

Research Progress of Drones in Precision Agriculture

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Abstract: As global agriculture transitions towards refinement, efficiency, and greenness, precision agriculture has become the core path to address the pain points of traditional agriculture. Drones, with their advantages of high mobility, low cost, and adaptability to complex farmlands, have become key supporting tools for precision agriculture. This paper focuses on the research progress of drones in precision agriculture, using literature review, comparative analysis, and inductive deduction methods to systematically sort out the technological evolution context in the three core dimensions of platform technology optimization, sensor data collection, and intelligent decision-making breakthroughs, and compare the differences in technical routes, scenario adaptation, and cost control between domestic and foreign studies. Analyze existing bottlenecks such as insufficient positioning accuracy in complex environments and inefficient multi-source data fusion, and evaluate the adaptation effects of recent research hotspots such as Beidou/GNSS + visual SLAM and deep learning models. The study identified the laws of technological evolution and the causes of differences at home and abroad, defined the key constraints of each bottleneck and the application boundaries of hot technologies, provided theoretical references for the localization of core technologies, the generalization of cross-scenario algorithms, and the construction of full-process automated closed loops, facilitated the deep integration of unmanned aerial vehicle technology and precision agriculture, and promoted the improvement of agricultural quality and efficiency and green development.

Keywords: Unmanned Aircraft; Precision Agriculture; Technological Advances; Localization Adaptation; Bottleneck Breakthrough

1. Introduction

In the past five years, the Central Document No.

1 has continuously focused on agriculture, rural areas and farmers, explicitly stating "accelerate the research and development and promotion of intelligent agricultural machinery equipment" and "advance the application of agricultural aviation technology", and the digital transformation of agriculture has become the core direction of policy and industry. Against the backdrop of global population growth, intensifying resource constraints and escalating demands for ecological protection, the traditional "extensive operation" is no longer sustainable. Precision agriculture, with "precise perception and intelligent decision-making" at its core, has become the key path to solve the pain points of agricultural production.

Agricultural drones, with their advantages of high mobility, strong terrain adaptability and low cost, have broken through the time and space limitations of traditional agricultural machinery and manual operations and quickly penetrated into key links such as crop growth monitoring, pest and disease early warning, variable fertilization and pesticide application: Zhou Yongya et al. have achieved a reduction rate of over 85% for Pinus cones pests by carrying green agents, balancing pest control effectiveness and ecological protection; Shi Changrong's diagnostic model for wheat nitrogen content based on multispectral data from drones reduced urea usage by 14.33%; Zhang Xin optimized the "RTK + visual assistance + high-precision IMU combination" navigation mode, reducing the flight path deviation in complex farmland scenarios from 0.5m to 0.15m, breaking through the bottleneck of terrain occlusion and signal interference; But as the demand for "precision and real-time" in precision agriculture increases, the shortcomings of the adaptability of unmanned aerial vehicle (UAV) technology have become increasingly prominent: insufficient positioning accuracy in complex farmland environments (forest occlusion, terrain undulations), lack of real-time and accuracy in multi-source sensor data fusion, and low degree of automation in the entire operation process; At the same time,

technologies at home and abroad are differentiated-foreign solutions are commercialized by the precision of core components and the maturity of algorithms, but local crops are poorly adapted and costly; Domestic research focuses on Beidou navigation integration and scenario adaptation, but faces the predicament of relying on imports for key components such as high-end chips and power systems, which have restricted the depth of application and large-scale promotion of the technology^[1-5]. A systematic review of the research progress of unmanned aerial vehicles (UAVs) in precision agriculture, an analysis of the laws of technological evolution, the causes of bottlenecks and the differences at home and abroad, can not only improve the theoretical system of the integration of precision agriculture and UAV technology, but also provide practical guidance for the upgrading of domestic technology and industrial landing. Based on this, this paper conducts a systematic review of the technical dimensions, research differences, bottlenecks and hotspots of drones in precision agriculture, providing references for research and application in related fields.

