Current status and future trends of precision agricultural aviation technologies

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Abstract: Modern technologies and information tools can be used to maximize agricultural aviation productivity allowing for precision application of agrochemical products. This paper reviews and summarizes the state-of-the-art in precision agricultural aviation technology highlighting remote sensing, aerial spraying and ground verification technologies. Further, the authors forecast the future of precision agricultural aviation technology with key development directions in precision agricultural aviation technologies, such as real-time image processing, variable-rate spraying, multi-sensor data fusion and RTK differential positioning, and other supporting technologies for UAV-based aerial spraying. This review is expected to provide references for peers by summarizing the history and achievements, and encourage further development of precision agricultural aviation technologies.

Keywords: precision agricultural aviation technology, remote sensing, aerial spraying, ground verification

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1 Introduction

The increase in intensive agriculture stimulated by the need to feed a growing global population has relied on the use of chemical pesticides as the first line of defense in crop protection programs[1]. The use of pesticides is an integral part of modern agriculture and contributes to the productivity and the quality of the cultivated crop[2]. It is estimated that the use of agrochemicals prevents a loss of up to 45% of the world's food supply[3]. However, there are continuing concerns from national governments and the general public surrounding the potential adverse effects of pesticides. This includes the environmental impact and risks to human health during application in the field and from residues remaining in the food chain. As a result, there are now important policy drivers strengthening the management of agricultural non-point source pollution and the promotion of low-toxicity and low-residue pesticides, such as China's "No.1 Central Document" of 2015. The Ministry of Agriculture of China also passed a reduction program for chemical fertilizers and pesticides, requiring a net zero growth in chemical fertilizer and pesticide applications by 2020. The main goal of agricultural aviation operations is the efficient and effective application of chemical fertilizers and pesticides. Precision Agricultural Aviation (PAA)

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Technologies (PAAT) have rapidly developed in recent years attracting the attention by the government departments and farm users as an effective means to reduce pesticide residues and adverse environmental impacts while enhancing the pesticide effectiveness.

There are a number of technologies that assist aerial applicators including global positioning systems (GPS) and geographic information systems (GIS), soil mapping, yield monitoring, nutrient management field mapping, aerial photography, and variable-rate (VR) controllers, as exhibited in Figures 1 and 2. Additionally, new nozzle types like pulse width modulation (PWM) and variable-rate nozzles can be integrated into these other systems enhancing application efficiency. Further, ground verification technologies, which include prediction models of droplet deposition and droplet detection sensors, allow for quick confirmation and optimization of PAATs. A decade has passed since development of the first VR, aerial application systems which provide applicators the ability to precisely apply products such as cotton growth regulators, defoliants, and insecticides using prescription maps developed using remote sensing and GPS/GIS technologies. Precision Agriculture (PA) technologies benefit the agricultural aviation industry through time and money savings. Airborne remote sensing allows for a new revenue source to agricultural aviators through remote sensing (RS) missions that would coincide with aerial spray applications. Remote sensing systems provide precise images for spatial analyses of plant stress due to water or nutrient status in the field, disease, and pest infestations. However, natural variations in biological characteristics, presence of disease and insects, and the interactions among these factors combine to influence crop quality and yield. Spatial statistics can often increase understanding of the field and plant conditions. Through image processing, remote sensing data are converted into prescription maps for variable-rate aerial application[4]. Ground verification technologies are an indispensable means of characterizing spray droplet deposition data which can be used to modify and optimize the setup and operation of aerial spray systems. Therefore, remote sensing, aerial spraying and ground verification technologies all combine to develop PAATs for use in agricultural protection and production practices. The research status and progress of PAATs are reviewed and summarized, with the three main components of remote sensing, aerial spraying and ground verification technologies highlighted. Based on the reviewed literature, trends in each component forecast are focused on key development directions in the areas of real-time image processing, variable-rate (VR) spraying, multisensor data fusion and real-time kinematic (RTK) differential positioning with the goal of promoting the further development of PAATs.

