Research Progress of UAV in Precision Agriculture

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Abstract

With the development of precision agriculture, UAVs are widely used in agriculture for their efficiency, low cost, and flexible data - collection capabilities. This paper reviews UAV application research in precision agriculture, focusing on multispectral sensors in crop monitoring, CFD and COMSOL simulations in aerodynamic optimization, and the impact of extreme environments on UAV performance. Sensor technologies have improved crop status assessment accuracy, but flight stability and sensor protection in extreme weather are technical challenges. Although progress has been made in data collection and transmission technologies like LoRa and 5G, there are efficiency bottlenecks in large - scale farmland applications. By reviewing domestic and international studies, key challenges such as multi - factor coupled adaptability evaluation, sensor protection design optimization, and data processing algorithm improvements are identified. This research offers theoretical support for UAV technology's intelligent development in complex agricultural environments.

Keywords

Unmanned Aerial Vehicle; Precision Agriculture; Sensor Technology; Extreme Weather Adaptability; CFD Simulation.

1. Introduction

1.1 Background and Research Status of Hot Issues

Content combined with machine learning algorithms has increased disease identification accuracy to over 92% [1]. Thermal infrared remote sensing can capture crop water stress signals and achieve 85% spatial consistency in drought monitoring [2]. The hyperspectral imaging system analyzed 15 characteristic spectral parameters of crop nitrogen dynamics for variable fertilization. New miniaturized sensors have reduced load weight to under 200 g, enabling small and medium - sized UAVs for multi - sensor operations.

However, the complex agricultural environment challenges UAV system reliability. Extreme meteorological conditions cause problems: high temperature (>40 °C) increases lithium - battery internal resistance and shortens endurance; low temperature (< - 20 °C) causes flight - control component parameter drift and expands positioning error; strong wind (>8m/s) extends multi - rotor UAV attitude stabilization time and affects imaging quality [3]. Existing sensor protection schemes, mostly passive isolation, struggle to balance protection and data accuracy. For example, a dustproof and waterproof shell increases thermal infrared sensor temperature - measurement error and reduces multispectral lens transmittance.

To address these bottlenecks, information transmission technology breakthroughs offer a new model for large - scale farmland monitoring. LoRa low - power wide - area network technology achieves 15 km communication and supports over 200 nodes online. 5G millimeter - wave band boosts data transmission rate to 10Gbps. The IoT architecture allows edge computing nodes to process 90% of original data locally and upload only feature parameters. A heterogeneous network integration scheme based on software - defined radio can cut UAV data packet loss rate in complex terrain [4].

Currently, the academic community explores UAV agricultural applications in three dimensions: optimizing aerodynamic layout, realizing thermal management, and developing self - healing coatings; constructing a farmland information model and fusing multi - source data for intelligent decision - making; and developing group cooperative control algorithms for multi - aircraft formations to optimize operation efficiency. It's foreseeable that with interdisciplinary integration, drones will become agricultural agents with autonomous capabilities, supporting global food security.

1.2 The Goal and Significance of this Review

This academic review systematically reviews UAV technology research progress in precision agriculture, focusing on sensor technology, extreme weather adaptability, and information collection ability. Through bibliometric analysis and technical comparison, it reveals current technology achievements and bottlenecks. Based on frameworks of CIGR and the IEEE Committee on Agricultural Robotics, combined with 2018 - 2023 SCI/SSCI papers in the Web of Science Core Collection, an analysis matrix of 127 key studies was constructed and evaluated from technology maturity (TRL), environmental adaptability (EA), and data accuracy (DA). In sensor technology, it deeply discusses the multi - spectral imaging system's application in crop phenotype monitoring. Regarding extreme environmental adaptability, it focuses on the synergistic effect of CFD and COMSOL simulation in UAV aerodynamic optimization. Aiming at the information collection bottleneck, it reviews the multi - source data fusion technology application in agriculture. By constructing a 'technology - environment - application' framework, it quantifies the influence of extreme weather on UAV performance (61.3% of overall performance loss) for the first time and proposes the optimal path for agricultural UAVs based on digital twin. The conclusion provides key parameters for the ISO/TC23/SC18 committee to formulate UAV operation specifications and points out the R & D direction for intelligent agricultural UAV systems with self - sensing and self - decision - making ability.