2. Literature Review

2.1 Limitations of Traditional Agricultural Techniques and Early Drone Applications

Under the demands of precision agriculture development, both traditional agriculture and early drone applications have shown significant deficiencies, and there is a sharp contrast between the technical logic and practical effectiveness.

Traditional agriculture, which is centered on experience-driven extensive management, has multiple inherent shortcomings. Management relies on manual inspection and experience-based decision-making, which is inefficient and subjective, making it difficult to meet the demands of "precision and real-time". Data collection relies on a single sensor and simple algorithms, with insufficient accuracy in identifying key information such as pests and diseases and crop growth; In terms of resource utilization, flood irrigation and blind fertilization are prominent, while traditional ground agricultural machinery is difficult to operate in complex terrains such as mountains and hills, unable to balance the triple goals of productivity, resources and ecology^[6-8].

Early drones, though attempting to break through the limitations of traditional models, failed to fully realize their value due to the constraints of technological maturity. Hardware-fixed path flight mode, simple fuselage structure, limited power system, resulting in short endurance and weak payload capacity, difficult to meet the demands of large-scale operations; The software lacks efficient autonomous navigation and path planning capabilities, and the operational accuracy depends on manual control; Functionally focused on a single plant protection spraying process, with weak sensor integration and data processing capabilities, unable to form a complete operation loop of "perception-analysis-execution", and limited for large-scale promotion^[9].

2.2 Research Progress of Unmanned Aerial Vehicles in Precision Agriculture at Home and Abroad

2.2.1 Research progress and technical features abroad

Research abroad started early and developed a path led by core technologies and commercialized. In terms of intelligent decision-making algorithms, Cornell University in the United States proposed to improve the YOLOv5 model, significantly enhancing the efficiency of crop pest and disease identification in complex contexts; In terms of platform technology, the Technical University of Munich in Germany has developed a modular multi-mission unmanned aerial vehicle (UAV) platform to adapt to a wide range of operation scenarios; In the field of sensor technology integration, Israeli companies have introduced micro thermal imaging sensing solutions to enhance precise perception of the physiological state of crops^[10-12]. But the high cost of core components in foreign solutions and insufficient adaptability to local crops and complex terrains limit large-scale application^[4].

2.2.2 Domestic research progress and local characteristics

Domestic research focuses on localization adaptation and breakthroughs in domestic production, achieving remarkable results in three core dimensions. In terms of platform technology optimization, Zhang Xin's team optimized the integrated navigation mode, reducing the deviation of complex farmland flight routes from 0.5m to 0.15m; Chen Yingfan

developed a precise spraying system with a waypoint positioning accuracy of 0.2m and a 28%-35% increase in pesticide utilization^[3,13]. Peng Jibo's team developed wind-resistant six-rotor models that combined lidar to enhance adaptability to complex terrains^[8]. In terms of sensing technology, the Institute of Microelectronics of the Chinese Academy of Sciences has broken through the core technology of low-cost multispectral sensors, which cost only one-third of similar international products; Shi Changrong built an optimized XGBoost model, and the R^2 for diagnosing nitrogen content in wheat reached 0.926; Liu Ying used the random forest algorithm, and the rice AGB inversion R^2 exceeded 0.8^[2,5,14]. In terms of intelligent decision-making and promotion, Zhou Yongya's team precisely applied pesticides to reduce the population density by more than 85%; Ma Daozhuo identified the optimal parameters for controlling rice pests and diseases, with a control efficiency of over 90% and an average yield increase of 3.67% per mu. At present, China still faces shortcomings such as reliance on imported high-end core components and insufficient real-time fusion of multi-source data^[1,15].

2.3 Existing Research Gaps

Although existing research explores the application of drones in precision agriculture in multiple dimensions, there are still three significant gaps.

First, there is a lack of an integrated analytical framework. Most reviews merely list technological advancements without deeply binding the core technology dimension with domestic and international differences, existing bottlenecks, and hotspots for solving problems, making it difficult to form a logical closed loop of "technology evolution-problem orientation-solution".

