OPTIMIZING REAL TIME DECISION MAKING IN UAVS WITH REINFORCEMENT LEARNING

Mammadov E.S.
National Defense University; Baku, Azerbaijan

This article examines the present application possibilities and near-term prospects of machine learning technologies in unmanned aerial vehicles, with emphasis on autonomy, perception, navigation, decision making, and coordinated multi-UAV operations. The analysis synthesizes results from recent field deployments and simulation studies to show how data driven models increase mission success under uncertainty, reduce operator workload, and expand the feasible envelope of operations in cluttered, dynamic, or communication constrained environments. In perception, supervised and self-supervised learning have enabled robust object detection, terrain classification, and semantic segmentation across diverse weather and illumination conditions by fusing RGB, thermal, LIDAR, radar, and GNSS inertial signals. Learning based visual inertial odometry and event camera pipelines improve state estimation at high angular rates, while learned depth completion stabilizes mapping in scenes with partial observability. In navigation and obstacle avoidance, model predictive control augmented by learned cost maps outperforms rule-based planners in urban canyons and forested areas where GPS is degraded, and end to end imitation learning from expert demonstrations reduces collision risk without hand crafted features.

Reinforcement learning contributes to decision making under nonstationary task and threat models. Algorithms such as Q Learning, DQN, PPO, and SAC learn policies that balance safety, energy, latency, and reward shaped mission objectives such as coverage, time to detect, and probability of intercept. Curriculum learning and domain randomization accelerate training and improve sim to real transfer, while risk sensitive policy optimization constrains tail events that matter for certification and public safety. At the fleet level, collective intelligence and swarm coordination enable distributed task allocation, adaptive formation control, and resilient coverage when individual platforms fail or communication links are intermittent. Market based assignments, consensus protocols, and graph neural network controllers maintain performance when topology changes, and mixed initiative control allows a single human to supervise many vehicles through intent level interfaces.

Three enabling vectors shape short term progress. The first is communication and compute. Edge offloading over 5G and future 6G reduces perception latency, while on board accelerators for convolutional, transformer, and graph workloads make inference feasible within strict size, weight, and power envelopes. Model compression through pruning, quantization, distillation, and low rank adaptation lowers energy per decision and extends endurance. The second is energy and airworthiness. Energy aware trajectory planning, aerodynamic learning for gust rejection, and predictive health monitoring increase mission length and reduce unscheduled landings. The third is trust, security, and compliance. Robustness to sensor spoofing and weather induced distribution shift, interpretable perception and control, secure command and control links with formal verification of safety invariants, and standardized test catalogs for regression prevent silent performance erosion as models evolve.

Sector case studies demonstrate tangible gains. In agriculture, multi spectral mapping with learned segmentation improves nitrogen prescription and pest hotspot detection, while coordinated route planning cuts flight hours per hectare. In environmental monitoring, anomaly detection on streaming video speeds early wildfire spotting and oil spill delineation. In public safety and disaster response, victim detection models and learned search patterns shorten time to first contact. In logistics and medical delivery, learned landing zone selection and wind aware path planning improve reliability under urban turbulence. Military and border protection applications leverage target recognition, pattern of life modeling, and cooperative geolocation, while remaining within the bounds of safety and responsible use.

Open challenges remain. Training data curation at scale is costly and biased, and the long tail of rare events limits generalization. Hardware variability across airframes complicates transfer of learned controllers. Battery energy density constrains long range missions, and high-fidelity simulation for aeroelastic effects is still maturing. Legal geofencing, privacy, and airspace integration must be encoded into planning stacks, not treated as afterthoughts. A research agenda that combines high quality datasets with uncertainty aware learning, hybrid model based and model free control, and continual learning under supervision is most likely to deliver certifiable performance.

The weight of evidence indicates a shift from scripted autonomy to data centric autonomy, where perception, prediction, and policy are learned from multimodal data and are refined through rigorous validation, closed loop testing, and lifecycle MLOps. As datasets, computer platforms, and certification frameworks improve, ML enabled UAVs will operate with greater independence and coordination across civilian and military domains while meeting stricter safety and reliability requirements.

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