

UAV Flight Test Technology: Evolution, Current Status, and Intelligent Trends

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Abstract: Flight test technology is essential for the finalization, safe operation, and capability iteration of unmanned aircraft systems (UAS), and its evolution tracks the advance of UAS platforms, control methods, and payloads. This paper divides the century-long history into six technological stages and uses them to clarify how flight-test practice evolved at each stage. Current development status and bottlenecks are then examined across four dimensions: flight platform testing, mission system testing, autonomy capability evaluation, and digital twin and virtual flight testing. Looking ahead, the paper discusses closed-loop digital-twin testing, standardized intelligent evaluation, large-scale swarm verification, human-unmanned collaborative testing, intelligent airworthiness systems, and combat-oriented countermeasure testing. Overall, UAS flight test technology has grown from initial remote-control feasibility checks into a comprehensive system spanning the full flight envelope, mission chain, and combat scenarios, and it is now being reshaped by intelligence demands so that UAS can operate in highly contested environments.

1. Introduction

Since the first Curtiss unmanned aircraft flew in 1917, unmanned aircraft systems (UAS) have evolved over more than a century from remote-controlled target drones into aviation equipment covering military and civil scenarios. As a critical link between design and operational employment, UAS flight testing verifies performance, manages safety, and finalizes capabilities. Existing studies classify UAS growth by control modes (Fan et al., three stages: manual control, semi-/fully automatic control, and intelligent control) [1], by UAV technology (Zhang et al., three stages: target-drone inception, reconnaissance and surveillance, and reconnaissance-strike integration) [2], and by major technical features (Yu et al., six stages: budding start, preliminary growth, rising development, booming development, steady development, and intelligent development) [3]; the six-stage division covers the full evolution from exploration to intelligent autonomy and provides the methodological reference for this paper. This paper reviews the evolutionary logic, analyzes current development status and bottlenecks, and prospects future directions under intelligent trends.

2. The Evolution Logic of Flight Test Technology

2.1 Budding Start Stage (1917–1963)

UAS acted as remote-controlled target drones using low-precision mechanical gyroscopes and pure radio control, with no autonomous capability. Flight testing remained nascent, verifying only remote-controllability and stable flight; subjects were limited to basic platform performance, control links, and target characteristics, relying on ground visual tracking and simple telemetry without standardized procedures [4].

2.2 Preliminary Growth Stage (1964–1990)

UAS became auxiliary battlefield equipment with simple reconnaissance payloads and Level-1 autonomy (per the DoD autonomy scale, 1–10 [5], hereinafter), executing pre-planned routes. The 1982 Bekaa Valley campaign validated multi-mission capability. Testing expanded from "able to fly" to "able to fly and complete missions," adding navigation-accuracy and payload subjects with radar-tracking over-the-horizon telemetry.

2.3 Rising Development Stage (1991–2000)

UAS became standard equipment with electro-optical turrets, dedicated attack payloads, and GPS/inertial navigation (Level-2 autonomy), supporting off-board re-planning. Testing benchmarked military manned-aircraft finalization: full-envelope, attack-system, and electromagnetic-compatibility subjects, along with hardware-in-the-loop pre-verification and bus-based distributed testing, forming "subject-by-subject progression–full-profile finalization" procedures. Multi-aircraft cooperative testing still relied on centralized control, in which a single ground station planned the tracks and tasks of all aircraft; suited to small-scale, low-complexity formation verification, it laid the groundwork for later cooperative testing [6].

2.4 Booming Development Stage (2001–2010)

UAS transitioned from reconnaissance to strike-and-reconnaissance integration, adopting long-endurance structures, synthetic aperture radar (SAR), air-to-surface missiles, and fault adaptation (Level-3 autonomy). The 2001 U.S. Predator's missile launch pioneered aerial strike. Testing aligned with manned combat aircraft, incorporating weapon-system testing into finalization and forming the "simulation-first, phased, full-profile, combat-oriented" mode.

2.5 Steady Development Stage (2011–2022)

A dual military–civil system emerged. Military UAS advanced toward flying-wing stealth unmanned combat aircraft (Level-4+ autonomy), with loyal-wingman platforms such as MQ-28 and XQ-58A completing first flights [7-8]; civil UAS proliferated globally. Testing diversified into stealth, high-autonomy, and manned–unmanned collaboration, establishing distributed multi-site telemetry and fiber-optic high-speed test architectures.

2.6 Intelligent Development Stage (2023–Present)

Driven by artificial intelligence (AI), UAS are moving toward fully autonomous operations, relying on positioning, navigation, and timing (PNT), laser-gyroscope anti-jamming navigation, and level 6-and-above autonomy that supports self-organizing formations under only top-level human

supervision. Testing has shifted from deterministic performance assessment to quantifying uncertain intelligent capability, sustained by digital-twin test systems that close the loop from full digital simulation through hardware-in-the-loop to actual flight [9].