Secondly, there is a lack of localization adaptation and quantitative comparison. There is insufficient attention paid to unique achievements such as domestic Beidou navigation integration, adaptation for characteristic crops, and localization of core technologies, and there is a lack of quantitative comparisons of technical performance, cost control, and implementation effects at home and abroad, making it difficult to clarify the entry points for technological upgrades and the boundaries for drawing on experience.

Thirdly, there is a lack of targeted assessment of the effectiveness of breaking through hot technical bottlenecks. The existing literature mostly generalizes the advantages of hot technologies and does not quantitatively analyze the solutions based on core bottlenecks such as insufficient positioning in complex environments; There is insufficient discussion on key implementation issues such as technology adaptation scenarios and cost-benefit ratios, and there is a lack of research on adaptation to characteristic crops such as fruit trees, which is disconnected from industrial demands.

3. Research Methods and Technical Routes (Method)

3.1 Research Methods and Data Sources

3.1.1 Data sources

The system searched core databases such as Web of Science, CNKI, IEEE Xplore, etc., using keywords such as "drone + precision agriculture", "optimization of agricultural drone platform", "drone pesticide application in orchards", etc., to screen highly cited papers, research results from authoritative institutions, and enterprise technology white papers from 2018 to 2025. Comprehensively collect research results in three core dimensions of platform technology, sensor acquisition, intelligent decision-making, and characteristic scenarios such as orchard pesticide application, and establish a standardized literature database to provide data support for subsequent research.

3.1.2 Core Research methods

Comparative analysis: Based on the constructed multi-dimensional comparative framework of "technical performance-adapted scenarios-cost control-implementation degree", on the one hand, compare the differences in technical routes of domestic and foreign research, clarify the strengths and weaknesses of both sides and the causes of formation; On the other hand, compare the differences in application effects of different technical directions (such as new energy power versus traditional power, multispectral sensing versus single-spectral sensing) to form a quantitative comparison table, providing a basis for technology selection and optimization direction.

Inductive deduction: Based on literature research data, first summarize the common and individual bottlenecks of unmanned aerial vehicles in the core technology dimensions and characteristic

scenarios of precision agriculture, and clarify the scope of influence and core constraints of each bottleneck; Then, in combination with recent research hotspots, deduce the potential directions for technological breakthroughs and establish a "bottleneck-hotspot fit analysis matrix" to achieve a precise match between bottleneck problems and solutions.

3.1.3 Research Implementation route

Literature search and screening: Determine the core database and keyword system, search and screen the literature materials that meet the requirements from 2018 to 2024, and establish a literature database covering three core dimensions and characteristic scenarios;

Review of core technology progress: According to the classification dimension of "platform technology-sensor acquisition-intelligent decision-making-characteristic scenario adaptation", extract key parameters and core achievements of the literature and construct the technology evolution map;

Multidimensional Comparison and bottleneck Analysis: Based on the multidimensional comparison framework, complete the comparison of domestic and foreign research and the effect comparison of different technical directions, and simultaneously summarize the existing technical bottlenecks and identify the core constraints;

Hotspot assessment and adaptation analysis: Summarize key technologies for breaking bottlenecks in recent years, quantitatively assess their application effects and adaptation scenarios, and construct and improve the bottleneck-hotspot adaptation analysis matrix;

Summary of Conclusions and Recommendations: Summarize the evolution patterns of technology in the field, identify key research directions for the future, and ultimately form a complete research report.

3.2 Data Sources

The data are mainly derived from three types of literature resources: first, core journal articles, including relevant research results published in journals such as Journal of Northeast Forestry University, Transactions of the Chinese Society for Agricultural Machinery, Precision Agriculture, and Rural Science Experiment; Second, dissertations, including doctoral and master's theses from universities such as Yangzhou University and Hebei University of Engineering; Third, industry reports and patent

documents, including research reports from authoritative institutions such as the Chinese Academy of Agricultural Sciences and the United States Department of Agriculture, as well as technical white papers from unmanned aerial vehicle-related enterprises. All the documents have been strictly screened to ensure the authority and reliability of the data^[1-3,5,10,16,17].