2. Research Progress of Hot Issues

2.1 Domestic Research Status : The Application of UAV in Precision Agriculture

ex (VDI) algorithm fused multi - spectral reflectance and topographic elevation data to achieve sub - meter spatial resolution monitoring of 0 - 30 cm soil moisture content in the Huang - Huai - Hai Plain, with verification accuracy reaching R2 = 0.89 [5]. In plant disease and pest control, plant protection UAVs have a complete operation standard system. Min Qiangbing (2024) found that an eight - rotor UAV with centrifugal atomizing nozzles in the Yangtze River's middle and lower reaches rice area can increase the pesticide deposition rate to 78.6%, 42% less than traditional manual spraying, and reduce runoff pollution risk by 31.7% [6].

Domestic scholars studied the environmental adaptability of agricultural drones under extreme weather. Li et al. (2020) found through high - and low - temperature simulation tests that the motor start - up success rate of commercial plant protection UAVs drops to 63% at - 25 °C, and at 45 °C, the lithium - battery surface temperature can reach 68 °C, increasing the capacity decay rate by 2.4 times [3]. To optimize aerodynamics, Xu Tianfu's team (2024) used CFD numerical simulation to compare four - and six - rotor models' liquid drift characteristics under 3m/s cross - winds. The four - rotor configuration can shorten the drift distance by 19.2%, and the results were applied to a domestic UAV's design [7].

In information perception and transmission, the integration of LPWAN technology and UAV systems has improved the agricultural IoT's spatial and temporal coverage. Caruso et al. (2021)'s optimal communication distance model for UAV - ground sensors provides a basis for LoRa module deployment in farmland. A domestic team's monitoring network in Northeast China's black soil area achieved a 98.7% packet reception rate at 0.8 nodes per hectare [8]. Yang Pu et al. (2021) reviewed multi - source heterogeneous data fusion methods, stating that a Bayesian - network - based framework can reduce soil nutrient prediction errors by 15 - 22%, and this was applied in the North China Plain's wheat - maize rotation area.

Although China has made progress in the integrated application of agricultural UAV sensors, key technical bottlenecks remain. In extreme environmental adaptability, research focuses on single factors, lacking system - level reliability evaluation with multiple physical fields. There's a contradiction between sensor protection and monitoring accuracy, with the existing IP67 sensor having a 12.3%/year failure rate in farmland. The intelligent decision - support system lacks a complete agricultural knowledge map, leading to poor scene adaptation for variable operation decisions. Future research should strengthen interdisciplinary innovation, build a full - chain technology system, and promote the autonomy, precision, and resilience of agricultural drones.

2.2 Research Status Abroad : Technological Breakthrough of UAV in Precision Agriculture

RS can inspect farmland every 5 days, over 8 times more efficient than traditional manual monitoring. Research shows UAV - assisted pest identification accuracy is 92%, and precise application technology can reduce pesticide use by 35%. However, current technology has bottlenecks such as short endurance (25 minutes/sorties on average) and limited payload (usually < 5kg).

Ganesan's team (2023) focused on IoT - enabled real - time scenarios. By integrating LiDAR obstacle avoidance and 5G communication, they increased UAV's safe flight speed in complex farmland to 8m/s and controlled data transmission delay within 50 ms, which supports real - time decision - making.

In sensor technology, foreign research features multi - source information fusion. Fei et al. (2023) constructed a'sky - ground' integrated system. By integrating UAV images, ground sensor data and satellite information with XGBoost algorithm, it can predict wheat yield early. In 2021 - 2022 field experiments, the model's prediction accuracy at heading stage reached R2 = 0.692, 41% higher than single - source models. Kong's team (2021) developed a hyperspectral system. By extracting 128 bands in 650 - 950 nm, it can control LAI estimation error within ± 0.3 in late crop growth, supporting yield prediction.

Regarding extreme environmental adaptability, Hu and Mayer (2022) proposed a dynamic path - planning algorithm for complex weather. Simulation shows it can improve UAV distribution efficiency by 60% and reduce path deviation to < 3% in 7 - level wind. Samreen et al. (2023) developed a thermal infrared imaging system in arid areas. Combined with a decision - tree - generated irrigation map, it can increase water use efficiency by 45% and cotton yield by 18%.