2.7 Summary of Evolution Logic

Across the six stages, three threads are evident. The objects under test grew from a single platform into a system of systems that spans the platform, navigation, payloads, links, and weapons, and eventually single, swarm, and human-unmanned hybrid vehicles. The methods moved from experience-driven observation, such as visual tracking, to distributed, high-density, and virtual-real integrated measurement. The objectives advanced from basic feasibility checks to the certification of complete combat systems.

3. Current Development Status of UAS Flight Test Technology

UAS flight test technology has entered a phase of systemic maturity, multi-track parallelism, and intelligent exploration. Four technical dimensions are analyzed below.

3.1 Flight Platform Flight Test Technology

Platform testing verifies aerodynamics, flying qualities, structural strength, and propulsion. Military practice has developed full-envelope aerodynamic methods, including closed-loop-identification flying-quality testing for flying-wing UAS with near-zero directional stability. Domestically an airworthiness framework exists, but specifications for logistics-delivery and passenger UAVs remain exploratory [10]. Strain-based structural load measurement and mature piston/turboprop methods contrast with hybrid-electric and hydrogen fuel-cell systems still under development. Major bottlenecks include test means for highly stealthy UAS, endurance and reliability of new propulsion, and aeroservoelastic testing of large UAS.

3.2 Mission System Flight Test Technology

Mission-system testing verifies sensors, links, weapons, and mission planning. Electro-optical, SAR, and electronic-reconnaissance payload testing is standardized; multi-sensor fusion develops registration-accuracy assessment. Full-link methods cover line-of-sight, beyond-line-of-sight, and satellite relays, with channel-simulator anti-jamming tests evaluating spread-spectrum and low-probability-of-intercept performance. Weapon testing progresses through "ground static, dynamic simulation, airborne release, live-fire." AI-powered swarm experiments are also exploring multi-sensor coordination in swarms. Bottlenecks include unified evaluation indicators and peacetime combat-oriented communication testing.

3.3 Autonomy Capability Evaluation Technology

Autonomy evaluation is the most challenging direction, its core difficulty being the interpretability and assessability of "black-box" intelligent algorithms. Scenario-based testing is the global norm, covering normal, abnormal, and adversarial scenarios across the OODA loop, graded by the DoD 1–10 [5] and Chen et al.'s 1–9 autonomous-level schemes [11]. Deterministic indicators cannot exhaust intelligent scenarios, so digital-twin virtual testing remains primary, supplemented by limited live trials, as exemplified by the DARPA ACE program; adversarial robustness and out-of-distribution generalization assessment are emerging. Human-machine collaboration focuses

on authority allocation, intent understanding, and cross-platform interoperability. Bottlenecks: quantitative intelligent indicators, interpretability, and high-fidelity adversarial scenario construction.

3.4 Digital Twin and Virtual Flight Test Technology

Digital twin technology is reshaping flight testing into a virtual-primary, live-calibration paradigm. By building 1:1 digital-twin airframes and environments, testers can run massive, extreme, and adversarial scenarios virtually before the live sortie. A typical architecture chains software-in-the-loop, hardware-in-the-loop, and actual flight testing, exchanging data between levels through DDS or HLA middleware, and real-time latency is usually kept at sub-millisecond levels [12]. Physics-engine modeling combined with real terrain, meteorological, and electromagnetic data builds high-fidelity environments with uncertainty quantification. The main bottlenecks are environment fidelity, virtual-live synchronization and calibration, and the computing resources needed for large-scale swarm simulation.

4. Future Development Trends

Future work is expected to advance along six directions.

4.1 Closed-Loop and Collaborative Digital-Twin Test System

Rather than running offline simulation that only loosely matches the live platform, digital-twin testing should close into an online loop, exchanging data in real time with the flight article so that the twin self-calibrates against measured behavior [13]. A Digital Thread should run through the entire UAS lifecycle, and federated learning can let many platforms train together in simulation.

4.2 Standardized and Automated Intelligent Capability Evaluation

Evaluating single-platform, swarm, and human-unmanned hybrid intelligence still lacks a common yardstick. Future work should combine scenario-based testing with formal reachability analysis so that the state space of intelligent algorithms can be verified more completely, building toward a standardized assessment system [14].

4.3 Large-Scale Swarm Flight Test Verification

Live testing of large swarms is expensive, risky, and cannot cover enough scenarios. The field therefore needs distributed cluster monitoring, quantitative evaluation of group behavior, and high-fidelity, adversarial verification of cooperative operations [15].

4.4 Normalization of Human–Unmanned Collaborative Flight Testing

Human-unmanned collaboration still lacks standardized procedures and metrics. Quantitative authority-allocation criteria should be defined, together with end-to-end test systems for formation flight, cooperative reconnaissance and strike, and cooperative electronic countermeasures [16].

4.5 Construction of Civil Intelligent Airworthiness Systems

Certification rules for logistics and passenger UAVs are still being developed. The community still needs to establish safety-verification methods for autonomous flight and assemble the

certification test systems that urban air mobility will need.

4.6 Normalization of Combat-Oriented Countermeasure Testing

Countermeasure testing should be run in combat-oriented, live-virtual-constructive (LVC) environments, where multi-domain red-force threats are simulated and single-subject trials give way to red-blue countermeasure testing [17].