4. Research Content and Core Framework

4.1 Review of Core Technology Dimensions

4.1.1 Platform technology optimization

Focus on three key areas: lightweight, long endurance, and anti-interference in complex environments to enhance the operational stability and scenario adaptability of the unmanned aerial vehicle platform. In terms of navigation, Zhang Xin's team optimized the fusion navigation of "RTK + visual assistance + high-precision IMU" for the complex farmland in Anhui Province, reducing the flight deviation from 0.50m to 0.15m and the signal recovery time from 3.0s to 0.8s, significantly improving the positioning reliability in occlusion and interference environments; At the same time, Beidou/GNSS and visual SLAM fusion technology continues to develop, providing more stable positioning support for mountainous and hilly operations^[3]. In terms of power and structure, new energy integration and intelligent power management technologies are constantly advancing to boost endurance and load capacity. Chen Yingfan's precise spraying system integrates DJI A3 Pro flight control and Jetson TX2, achieving a 0.2m waypoint positioning accuracy; Peng Jibo's team developed a wind-resistant six-rotor model to meet the demands of rice in mountainous and hilly areas, and combined it with lidar to enhance terrain adaptability and expand the operational boundaries of unmanned aerial vehicles^[8,13].

4.1.2 Upgrade of sensing and data acquisition

Focus on miniaturization, low cost and collaborative acquisition capabilities of three types of sensors: multispectral, thermal imaging and lidar. In terms of multispectral data, Shi Changrong achieved wheat nitrogen content diagnosis based on Mavic 3 multispectral data and optimized XGBoost model $R^2 = 0.926$; Zhang et al. developed low-cost multispectral sensors at a cost of only one-third of their international counterparts, significantly lowering the threshold for large-scale application. In terms

of thermal imaging and lidar, Cohen et al. proposed an integrated micro-thermal imaging solution to enhance the perception of crop physiological states; Domestic research focuses on multi-sensor fusion to enhance the ability to extract information under complex canopies^[2,5,12]. In terms of calibration techniques, Liu Ying proposed a method for extracting hyperspectral image spectra, which enhances data stability in high-temperature and high-humidity environments through precise calibration^[14].

4.1.3 Breakthroughs in Data processing and intelligent decision-making

AI algorithms and path planning technologies drive drones to upgrade from data collection to intelligent decision-making. In terms of pest and disease identification, Brown et al. proposed an improved YOLOv5 model to enhance identification efficiency in complex backgrounds; Zhou Yongya's team combined drone monitoring with precise pesticide application algorithms to reduce the population density of pinus cones pests by more than 85%; Mi Xiaodong optimized the pesticide application strategy for orchard scenarios to improve control accuracy in complex environments. In terms of crop growth monitoring, Liu Ying combined vegetation index and texture features and used random forest to achieve high-precision estimation of rice AGB and SPAD, with AGB inversion $R^2 > 0.8$ at the ear stage. In terms of path planning, Muller et al. proposed a modular multi-task platform that supports adaptive operations in multiple scenarios. In terms of decision support, Shi Changrong built a diagnostic model for wheat nitrogen content, achieving a 14.33% reduction in urea usage^[1,2,10,11,14,17].

4.2 Analysis of Differences between Domestic and International Studies

4.2.1 Differences in technical routes

Foreign countries focus on high precision of core components and generalization of algorithms,

such as Muller et al.'s modular platform and Brown et al.'s cross-crop identification model, emphasizing universality and commercialization^[10,11]. In China, the focus is on local scene adaptation and domestic substitution, such as the complex farmland navigation optimization by Zhang Xin's team, the wind-resistant model by Peng Jibo's team, the low-cost sensor by Zhang et al., and the orchard-specific technology by Mi Xiaodong^[3,5,8,17].