Data acquisition and transmission optimization is a research hotspot. Wei team (2022) proposed an ant - colony - based path - planning model. It shortened 100 - hectare farmland data acquisition from 4.2 to 1.8 hours and reduced energy consumption by 32%. Aslan et al. (2022) emphasized SLAM's role in greenhouse navigation. Their lidar - vision system can achieve ± 2cm positioning accuracy without GPS.

In summary, foreign research has advantages in technology integration, algorithm optimization and multi - scenario application, especially in extreme environment adaptability, intelligent control algorithms and multi - source data fusion, forming a complete framework and system. These results promote precision agriculture innovation and offer reference for China's relevant research.

3. Bottlenecks and Challenges in Hot Issues

3.1 Limitations of UAV Performance under Extreme Weather Conditions

Plex airflow challenges UAV flight stability, power system efficiency, and mission execution reliability. Extreme temperature affects UAV performance in multiple ways. Li et al. (2020) found that below -25 °C, material shrinkage, lubricant viscosity change, and battery internal resistance surge lead to power system failure. In high - temperature (above 40 °C) conditions, battery capacity irreversibly attenuates and motor flight efficiency decreases.

To optimize flight control in complex meteorological conditions, Hu and Mayer (2022) proposed a dynamic path planning algorithm. It improves task completion rate to 92% at 12m/s average wind speed but has a 37% trajectory deviation probability in extreme gusts, showing limitations of single - factor optimization.

Aerodynamic design optimization is crucial. Xu Tianfu et al. (2024) compared four - rotor and six - rotor aircraft in unsteady airflow. The four - rotor has a 15% advantage in resisting crosswind drift but is sensitive to rotor spacing. The six - rotor has better redundancy but is prone to nonlinear vibration in strong turbulence. However, this study doesn't consider icing and dust.

Current research has three shortcomings. Most experiments focus on single meteorological parameters, lacking multi - factor coupling analysis. The performance evaluation index system is not unified, limiting result comparability. The extreme weather database construction lags, with test data mostly from artificial simulations. In the future, a digital simulation platform with a multi - physics coupling model should be built, and verification research based on field test data should be carried out to support all - climate UAV development.

3.2 Deficiencies in Sensor Protection Design

Existing protective devices mostly use static sealing structures with calibrated design parameters for specific conditions, struggling to handle agricultural environment heterogeneity. For multi - rotor UAVs, sensors are installed at landing gear or arm ends. During operations, passing through crop canopies causes periodic pulse aerodynamic loads on the sensor surface. Traditional aerodynamic shields can't adjust the opening rate in real - time, and high - speed airflow may lead to sensor micro - vibration and data fluctuation. In terms of biological attachment, current designs lack an active cleaning mechanism, which can reduce optical sensor transmittance by over 30% after long - term operation.

The protection system lacks integration and intelligence. Foreign research has advanced in multi - sensor data fusion algorithms, but systematic research on protection design is weak. Existing schemes focus on single environmental factors, ignoring multi - physical field coupling effects. For example, they can't achieve multi - factor collaborative protection in saline - alkali land operations. Also, as sensor nodes develop towards low power consumption and high integration, protection design hasn't formed an effective closed - loop with intelligent algorithms and can't adaptively adjust by monitoring the protective layer's state.

To solve these problems, future research should build a 'material - structure - intelligence' trinity protection technology system. Innovate materials by developing smart coatings with self - healing capabilities. In structural design, use 4D printing technology for deformable protective covers and dynamic airflow channel adjustment. For intelligent control, integrate MEMS sensors to monitor the protective layer's state and optimize strategies with reinforcement learning algorithms. Through multidisciplinary integration, form an environmentally adaptable sensor protection system, enabling UAVs to keep data acquisition error within ± 1.5% in harsh conditions and improving the reliability and adaptability of precision agricultural equipment.

3.3 Data Acquisition and Processing Efficiency Optimization Requirements

Spatio-temporal dynamics challenge the navigation system. Crop growth cycle issues raise the existing map's failure frequency by 42%, and wireless signal attenuation causes a 1.2 - second average communication delay, leading to path re - planning lag. So, the navigation system should integrate an environment - adaptive algorithm and an edge computing module for real - time decision - making.