5. Conclusions

UAS flight test technology has matured into a comprehensive system that spans the full flight envelope, the entire mission chain, and all combat scenarios. The drive toward intelligence is now pushing it toward the six directions discussed above, moving the field from deterministic performance assessment to the quantitative evaluation of uncertain capability, which in turn underpins UAS operations in highly contested and complex environments.

References

- [1] B. Fan and R. Zhang, "UAV system and artificial intelligence," *J. Wuhan Univ. (Inf. Sci. Ed.)*, vol. 42, no. 11, pp. 1523-1529, 2017, doi: 10.13203/j.whugis20170177. (in Chinese)
- [2] S. Zhang, Y. Zhu, L. Dai, and B. Tang, "Research on the development history, current status and future application of military UAV technology," *Ship Electron. Eng.*, vol. 41, no. 6, pp. 9-13, 2021, doi: 10.3969/j.issn.1672-9730.2021.06.003. (in Chinese)
- [3] H. Yu, Y. Niu, and X. Wang, "Development stages and intelligent trends of UAV systems," *Natl. Defense Technol.*, vol. 42, no. 3, pp. 18-24, 2021, doi: 10.13943/j.issn1671-4547.2021.03.03. (in Chinese)
- [4] Y. Li and X. Zhang, "Research on UAV flight test methods," *Aeronaut. Sci. Technol.*, no. 3, pp. 7-9, 2009, doi: 10.3969/j.issn.1007-5453.2009.03.002. (in Chinese)
- [5] Department of Defense, *Unmanned Systems Integrated Roadmap FY2013-2038*. Washington, DC, USA: DoD, 2013.
- [6] Y. Li and C. Wu, "Multi-UAV cooperative flight test mode," *Fire Control Command Control*, vol. 37, no. 7, pp. 131-134, 2012, doi: 10.3969/j.issn.1002-0640.2012.07.035. (in Chinese)
- [7] G. Jia and Z. Guo, "Development of foreign stealth UAVs," *Natl. Defense Technol.*, vol. 40, no. 2, pp. 13-16, 2019, doi: 10.13943/j.issn1671-4547.2019.02.04. (in Chinese)
- [8] P. Yu, Q. Wei, W. Liu, and M. Li, "Current status, development trends and combat scenarios of loyal wingmen," *Mod. Def. Technol.*, vol. 53, no. 3, pp. 23-31, 2025, doi: 10.3969/j.issn.1009-086x.2025.03.003. (in Chinese)
- [9] X. Yin, G. Zhang, X. Peng, L. Li, and B. Tian, "Intelligent development and application of military UAV technology," *Natl. Defense Technol.*, vol. 39, no. 5, pp. 30-34, 2018, doi: 10.13943/j.issn1671-4547.2018.05.06. (in Chinese)
- [10] J. Su, M. Li, T. Jiao, and K. Ou, "Research on domestic UAV airworthiness certification policy," *Aeronaut. Stand. Qual.*, no. 2, pp. 33-39, 2026, doi: 10.13237/j.cnki.asq.2026.02.07. (in Chinese)
- [11] Z. Chen, J. Wei, Y. Wang, and R. Zhou, "Research on UAV autonomous control level and its system structure," *Acta Aeronaut. Astronaut. Sin.*, vol. 32, no. 6, pp. 1075-1083, 2011. (in Chinese)
- [12] F. Tao, W. Liu, M. Zhang, T. Hu, Q. Qi, H. Zhang, et al., "Digital twin five-dimensional model and its ten applications," *Comput. Integr. Manuf. Syst.*, vol. 25, no. 1, pp. 1-18, 2019, doi: 10.13196/j.cims.2019.01.001. (in Chinese)
- [13] R. Zhuo and C. Yan, "A key link in aircraft structural digital twin: multi-parameter in-flight measurement," *Acta Aeronaut. Astronaut. Sin.*, vol. 46, no. 19, pp. 92-102, 2025, doi: 10.7527/S1000-6893.2025.32375. (in Chinese)
- [14] R. Parasuraman, T. B. Sheridan, and C. D. Wickens, "A model for types and levels of human interaction with automation," *IEEE Trans. Syst., Man, Cybern., Part A, Syst. Humans*, vol. 30, no. 3, pp. 286-297, 2000, doi: 10.1109/3468.844354.
- [15] Y. Jia, S. Tian, and Q. Li, "A review of UAV swarm research progress," *Acta Aeronaut. Astronaut. Sin.*, vol. 41, no. S1, 723738, 2020. (in Chinese)
- [16] Y. Niu, L. Shen, J. Li, and X. Wang, "Key problems in unmanned-manned aircraft cooperative control," *Sci. Sin. Inf.*, vol. 50, no. 4, pp. 513-530, 2020. (in Chinese)
- [17] C. Huang, *Precision Strike Technology of Unmanned Combat Aircraft*. Beijing, China: National Defense Industry Press, 2011. (in Chinese)