflict probability and operational response.

3.2. Balancing Efficiency and Safety in Autonomous Avoidance

UAV avoidance planning generally relies on graph-search, sampling-based, optimization-based, or learning-based methods. Guban and Haque [14] noted that conventional methods such as A* and RRT* are structurally transparent but lose efficiency in highly dynamic, high-dimensional environments, whereas model predictive control (MPC) and trajectory optimization can explicitly enforce dynamic and safety constraints at the cost of greater real-time computation.

Kalidas et al. [15] demonstrated that deep reinforcement learning can use visual inputs to avoid both static and moving obstacles, although learning-based policies typically lack explicit formal safety guarantees. Tang et al. [16] further observed a growing convergence between learning and optimization methods in UAV collision avoidance. From an operational-management perspective, this convergence reflects a fundamental trade-off between safety and efficiency. Excessively conservative rules can reduce airspace capacity and mission efficiency, whereas heavy reliance on high-performance learning algorithms can increase opacity and behavioral unpredictability. A more suitable architecture for scaled operations is therefore hierarchical: learning components can interpret complex scenes and generate efficient candidate actions, while rule-based or optimization-based components enforce non-negotiable safety constraints.

The work of Xue et al. [17] on dynamic multi-UAV path planning under incomplete information also shows that explicitly modeling uncertainty can improve decision

robustness. Future low-altitude operations should therefore incorporate perception confidence, traffic density, and safety constraints into onboard decision logic so that operational efficiency and safety can be balanced dynamically rather than treated as separate objectives.

4. Low-Altitude Air Traffic Management and Integration of Visual Information

4.1. UTM, U-space, and China's Low-Altitude Management Framework

As visual navigation moves from single-vehicle autonomy to scaled operations, it must function within traffic-management systems that differ in organization, service provision, and information rules. The U.S. UTM concept emphasizes distributed coordination among operators, service suppliers, and regulators; U-space relies more heavily on regulation-driven, service-oriented management; and China's low-altitude operational framework places greater emphasis on categorized operations under government-led coordinated supervision.

Panov and Ul Haq [18] analyzed information requirements for autonomous guidance in U-space and identified visual situational awareness as particularly difficult to standardize because of its unstructured form, high bandwidth demand, and stringent timeliness requirements. Wiedemann et al. [19] compared advanced air mobility policies across countries and likewise found substantial variation in regulatory approaches and operational flexibility. Ali et al. [20] further showed that differences in airspace classification, communication protocols, and conflict-management mechanisms complicate cross-system coordination for heterogeneous aircraft operations. For visual navigation, the key management question is therefore not whether images can be transmitted to the ground, but whether vision-derived safety states can enter the management system under common rules and be interpreted, used, and audited by other operators and regulatory actors.

Table 2. Management requirements for integrating visual information across low-altitude traffic-management frameworks

Framework	Primary operating logic	Requirement for visual-information integration	Key management concern
U.S. UTM	Distributed service coordination	Standardized onboard safety-state information	Data consistency among service providers
European U-space	Regulation-driven, layered services	Compatibility with U-space service interfaces	Semantic consistency and interoperability
China's low-altitude management framework	Categorized operations under government-led coordinated supervision	Integration with operational supervision and local platforms	Data standards and regulatory alignment

4.2. Information Management for Multi-UAV Collaborative Perception

Collaborative visual perception can reduce the field-of-

view and occlusion limitations of a single UAV, but its practical value depends heavily on communication reliability and information-sharing mechanisms. Li et al. [21] studied cooperative conflict detection and resolution for 6G-enabled UAVs and showed that low-latency communications can enhance multi-aircraft situational awareness. Sanchez-Aguero et al. [22] experimentally demonstrated the feasibility of 4G/5G cellular networks as communications infrastructure for UAV operations.

For low-altitude traffic management, however, more information is not necessarily better. Raw video imposes substantial bandwidth and computing loads, and under congestion or link interruption, indiscriminate transmission may interfere with safety-critical traffic. Alshaibani et al. [23] showed that network conditions directly affect the reliability of UAV information exchange. Meng et al. [24], from the perspective of UAV-enabled integrated sensing and communication (ISAC), summarized resource-allocation, interference-management, and cooperative-sensing issues in single- and multi-UAV settings, indicating that future collaborative perception will require tighter coordination between sensing and communication resources.

Multi-UAV visual collaboration should therefore incorporate a safety-information priority mechanism. Information directly relevant to conflict assessment, such as target position, velocity, confidence, timestamps, and risk level, should receive transmission priority, whereas routine imagery and non-critical perception data may be compressed, delayed, or processed locally. Such differentiated information management can help preserve safety-critical functions under constrained communication resources.

4.3. Standardization and Interoperability of Visual Safety Information

The central challenge in integrating vision into traffic-management systems is the lack of a common representation and validation mechanism for vision-derived information. Woolsey [25] proposed incorporating non-traditional sensing information into enterprise UTM through standardized interfaces, illustrating that onboard sensor outputs must first be structured before they can become usable traffic-management data.