4.2.2 Differences in core strengths

Foreign strengths lie in high-precision components, mature algorithms and commercialization capabilities, such as Cohen et al.'s thermal imaging system and Brown et al.'s recognition model. Domestic advantages are reflected in strong scene adaptability, low cost, and outstanding Beidou integration. For example, Chen Yingfan's spraying system has increased pesticide utilization by 28%-35%, and Shi Changrong's nitrogen diagnosis solution takes both accuracy and cost into account. The overall equipment cost is only 1/3-1/2 of that abroad, making it more suitable for small and medium-sized farmers^[2,10,12,13].

4.2.3 Differences in scene adaptation and implementation

Foreign technologies are more suitable for large-scale plain farmland, but they are not well adapted to mountainous and hilly areas and special crops, and the high cost of equipment limits the application of small and medium-sized farmers. China covers a wide range of terrains including plains, hills and mountains, is suitable for crops such as rice, wheat, red pine and fruit trees, and lowers the threshold through the aerial spraying service model. By 2024, the annual operation area of agricultural drones in China has exceeded 1.5 billion mu, and the large-scale application has achieved remarkable results.

4.3 Analysis of Existing Technical Bottlenecks

Table 1 analyzes the various bottlenecks of the existing technology.

Table 1. Analysis of Existing Technical Barriers

Bottleneck type	Form of expression	Impact scope	The underlying cause
Inaccurate positioning accuracy in complex farmland environments	In areas with dense trees and undulating terrain, the navigation signal is prone to interruption.	It covers over 60% of the mountainous and hilly farmland as well as characteristic orchards in the country, directly hindering the promotion of large-scale and precise operations in these areas.	The single navigation system has weak anti-interference capability and insufficient real-time performance of multi-sensor data fusion; complex terrain and crop canopy obstruction lead to signal attenuation.

The accuracy and real-time performance of multi-source data fusion are lacking.	There are issues of temporal misalignment and scale mismatch in sensor data such as multispectral, thermal imaging, and LiDAR data.	It directly acts on core scenarios that rely on multi-source data, including crop nitrogen content monitoring, early warning of pests and diseases, biomass estimation, etc., and particularly influences the precise management decisions for specialized agriculture.	The calibration standards for sensors are not uniform, and the data synchronization transmission protocol is not complete; the fusion algorithm has insufficient adaptability to the dynamic environment of farmland and the scenes of characteristic crops.
The automation level of the entire homework process is low.	Route planning requires manual intervention in setting terrain parameters. Even after pest and disease identification, a manual formulation of the pesticide application plan is still necessary. In complex scenarios, obstacle avoidance relies on the experience of the pilot.	Limiting the efficiency improvement of large-scale operations exacerbates the technical implementation difficulties in scenarios where there is a shortage of professional pilots.	The autonomous decision-making algorithm fails to respond adequately to the dynamic changes in farmland and unique scenarios; the collaboration between unmanned aircraft and the agricultural Internet of Things is not tight.
The challenge of balancing low cost with high performance	Key components such as high-precision sensors and core power systems are imported, which results in high costs for high-performance unmanned aerial vehicle equipment and makes it unaffordable for small and medium-sized farmers.	Limiting the large-scale promotion of technology in rural areas of the central and western regions, among small and medium-sized farmers, and in specialized agriculture.	The domestic technology for the production of core components such as high-end chips and special sensors is still not yet mature.
Does not have a close coordination and linkage with the Internet of Things and the agricultural big data platform	The data formats collected by unmanned aerial vehicles are not uniform, making it difficult to synchronize them in real time to the agricultural big data platform. The decision-making instructions generated by the platform cannot directly drive the unmanned aerial vehicles to perform operations; instead, manual intermediate operations are required.	Hinders the full-chain intelligent development of smart agriculture and restricts the digital transformation of characteristic agriculture.	Lack of unified data transmission and interface standards; The communication protocols between the unmanned aircraft control system and the big data platform are incompatible, and the research on collaborative algorithms is lagging behind.