Figure 1 Precision agricultural aviation technology

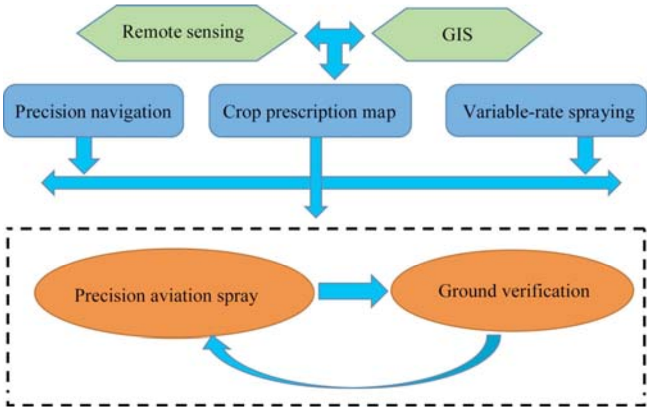

Figure 2 The composition of PAATs

2 Remote sensing technologies for PAA

The rapid acquisition and analysis of crop information is a prerequisite, and forms the basis, for carrying out precision agricultural practices proving the key to breaking the bottleneck restricting the development and application of precision agriculture[5]. With an increasing population and a commensurate need for increasing agricultural production, there is an urgent need to improve management of agricultural resources. Remote sensing is being used with GPS, GIS, and VR technologies to ultimately help farmers maximize the economic and environmental benefits of crop pest management through precision agriculture[6]. RS technology has been advanced rapidly becoming one of the most important directions in the development of PAAT[4] in recent years, providing imagery data for crop diseases and insect pests at different spatial, spectral and temporal resolutions, ultimately providing guidance in aerial application decisions. The existing agricultural RS technologies are divided into satellite, aircraft and unmanned aerial vehicle (UAV) platforms, each of which is discussed in the following sections.