A practical visual-safety message should at least represent target class, position and associated uncertainty, relative motion state, conflict probability, perception confidence, timestamp, and data provenance. Compared with transmitting complete images, such structured safety-state information is better suited to data fusion, operational monitoring, and conflict management. Interoperability is also a regulatory-coordination issue. Differences among UTM, U-space, and China's low-altitude management framework in communication protocols, data formats, and conflict-management mechanisms can restrict the movement of visual safety information across platforms and operational domains.

Security must also be considered. Aldaej et al. [26] and Yaacoub et al. [27] identified threats to UAV networks including data injection, spoofing, and communication hijacking. Once visual information directly contributes to conflict assessment, data authenticity and integrity become part of operational safety rather than merely cybersecurity. Standardized interfaces should therefore incorporate identity authentication, integrity verification, timeliness checks, and mechanisms for isolating anomalous data.

5. Operational Risk Management and Safety Assurance for Learning-Based Vision Systems

5.1. From Technical Failures to Operational Risk

Computer-vision studies commonly evaluate models using accuracy, recall, trajectory error, and related performance metrics, whereas low-altitude traffic management ultimately concerns conflict probability, accident consequences, and operational acceptability. The approach of Fitrikananda et al. [12], which maps perception performance to collision risk, provides one example of how these two categories of metrics can be connected.

A distinctive feature of vision systems is that their degradation is often strongly dependent on environmental conditions and data distribution. Changes in illumination, rain or fog, glare, target scale, and domain distribution may produce nonlinear reductions in performance. Charnsethikul et al. [28] likewise identified perception-system failures as an important operational risk in urban air mobility. A single fixed failure rate is therefore unlikely to characterize a learning-based vision system adequately. Operational risk management instead requires a causal chain linking operating scenario, visual failure mode, decision impact, and safety consequence. A missed detection of a small long-range target, for example, may first interrupt continuous tracking, then degrade time-to-collision estimation, and ultimately increase the risk of a missed conflict alert. Such causal reasoning helps operators and regulators identify which technical failures are genuinely safety-critical.

5.2. Safety Assurance Mechanisms for Learning-Based Vision Systems

Traditional aviation assurance emphasizes explicit requirements, traceable development processes, and reproducible verification. Deep-learning-based vision systems, by contrast, depend heavily on training data and produce probabilistic outputs, creating a substantial mismatch with conventional assurance logic. Runtime assurance offers a practical engineering response. Under this approach, a high-performance learning component is permitted to perform complex perception tasks while an independent monitor and fallback mechanism enforce safety boundaries. The learning component remains active while its outputs are within acceptable limits; when confidence degrades or a safety boundary is exceeded, the system transitions to rule-based control, conservative planning, or another predefined safe state.

Alharbi et al. [29] used explainable machine learning to support safe and efficient UAV operation, illustrating how model-state interpretation and runtime monitoring can contribute to safety assurance. From a safety-regulation perspective, the assurance target therefore needs to expand from the algorithm alone to an integrated system comprising the algorithm, training data, operating environment, and safety monitor. Rather than assuming that a learning model will remain equally reliable in every unknown environment, operators and regulators should define its approved operating envelope, degradation triggers, and procedures for handling abnormal outputs.

Navigation integrity must also be considered. Wang et al. [30] investigated the use of redundant inertial sensors to

enhance navigation integrity for UAM, indicating that high-assurance operations generally should not depend on a single sensing source. Future visual-navigation architectures are therefore likely to rely on redundant fusion of vision, inertial sensing, radar, and collaborative information, with dynamic switching or weighting based on the real-time confidence of each source.

Table 3. Major regulatory and assurance challenges for learning-based vision systems

Challenge	Implication for operational management	Potential safety-assurance pathway
Black-box behavior and limited explainability	Difficult to trace the basis of safety-critical decisions	Explainability analysis; failure-mode libraries
Long-tail scenarios	Conventional testing may miss rare but hazardous conditions	Critical-scenario generation; adversarial testing
Operational distribution shift	Offline performance may not represent real operations	Runtime monitoring; dynamic degradation strategies
Simulation-to-reality gap	Risk assessments may be overly optimistic	Combined simulation and flight-test validation
Failure of a single sensing source	Potential single point of failure	Multi-sensor redundancy; integrity monitoring

5.3. Datasets, Digital Twins, and Safety Validation

Existing UAV vision datasets mainly support individual tasks such as object detection, tracking, visual localization, and semantic segmentation. Few datasets jointly annotate perception outputs and downstream safety outcomes such as successful conflict detection, avoidance performance, or operational risk. Rampriya et al. [31] released a UAV-captured railway dataset with annotations for track segmentation and obstacle detection, providing a useful benchmark for vision assessment in a specific application domain. Such datasets, however, do not capture the communication conditions, traffic-flow characteristics, and operating rules encountered in high-density low-altitude airspace. Consequently, higher detection accuracy on conventional computer-vision datasets cannot by itself demonstrate traffic-level safety. Future safety-validation datasets need to represent visual conditions, target motion, traffic density, communication state, and final safety outcomes in an integrated manner.