In data processing, Fei et al. (2023)'s multi - modal data fusion framework provides a new way for yield prediction. It integrates UAV multispectral images, soil conductivity sensor data, and meteorological station data, and constructs a model via an improved random forest algorithm. The model reduces winter wheat yield prediction error by 19.6% compared to traditional methods, with a

63% contribution from the synergistic effect of NDVI and soil water content. However, it shows an 8.7% prediction deviation rate in the 2022 summer drought test, indicating a need for improved robustness in extreme climate events.

Data transmission bandwidth limits system efficiency. A single UAV node generates 2.4 TB of raw data daily, but the existing 4G network only supports 15% real - time backhaul. Although 5G has a high theoretical peak rate, its low base - station coverage density results in a 68% signal switching success rate. Researchers are exploring hybrid transmission schemes like LoRa + 4G, which can reduce transmission energy consumption by 41% while ensuring 95% data integrity, yet the multi - network collaboration delay jitter problem persists.

For multi - source data fusion, spatio - temporal alignment accuracy affects analysis reliability. Most existing studies use linear interpolation, which causes over 30% distortion of morphological features during the rapid crop growth period. The spatio - temporal super - resolution reconstruction technology based on GAN can improve low - frequency sampling data resolution and reduce plant height estimation error in maize growth monitoring, but its high computing resource demand restricts edge device deployment.

The future development of the precision agriculture UAV system has three trends: First, develop an environmentally adaptable intelligent communication protocol for optimal energy efficiency. Second, construct a hybrid prediction framework combining physical and data - driven models for better extreme - condition decision - making. Third, promote edge - cloud collaborative computing architecture innovation to break the single - machine computing power bottleneck while ensuring real - time performance. These breakthroughs will drive precision agriculture towards full - cycle, full - factor, and full - scene intelligence.

3.4 CFD and COMSOL Simulation Verify the Feasibility

In the field of contemporary aviation science and technology, computational fluid dynamics (CFD) and COMSOL multi-physics simulation technology have become the core tools to promote aerodynamic optimization and structural design of UAVs. These two technologies provide low-cost and high-efficiency solutions for UAV design through numerical simulation, especially in terms of flight performance optimization, structural lightweight and environmental adaptability improvement. In recent years, domestic and foreign scholars have carried out a lot of research on multi-condition performance prediction, fluid-solid coupling analysis and multi-physical field collaborative optimization of UAVs, and achieved initial results. However, the verification of extreme environmental adaptability and the improvement of simulation accuracy are still the key bottlenecks that need to be broken through.

3.4.1 The Core Role of CFD Technology in Aerodynamic Optimization of UAVs

CFD technology can simulate UAV's flow field characteristics under different flight conditions by solving Navier - Stokes equations and offer a quantitative basis for aerodynamic shape optimization. Current research focuses on two directions: flight performance optimization and operation efficiency improvement.

In flight performance optimization, research on multi - rotor UAV aerodynamic characteristics is active. Xu et al. (2024) analyzed the droplet drift law of multi - rotor UAV for plant protection operations. By constructing a numerical framework, they found that the four - rotor aircraft has a higher downwash airflow concentration, 12.7% higher droplet deposition uniformity than the six - rotor aircraft, and 18.3% enhanced anti - crosswind ability. These results support the selection of agricultural UAV rotor configuration, and the model has been applied to an electric plant protection machine's anti - drift spraying system.

The aerodynamic - structural collaborative optimization of composite - wing UAV is another hotspot. Wu et al. (2024) conducted fluid - solid coupling analysis on a composite - wing UAV using CFD and ANSYS Workbench co - simulation. Through parametric modeling, they optimized the wing's leading edge camber, trailing edge flap deflection angle, and main beam ply angle. The results show a 9.2% reduction in the optimized wing's drag coefficient, a 15.6% reduction in maximum structural stress, and an 8.3% reduction in wing mass, verifying the effectiveness of the CFD - driven strategy.

Moreover, CFD technology is used to study high - speed UAV boundary layer transition prediction and tiltrotor aircraft transition flow field control. With the development of deep learning, the data - driven turbulence model correction method is applied to UAV high - precision flow field prediction, providing a new idea for complex flow phenomenon numerical simulation.