2.1 Satellite-based remote sensing technologies for PAA

With the advantages of macroscopic, fast, accurate, dynamic and abundant information, satellite-based RS technologies are widely used to provide guidance in global agricultural production. Jonas and Gunter[7] examined the potential of multi-spectral RS for a multi-temporal analysis of crop diseases. Three high-resolution RS images were used to execute a spatio-temporal analysis of the infection dynamics with a decision tree, developed using Mixture Tuned Matched Filtering (MTMF) results and the Normalized Difference Vegetation Index (NDVI), applied to classify the data into areas showing different levels of disease severity. Han et al.[8] utilized a novel method termed 'extended spectral angle mapping (ESAM)' to detect citrus greening disease using hyperspectral image acquired by an airborne hyperspectral HS imaging system (an AISA EAGLE VNIR Hyperspectral Imaging Sensor, Spectral Imaging Ltd., Oulu, Finland), and a multispectral image acquired by the WorldView-2 satellite. The results demonstrated that the detection accuracy using hyperspectral imaging could be enhanced. Dutta et al.[9] identified the stripe rust affected areas of wheat crop as well as evaluation of RS derived indices by using the surface temperature data extracted from Meteorological and Oceanographic Satellite Data Archival System. Bhattacharya and Chattopadhyay[10] characterized disease outbreak (stage-I) and persistence (stage-II) with satellite-based data of surface reflectance in red (R), near infrared (NIR) and shortwave infrared (SWIR) bands, land surface temperature (LST) data from Moderate Resolution Imaging Spectroradiometer (MODIS). Silva et al.[11] enabled the production of risk maps for agricultural pests with a degree of spatial and temporal detail based on satellite RS data and surface temperature data. Johnson[12] achieved the assessment and prediction of maize and soybean yield by using the NDVI and LST data obtained from satellite RS. Son et al.[13,14] established the relationship model between bivariate data enhanced vegetation index (EVI) and leaf area index (LAI) and yield in different growth stages of rice based on the MODIS, estimating rice growth and yield forecasts. Yuan et al.[15] employed three different methods and two kinds of vegetation indices that were selected from many RS features in satellite imagery based on the T-test and cross-correlation test to construct the inversion model of winter wheat powdery mildew. Jing et al.[16] established the severity estimating model of cotton verticillium wilt using partial least squares (PLS) regression analysis and RS factors identified by the pre-processed IKONOS (defined acronym) image, calculating the severity level of each pixel in the region of cotton veritcillium wilt. These above research results will be handy tools for planners to expedite relief measures in case of epidemic with more focused zones of infestation as well as for crop insurers to know the location and extent of damage affected areas. In order to improve the predictive accuracy about crop pests, many researchers have done a lot of related works in recent years. Zhang et al.[17] established a powdery mildew (PM) of wheat forecasting model in terms of the logistic regression analysis using RS data and corresponding ground truth data, the result showed that the disease risk map could reflect the general spatial distribution pattern of PM occurrence in the study area, with an overall accuracy of 72%. They also demonstrated the disease risk maps that were able to depict the spatial distribution of powdery mildew and its temporal dynamic in the study area based on meteorological and RS observations associated with crop characteristics and habitat traits[18]. Luo et al.[19] indicated that the 2-dimensional feature spaces established for LST and modified normalized difference water index (MNDWI) of wheat, could be used to discriminate the wheat aphid damage degrees over a large scale using only thermal infrared band and multispectral satellite imagery and the overall accuracy was 84%. Tang et al.[20] established three different types of models to predict aphid occurrence at the filling stage of wheat using information from multi-temporal HJ-CCD optical data and HJ-IRS thermal infrared data, and further evaluated the accuracy of each model, the overall prediction accuracy of the relevance vector machine (RVM) was 87.5%. Ma et al.[21,22] structured different feature selection algorithms for developing the powdery mildew forecasting model of wheat based on a number of characteristic variables obtained from RS imagery, the overall accuracy with minimum redundancy maximum relevance (mRMR) algorithms was 88.4%. These results further improve the predictive accuracy of crop pests and provide a reference for RS monitoring of other crop diseases.

2.2 Airborne remote sensing technologies for PAA

Airborne remote sensing is a flexible and versatile allowing for fields to be imaged at variable altitude depending on the spatial resolution required. It also benefits aerial applicators through the potential of an additional revenue source as agricultural aircraft are easier to schedule for frequent RS missions coinciding with aerial spray applications. In particular, airborne RS technologies have recently made tremendous improvements and are currently integrated into precision agricultural applications[23-26]. Thomson et al.[27] evaluated a field imaging system on agricultural aircraft using low-cost digital video to distinguish broadleaf weeds from cotton. Huang et al.[25] concluded that the Tetracam camera in its present state is more suitable for slower moving platforms that can fly close to the ground, such as an UAV; the MS 4100 imaging system worked well mounted on an agricultural aircraft like the Air Tractor 402B. Lan et al.[6,24] demonstrated the capability and performance of the MS 4100 airborne imaging system for crop pest management, as depicted in Figure 3. Airborne RS technologies have also been employed for detecting crop disease and assessing its impact on productivity[28-31]. Ye et al.[32] used airborne multi-spectral imagery to discriminate and map weed infestations in a citrus orchard. Zhang et al.[33] investigated the use of aerial multispectral imagery and ground-based hyperspectral data for the discrimination of different crop types and timely detection of cotton plants over large areas. Willers et al.[34] presented site-specific approaches to cotton insect control by developing sampling and airborne RS analysis techniques. Chanseok et al.[35] established a general-purpose model for predicting the nitrogen content of rice at panicle initiation stage using three years of data, and applied it in practice. Manuel et al.[36] established a model to quantify and discriminate between red leaf blotch severity levels according to canopy temperature and vegetation indices which were calculated from thermal and hyperspectral imagery. The results demonstrated the feasibility of early detection and quantification of red leaf blotch using high-resolution hyperspectral imagery. Kumar et al.[37] proposed a method to detect the areas of citrus groves infected with citrus greening disease [Huanglongbing (HLB)] using airborne hyperspectral and multispectral imaging. Song et al.[38] studied the influence of soil nitrogen supplies and variable fertilization on winter wheat growth condition by using specific spectrum characteristic parameters which were obtained from the airborne hyperspectral images. Bao et al.[39] focused on estimating winter wheat nitrogen content from hyper-spectral airborne images and ground measured spectral data, and research methods for variable-rate fertilization based on RS images by combining the nitrogen estimation method and Lukina's diverse fertilization model. In addition, Wang et al.[40] improved the detection accuracy of rice nitrogen level under shadow conditions by spectral correction of rice RS images obtained from the binocular multispectral image acquisition system (Canon EOS 5D Mark II Camera, Company Canon Inc., Ohta-ku, Tokyo, Japan) with average error of 11.5% for NDVI.