Digital twins provide a potential platform for this type of validation. Souanef et al. [32] proposed a digital-twin framework for future airspace in which real-world data and virtual environments are coupled to support airspace analysis and optimization. For visual navigation, a digital twin can be used not only to test algorithms but also to represent vehicle states, traffic density, communication conditions, and management rules, enabling system-level risk evaluation.

A more credible safety-validation process should operate as a closed loop. Safety-critical scenarios can first be generated in simulation to test perception and decision functions; limited flight tests can then provide empirical performance data; those data can be used to calibrate the simulation environment; and large-scale risk testing can subsequently be repeated. This process can transform digital

twins from stand-alone algorithm-testing tools into instruments for low-altitude operational safety management and regulatory evaluation, allowing operators and regulators to assess the risks associated with new algorithms, vehicle types, or operating rules before deployment.

6. Key Challenges and Regulatory Pathways for Scaled Low-Altitude Operations

The literature reviewed above suggests that, as visual navigation moves into scaled low-altitude operations, the principal challenge is no longer isolated technical optimization but coordination among technical performance, risk control, operational management, and regulatory oversight.

First, a mapping mechanism is needed between technical metrics and operational safety metrics. Visual systems are commonly evaluated using localization error, detection accuracy, and depth error, whereas operational management is more concerned with the probability of missed conflicts, minimum separation, and collision risk. Quantitative relationships between these metric classes are required if changes in algorithmic performance are to be converted into safety information that can support operational approval and risk control.

Second, autonomous decision-making should become risk-driven. Visual outputs are inherently uncertain, yet many avoidance systems still treat perception estimates as deterministic planner inputs. Future systems should explicitly incorporate perception confidence into conflict detection and path planning so that separation margins and decision conservatism can adapt to both sensing quality and traffic density.

Third, visual safety information should be standardized and made interoperable across platforms. UTM, U-space, and regional low-altitude management platforms differ in organizational structure and technical interfaces. Without common semantics, vision-derived information cannot be shared reliably across operational actors. Future standards should therefore specify core visual-safety fields, update rates, confidence representations, and data provenance so that cross-system operations can be supported on a common information basis.

Fourth, learning-based perception should be managed across its full life cycle. The safety of a deep-learning model depends not only on network architecture but also on training data, the operating environment, and subsequent model updates. Version control, scenario-coverage assessment, runtime anomaly monitoring, and revalidation after updates should therefore be incorporated into development, deployment, and operational management.

Fifth, regulatory validation should combine digital twins with flight testing. Digital-twin environments can exercise complex and hazardous scenarios at scale, but simulation bias must be continuously corrected using flight-test data. In the longer term, digital-twin scenario libraries may support operational approval, evaluation of algorithm updates, and post-event reconstruction, thereby linking development validation with operational oversight.

Overall, the further development of low-altitude visual navigation cannot be driven by perception algorithms alone. Effective deployment requires coordination among visual sensing, flight-control decision-making, communication

services, operators, and regulatory systems. Technical advances become operational safety capabilities only when they are embedded in standards, interfaces, risk-assessment procedures, and verifiable assurance processes.

7. Conclusion

This review examined UAV visual navigation for low-altitude air traffic safety from the perspectives of perception capability, decision safety, and compatibility with traffic management. At the perception level, visual SLAM, object detection and tracking, and depth estimation already provide important capabilities for autonomous operation, but illumination changes, small targets, occlusion, scale ambiguity, and other low-altitude environmental factors continue to introduce substantial uncertainty. For scaled operations, the next step is therefore not merely to improve average algorithmic accuracy, but to establish explicit relationships among perception performance, position integrity, and safety consequences.

At the decision level, perception errors propagate through state estimation, conflict detection, and path planning, ultimately affecting separation and avoidance performance. Risk-driven probabilistic conflict assessment and hybrid learning-optimization decision architectures are therefore more consistent with the requirements of low-altitude air traffic safety than approaches focused solely on rapid decision generation.

At the management level, UTM, U-space, and China's low-altitude operational framework differ in organization and regulation, but all require onboard information to be exchanged, interpreted, and validated reliably. Because visual information is unstructured, data-intensive, and strongly dependent on operating conditions, converting vision-derived outputs into standardized and traceable safety information is a prerequisite for integrating visual navigation into traffic-management systems. At the same time, the data dependence and probabilistic outputs of deep-learning perception challenge conventional assurance practices, indicating a need to move from algorithm-only certification toward system-level assurance that includes operating scenarios, model state, runtime monitoring, and safe degradation.

In summary, the central challenge in UAV visual navigation is shifting from the limitations of individual algorithms to the absence of unified metrics, interfaces, and validation mechanisms across perception, decision-making, and traffic management. Future research should place greater emphasis on standardized visual safety information, risk-driven decision-making, life-cycle management of learning-based systems, and integrated digital-twin/flight-test validation so that visual technologies can evolve from onboard functions into safety capabilities accepted by both operators and regulators.

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