5. Evaluation of Research Hotspots

5.1 Beidou/GNSS and Visual SLAM Fusion Positioning Technology

Technological innovation points: Build a dual-modal positioning system of "global positioning + local blind spot filling", provide global position references through Beidou/GNSS, and visual SLAM fills positioning gaps in signal occlusion scenarios, enhancing positioning continuity in complex environments.

Quantification of adaptation: The fusion solution by Zhang Xin's team reduces positioning error from 0.5m to 0.15m in complex farmland scenarios and improves positioning stability to over 95%; In orchard scenarios, it can reduce the positioning deviation caused by canopy occlusion and shorten the signal

interruption recovery time by 73.3%^[3].

Application boundaries: Suitable for farmlands and orchards with complex terrain ranging from 500 to 5,000 mu. Data processing efficiency in ultra-large-scale scenarios needs to be optimized.

5.2 Deep Learning optimizes crop pest and disease identification models

Innovation points: Based on improved algorithm frameworks such as YOLOv5 and Transformer, the attention mechanism and few-shot learning techniques are introduced to enhance the ability to identify complex backgrounds, early minor pests and diseases, and adapt to sample scarcity scenarios for characteristic crops^[10].

Quantification of adaptation: The improved YOLOv5 model by Brown et al. achieved an

accuracy rate of 92% for pest and disease identification, an 18-percentage-point increase over traditional algorithms; Domestic optimized models for special crops such as pinus cones have achieved an accuracy of 88% in small sample scenarios; The optimized model for fruit tree pests and diseases has a recognition accuracy rate of over 90%^[10,17].

Application boundaries: Suitable for monitoring major crops and specialty crops such as wheat, rice, red pine, fruit trees, etc. Robustness needs to be improved under extreme weather conditions.

5.3 New Energy and Intelligent Power Management Systems

Innovation points: Integration of new energy power sources such as photovoltaic films and hydrogen fuel cells, combined with intelligent power distribution algorithms to optimize the balance between endurance and load capacity and reduce operational energy consumption .

Adaptation quantified: Existing new energy drones have a maximum single-charge endurance of up to 120 minutes, a 50% improvement over traditional lithium batteries; The intelligent power management system reduces energy consumption during operation by 15% to 20%, which can meet the continuous operation requirements of large-scale farmland and contiguous orchards^[13].

Application boundaries: Adapted to large-scale farmland and contiguous orchards in plains, and scattered orchards in mountainous areas where supply convenience is insufficient.

5.4 "Data Collection-Transmission-Analysis-Decision-Making-Execution" Closed-loop Collaborative Technology

Innovation points: Unify the data interface standards for unmanned aerial vehicles and agricultural big data platforms, develop edge computing and cloud-based collaborative decision-making algorithms, and achieve full-process automated closed-loop^[13].

Adaptation effect quantification: Chen Yingfan's precise spraying closed-loop system has increased pesticide utilization by 28%-35% and reduced operation response time from 30 minutes to 5 minutes; Ma Daozhuo's closed-loop solution for rice pest control achieves over 90% effectiveness with a 10% reduction in pesticide use; In orchard scenarios, it can enhance the

efficiency and effectiveness of precise pesticide application^[13,16].

Application boundaries: Suitable for large-scale smart farms and contiguous orchards, where small-scale farmers' scattered planting and scattered orchard scenarios have higher synergy costs.

6. Conclusion

6.1 Core Conclusions

6.1.1 Trends in technological evolution

Research on unmanned aerial vehicles (UAVs) in precision agriculture shows clear multi-dimensional evolution characteristics: In the core dimension, platform technology is evolving towards lightweighting, long endurance, and adaptation to complex environments; sensor acquisition technology is focusing on multi-source integration and low-cost upgrades; intelligent decision-making technology is achieving autonomous breakthroughs led by AI algorithms; The adaptation of characteristic scenarios has gradually shifted from supplementary research to targeted development, becoming an important extension direction for technology application.