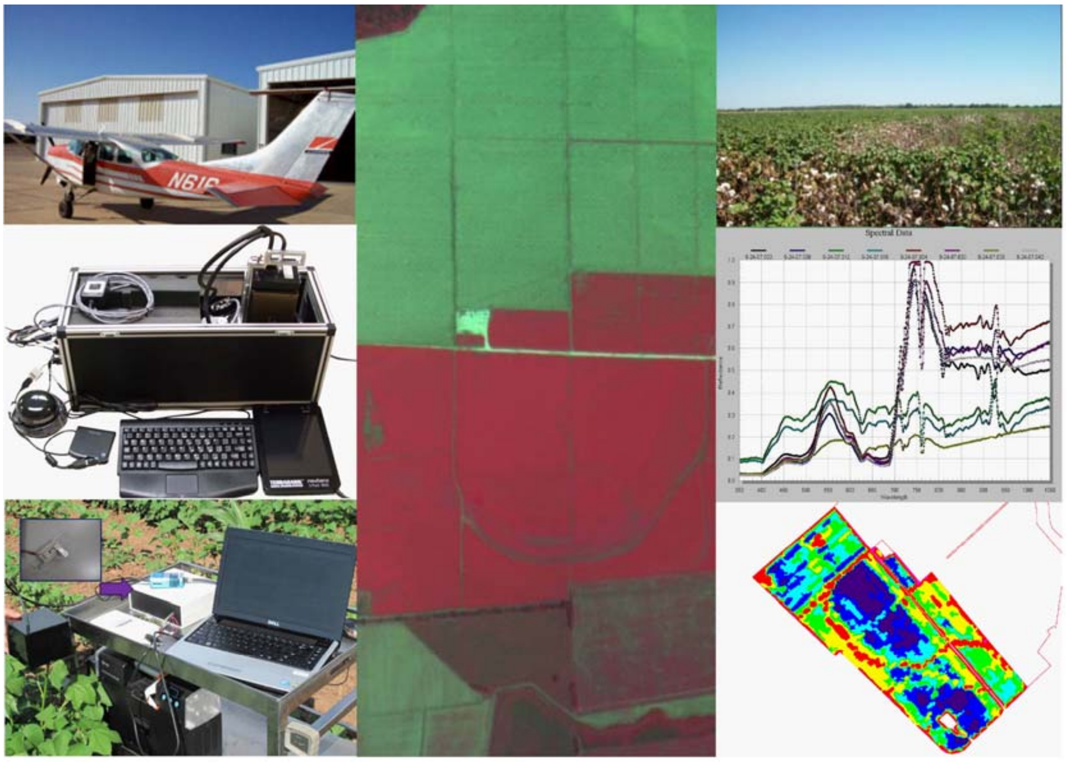

Figure 3 Airborne remote sensing

2.3 UAV-based remote sensing technologies for PAA

The accurate acquisition of agricultural information is critical to precision agricultural production management and decision-making supporting the need for continued development and application of crop information monitoring technologies[41]. UAV technologies offer one of simple construction, low cost operation and maintenance, a compact and light weight footprint, simple operation and high flexibility as a RS platform[42-44]. The development of UAV-based RS technologies has greatly expanded the application range of agricultural RS in monitoring crops on small and medium scales. In recent years, the rapid development of compact, lightweight and durable sensors and devices has promoted further development of UAV-based RS technologies[45,46]. Chosa et al.[47] used an UAV to carry a commercial digital camera for true-color images and a plant cover ratio camera for near-infrared images to monitor rice plant growth over a region in order to define a cropping system that could produce higher-quality paddy rice, and the results indicated that the monitoring method using a UAV was easier and cheaper than other remote sensing methods. Swain et al.[48] used a radio-controlled, unmanned, helicopter-based low-altitude remote sensing (LARS) platform to acquire quality images with high spatial and temporal resolution in order to estimate the yield and total biomass of a rice crop. The study demonstrated the suitability of using LARS images as a substitute for satellite images for estimating leaf chlorophyll content in terms of NDVI values (R^2=0.897, RMSE=0.012). Hunt et al.[49,50] evaluated these very-low-cost, high-resolution images acquired from radio-controlled model aircraft for use in estimating nutrient status of corn and crop biomass of corn, alfalfa, and soybeans, finding high correlations between leaf area index (LAI) and the green normalized difference vegetation index (GNDVI) to provide guidance for accurate management of crops. Lelong et al.[51] obtained the RS images of different varieties of wheat in the visible and near-infrared domains using a combination of simple, digital cameras with spectral filters mounted on UAV, and established a robust and stable generic relationship between LAI and NDVI, and nitrogen uptake and GNDVI. Noguchi et al.[52] is committed to monitoring the nutritional status of rice through farmland detection technologies based on UAV RS to achieve the precise management and fertilization of paddy fields. Sugiura et al.