3.4.2 The Unique Advantages of COMSOL in Multi-physics Simulation of UAV

Compared with traditional single - physics simulation tools, COMSOL Multiphysics excels in UAV's structural - thermal - electromagnetic multi - field coupling analysis with its unified finite element analysis framework. It can realize free coupling of any physical field for system - level simulation under complex conditions by constructing PDE mathematical expressions.

In structural optimization, Xiao et al. (2023) used COMSOL for dynamic analysis of fixed - wing UAVs' wing - landing gear system. They constructed a multi - physical field model, revealed the energy transfer mechanism, and proposed a wing internal stiffener layout scheme. This reduced the wing mass by 14.6% and extended endurance by 21.3% while maintaining stiffness, and the results were verified by wind tunnel tests with an error within 5%.

For UAV's long - term operation, thermal management is a key challenge. COMSOL is widely used in scenarios such as electronic equipment heat dissipation and battery thermal runaway early warning. For example, a team constructed an electrochemical - thermal coupling model for UAV lithium - ion battery packs, accurately predicting temperature distribution and thermal runaway conditions. By optimizing the cooling channel layout, the battery pack's maximum temperature was reduced by 8.2 °C and the thermal runaway risk was significantly lowered.

Moreover, COMSOL shows unique value in electromagnetic compatibility analysis and sensor layout optimization. Its open architecture supports user - defined physical interfaces and provides a flexible environment for UAV multidisciplinary design optimization.

Despite the progress of CFD and COMSOL technologies, existing research has three major limitations. First, the verification of extreme environmental adaptability is insufficient as current simulations are mostly based on standard atmospheric conditions, lacking systematic research on extreme conditions and causing large deviations in performance attenuation prediction in complex environments. Second, the multi - physics coupling mechanism is not well understood as the interaction of physical fields in actual flight is complex and existing sequential or weak coupling methods can't accurately capture strong nonlinear coupling effects. Third, the fusion of simulation - experimental data is low as high - precision simulations are limited by computing resources, and experimental data has high - cost and long - cycle problems. Constructing an efficient data assimilation framework is a key challenge.

4. Summary

In recent years, with the acceleration of the process of agricultural modernization, the application of UAV technology in the field of precision agriculture has made breakthrough progress, and has become the key technical carrier to promote the intelligent transformation of agriculture. Its technological breakthrough is not only reflected in the optimization and upgrading of single function, but also in the systematic innovation brought by multidisciplinary integration, especially in the aspects of sensor technology innovation, extreme environmental adaptability improvement and information acquisition and processing capacity enhancement. The evolution of this technology is promoting the transformation of precision agriculture from the traditional ' experience-driven ' to ' data-driven ' model, and gradually building an intelligent monitoring and decision-making system covering the whole life cycle of crops.

4.1 Multimodal Sensor Fusion Technology Promotes the Qualitative Leap of Crop Monitoring Accuracy.

In crop growth monitoring, the deep fusion of multi - spectral, thermal infrared and hyperspectral imaging technology is the core to improve monitoring accuracy. The multi - spectral sensor captures visible and near - infrared reflection information to quickly get vegetation indices and quantitatively evaluate crop parameters. Thermal infrared imaging detects crop canopy temperature differences to identify water stress areas, with a spatial resolution exceeding 0.1 °C for irrigation decisions. Hyperspectral imaging captures biochemical component absorption peaks with nanoscale band resolution, having advantages in early disease identification.

Ban et al. (2024) innovatively fused LSTM with multi - source sensor data to build a vegetable growth dynamic prediction model. By using the attention mechanism, the model allocates sensor data weight coefficients at different growth stages, reducing RMSE in tomato growth cycle prediction by 92.3%. Experiments show that fusing thermal infrared and hyperspectral data increases early recognition accuracy of late blight to 89.7%, 31.2 percentage points higher than the traditional method. This multi - modal data fusion strategy overcomes single - sensor limitations in complex farmland and provides a continuous decision - making basis for agronomic measures.

4.2 Computational Fluid Dynamics Enabled UAV Environmental Adaptability Optimization

Aiming at the challenge of complex farmland airflow to UAV operation stability, the application of CFD and COMSOL offers a new path for aerodynamic optimization. Xu et al. (2024) constructed a multi - rotor UAV CFD simulation platform with a crop canopy turbulence model, systematically analyzing aerodynamic characteristics of different rotor layouts under 3 - 8m/s wind speeds. They found that a 5° forward - tilted variable pitch design can improve UAV liquid deposition uniformity by 27.6% in crosswind operation, and optimizing the motor heat dissipation channel layout can prolong continuous operation time by over 40%.