6.1.2 Core differences in research at home and abroad

Foreign research focuses on high-precision core components and modular algorithms, with high maturity in commercialization, but high equipment costs and insufficient localization adaptation, making it difficult to cover mountainous and hilly areas and special crop scenarios; Domestic research focuses on localized scene customization and breakthroughs in core technology localization, with significant advantages in scene adaptation and cost control, and more targeted research on characteristic crop technology adaptation, but still relies on imports for high-end core components, which has become a core constraint on technological upgrading.

6.1.3 Directions for breaking through bottlenecks

To break through existing technical bottlenecks, focus on the core constraints and make precise efforts: Insufficient positioning accuracy in complex environments requires strengthening multi-sensor real-time fusion technology; Low efficiency in multi-source data fusion requires unified calibration standards and optimized scene adaptation algorithms; Full-process

automation requires enhancing the responsiveness of autonomous decision-making algorithms and strengthening IoT collaboration; A balance between low cost and high performance requires accelerating the localization process of core components; There is a need to strengthen targeted technology research and development and data accumulation when there is insufficient adaptation to specific scenarios. Existing hot technologies have a significant breakthrough effect on core bottlenecks (such as Beidou/GNSS + visual SLAM reducing positioning error by 70%), but the application boundaries need to be clearly defined in combination with the differences in major/characteristic crop scenarios to achieve precise selection.

6.2 Research Prospects

6.2.1 Localization of core technologies: Breaking monopolies and strengthening self-positioning capabilities

Increase investment in research and development of key components such as high-end sensor chips and core power systems to break foreign technological monopolies and address the core issues of high costs and reliance on imports for high-performance equipment;

Strengthen the deep integration of Beidou navigation with unmanned aerial vehicles, optimize multi-source fusion navigation algorithms, and specifically improve positioning accuracy in complex farmland environments and special scenarios such as fruit trees and red pines.

6.2.2 Generalization of cross-scenario algorithms: Adapt to diversity and enhance data fusion efficiency

Develop universal AI algorithm models for different terrains such as plains/hills/mountains and different categories such as staple crops/specialty crops, and enhance the cross-scenario adaptability of the models by relying on small sample learning techniques;

Optimize the multi-source data fusion algorithm to address core issues such as temporal misalignment and scale mismatch, taking into account the multi-source data fusion requirements for both major crops and specialty crops.

6.2.3 Build a full-process automated closed loop: Connect links to achieve autonomous operations Unify the data interface standards for drones and agricultural Internet of Things, develop

intelligent decision-making algorithms based on edge computing and cloud collaboration, and break down "data silos";

Enhance the integrated capabilities of autonomous obstacle avoidance, path planning, and operation execution of drones, build a fully automated closed loop of "data collection-transmission-analysis-decision-making-execution", and focus on optimizing the automated operation process in characteristic scenarios such as orchards.

6.2.4 Deepening of characteristic scene technology: Precise adaptation to meet personalized demands

Focus on special crops such as fruit trees and deepen the research and development of specialized technologies such as drone pesticide application, intelligent obstacle avoidance, and precise monitoring;

The system accumulates operation data of characteristic scenarios, iteratively optimizes adaptation algorithms, and precisely meets the personalized and refined demands of characteristic agricultural production.

6.3 Research Limitations and Improvement Suggestions

The limitations of this study are mainly reflected in two aspects: First, the literature search period is limited to 2018-2024, which may omit some important early research results; , the case analysis was based on literature data, lacking field validation, and the assessment of the actual effect of the technology implementation was not comprehensive enough.

Future improvement suggestions: First, extend the literature retrieval period, supplement the early classic research results, and complete the sorting of the technological evolution context; Second. Increase field research and experiments to obtain first-hand data and verify the practicality and reliability of the literature conclusions; Third, focus on specific crop scenarios and conduct specialized research to enhance the pertinence and practical value of the research.

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