[53,54] developed a system to generate an information map of crop status and land topographical features using images and distances obtained from an UAV mounted imaging sensor and laser range finder. These above researches showed that the remote sensing images obtained by UAV-based LARS platform can well replace the satellite images to estimate the yield and biomass of crops. Sullivan et al.[55] evaluated a less expensive system comprised of an UAV equipped with a thermal infrared (TIR) sensor for detecting cotton response to irrigation and crop residue management. The results indicated that TIR emittance exhibited greater sensitivity to canopy response as compared to ground truth measurements, and the TIR imagery acquired with a low-altitude UAV could be used as a tool to manage within-season canopy stress. Zhu et al.[56] corrected and applied the leaf and canopy images obtained from an UAV scanner (EPSON EXPRESSION 1680, Epson(China) Co., Ltd) to assess the rice nitrogen status on leaf level to canopy level by image analysis. Qiao et al.[57,58] measured the canopy reflectance of wheat damaged by Blumeria graminis f.sp. tritici using UAV mounted ASD hand-held spectroradiometers allowing for disease index (DI) values to be determined. The correlation between reflectance and DI, and NDVI and DI, were then calculated, and the reflectance of low altitude remote sensing was well correlated with NDVI moreover. This indicates that it is prospective in using UAV-based remote sensing to monitor the development of wheat PM in the fields non-destructively and helpful in the investigation of occurrence area of the disease. Li et al.[59] designed a low-altitude land surface UAV observation system consisting of an UAV platform and a multispectral camera to obtain images of winter wheat at its five growth stages, and proposed a new approach using time-series histograms of vegetation index to refine the threshold value for extracting vegetated pixels from images. The results showed that the UAV system is available to obtain surface images feasibly and the new vegetated pixel retrieval method can provide reasonable fractional vegetation cover (FVC) which is generally consistent with the five growth stages of the winter wheat. Zhou et al.[60] registered and stitched low-altitude RS images of rice acquired by UAV based on the improved algorithm of Harris corner self-adaptive detection resulting in an average registration rate of 98.95%. Tian et al.[61] analyzed the spectral characteristics of winter wheat and proposed an automatic classification algorithm to classify different crop objects based on the RS images. The results showed that, compared to other commonly used methods, this automatic classification method has higher accuracy and universality with a reduced time requirement. This method has extensive application for extracting crop information from mass data from of UAV systems.