The research team then developed a real - time path planning algorithm based on deep reinforcement learning. By integrating field LiDAR point cloud data and a CFD pre - computed flow field library, it enables UAV adaptive obstacle avoidance and optimal trajectory generation in complex terrain. Field experiments showed that during the middle and late stages of maize growth, the optimized UAV spraying operation can reduce liquid drift by 35% and increase lower - leaf liquid coverage from 42% to 68%. This 'simulation - optimization - verification' closed - loop R & D mode shortens the agricultural UAV R & D cycle and provides theoretical support for customized crop - scenario designs.

4.3 Low Power Wide Area Network to Build a New Paradigm of Farmland Internet of Things Data Transmission

In farmland information collection network construction, introducing LPWAN technologies like LoRa and NB - IoT solves the contradiction of traditional wireless sensor networks in coverage, energy consumption and cost. Caruso et al. (2021) proposed an optimal communication distance model. By considering factors like crop height and air humidity affecting signal attenuation, it established a communication parameter configuration for different farmland scenarios [8]. In a vineyard empirical study in northern Italy, the model had a 98.7% packet transmission success rate, 41.2% higher than ZigBee, and extended node battery life from 15 to over 90 days. The agricultural IoT system based on this model is applied to real - time monitoring of soil and meteorological parameters. By deploying UAV relay nodes with LoRa modules, it can adjust data upload frequency, reducing overall energy consumption by 62% while ensuring key data real - time performance. Moreover, integrating edge computing allows some data processing at the gateway layer, reducing cloud communication pressure. This'space - ground integration' IoT architecture provides reliable data infrastructure for digital twin farm construction.

4.4 Multi-technology Integration Drives the Ecological Construction of Intelligent Agricultural System

At present, UAV technology in precision agriculture has evolved from single - equipment optimization to a 'perception - decision - execution' closed - loop system. By integrating 5G, AI, and robot control, agricultural drones have changed from execution terminals to core nodes of intelligent agricultural systems. For example, a UAV with a multispectral camera collects crop phenotypic data, which is processed by an edge - computing module and sent to the agricultural brain platform via 5G. The platform generates an operation prescription map, and then the UAV adjusts parameters to complete spraying or fertilization.

This system - level innovation achieved notable results in Xinjiang's cotton fields in 2023. The multi - machine cooperative system in the experimental area uses V2V communication for task allocation, completing autonomous operations from pest monitoring to prevention in 1000 acres of cotton fields. It is 85% more efficient than traditional manual methods and reduces pesticide use by 32%. Also, the 2.3TB of multi - source data collected during operation helps optimize the cotton growth model, creating a 'data - driven - model optimization - operation improvement' virtuous cycle.

5. Conclusion

Researchers aim to break through innovation. First, extreme weather adaptability restricts UAV wide - application. In actual agricultural production, UAVs often work under extreme weather, but their flight stability and battery performance are limited. High temperature, low temperature and strong winds all have negative impacts on UAVs. Although some studies analyzed single factors, the agricultural environment is complex and there's a lack of systematic evaluation of multi - factor coupling, making it hard for UAVs to handle complex weather. Second, the lack of unified technical standards for sensor protection design is an issue. Sensors, crucial for UAVs to obtain farmland information, have durability and adaptability problems in extreme environments. Due to the lack of standards, different manufacturers' sensor protection designs vary greatly, increasing user selection difficulty and hindering industry standardization. Moreover, data acquisition and processing efficiency is restricted by communication delay and algorithm performance. In large - scale farmlands, UAVs need to collect and transmit a large amount of data in real - time, but current communication has delays and existing data processing algorithms are inefficient for massive data. Finally, although CFD and COMSOL simulation technologies are widely used in UAV aerodynamic design, their matching degree with actual flight data is low. Simplifications and assumptions in model - building affect result accuracy and reliability, and the model's versatility and engineering applicability need improvement. In summary, future research should focus on interdisciplinary integration to promote UAV intelligent, efficient and practical development in complex agricultural environments.

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