3 Aerial spraying technologies

Agricultural aerial spraying, which falls into both manned and unmanned platforms, is a critical agricultural aviation service providing efficient and effective application for crop pest control allowing for rapid response to sudden pest outbreaks of pests and the ability to apply crop production and protection products in terrain difficult for ground based systems, such as rice. Additionally, unmanned agricultural aviation spraying has the advantage of low labor operational costs with no damage to crops or soil physical structure due to wheel or track damage. Therefore, aerial spraying technologies has been widely used and promoted in agricultural production [62-64].

3.1 Manned aircraft-based spraying technologies

The United States of America is the first country to use aircraft for pesticide spray application. As early as 1906, large aircrafts were used for spraying chemical pesticides to eliminate grass pests in Ohio, opening the way for the further use and development of manned aircraft spraying technologies. With the rapid development of electronic and information technology, precision agricultural technologies, such as electrostatic spraying technology, variable-rate spraying technology and precision navigation and positioning technology, has gradually begun to be applied to aerial spraying operation, so that the aerial spraying application more accurate.

In 1960s, Calton et al.[65-67] conducted a study on electrostatic aerial spraying technology and developed an electric rotary nozzle designed to reduce spray drift. The results showed that electrostatic spray technologies can decrease droplet drift to a certain degree by accelerating the deposition process of charged droplets and increasing the penetration of droplets in crop canopy. As shown in Figure 4, with the maturity of technologies and products, electrostatic spray technologies have been used on a variety of small and medium aircraft[68]. Ru et al.[69] designed an aerial electrostatic spray system for Y5B aircraft, and conducted experimental studies examining the effective spraying width, droplet deposition characteristics and drift. In recent years, the availability and use of variable-rate application systems, such as the AG-FLOW system developed by Canada AG-NAV Inc., has increased[62]. In 2016, the precision agricultural aviation team of South China Agricultural University tested the system on the AS350B3e helicopter, verified the system's effectiveness, as shown in Figure 5. The Wingman GX system developed by Adapco Inc. provides basic flight guidance, flight records and spray flow-rate control and can potentially be used to reduce the amount of pesticide drift beyond the intended area through accurate analysis of meteorological information and maximizing the quality of spray[62]. The Satloc M3 system developed by Hemisphere Inc., which is primarily used with the AirTrac software and the AerialAce flow controller, was tested by Thomson et al.[70] on an Air Tractor 402B aircraft and analyzed for flow control accuracy and swath deposition positioning. And the Satloc G4 system was tested by the precision agricultural aviation team of South China Agricultural University in 2016 in Jiamusi, Heilongjaing Province, as shown in Figure 6. Zhang et al.[71] designed a control system for variable-rate pesticide application for manned helicopters and conducted a series of tests that showed that when the speed of the helicopter was less than 160 km/h, the error between the actual application rate and the intended application rate was less than 10%.

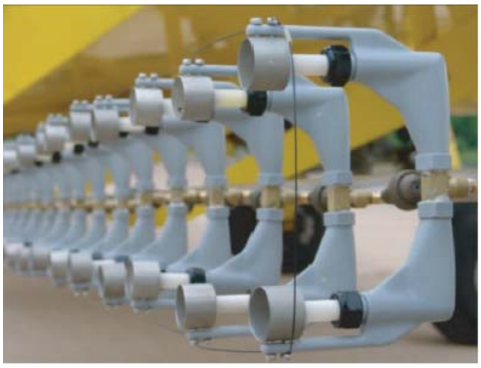

Figure 4 Spectrum electrostatic spray system

Figure 5 Manned aircraft-based spraying with AG-FLOW system

Figure 6 Manned aircraft-based spraying with Satloc G4 system

Application droplet size, which is one of the primary factors impacting spray deposition and drift, is controlled by application airspeed, nozzle type and operational setup, spray pressure and the physical properties of the spray solution. Lan et al.[72] examined four drift control adjuvants in a series of spray drift studies under aerial applications conditions using an Air Tractor AT-402B, and showed that the deposition, droplet size, droplet coverage, and total drops were highly correlated to the drift distance and adjuvant type. Huang and Thomson[73] studied the characteristic of droplet deposition and drift under different nozzle operational setups at different applications heights showing that droplet deposition in the spray swath was not significantly influenced by application height, but application height had a significant effect on spray deposition from drift samplers, along with wind direction and relative humidity. Fritz et al.[74] evaluated a proposed test plan for the validation testing of pesticide spray drift reduction technologies (DRTs) for row and field crops, focusing on the testing of spray drift and droplet deposition of the spray system on the Air Tractor 402B airplane under full-scale field evaluations. Wang et al.[75] studied the impact of flight height and nozzle configuration of the Robinson R-44 helicopter and the Bell 206 helicopter on droplet deposition distribution in paddy fields and the control effect of rice blast.

Zhang et al.[76] evaluated the effective swath width of the spraying systems on two fixed wing airplanes M-18B and Thrush 510G in different environmental parameters (wind speed, temperature, humidity) and nozzle angle conditions, and analyzed the characteristics of droplet deposition distribution under different types and different spraying operation parameters. The above-mentioned researches greatly promoted the improvement and promotion of aircraft spraying technologies.

3.2 UAV-based aerial spraying technology

The world's first unmanned aerial vehicle for spraying pesticides was developed and produced in 1990 by Yamaha Corporation in Japan for application of insect pest control products on rice paddies, soybeans and wheat[77,78]. Compared to aircraft-based aerial spraying technology, UAV-based aerial spraying technology was developed rapidly in agricultural aviation applications due to its advantages of low operating height, less drift, low cost and high flexibility and so on[64,79,80]. In recent years, the development of UAV-based spray systems and application technologies for low-altitude and low-volume spraying have made a significant progress, and various types of UAVs are used to spray for a variety of crops, as shown in Figure 7. Huang et al.[81] developed a low volume spray system for use on a fully autonomous UAV to apply crop protection products on specified crop areas. The system showed good potential for vector control in the areas not easily accessible by personnel or equipment. Zhu et al.[82] developed a PWM controller for a UAV precision sprayer for agriculture which was shown to have potential as a precision spray system allowing for variable rate applications. Ru et al.[83] designed an electrostatic spray system for the XY8D UAV and showed that droplet deposition was increased under field conditions compared with conventional spray. Xue et al.[84] designed a UAV system with an electronic control system to activate spray applications based on specific GPS coordinates allowing for route planning and autonomous applications over pre-programmed locations.

a. P-20 UAV spraying on wheat by XAIRCRAFT Co., LTD

b. HY-B-15L UAV spraying on cotton by Shenzhen Hi-tech New Agriculture Technologies Co., LTD

c. 3WQF125-16 UAV spraying on cole by Quanfeng Aviation Plant Protection Technology Co., LTD

d. TXA-Xiangnong UAV spraying on rice by Guangzhou Tianxiang Aerospace Science and Technology Co., LTD

Figure 7 Four working UAVs for different crops

With the wide application of UAV-based aerial spraying, domestic and foreign scholars explored application quality pest control efficacy using these systems under field conditions. Durham et al.[85] deployed an unmanned aerial vehicle for spraying a semicommercial scale vineyard, and assessed the resulting spray deposition and work rate of the UAV spray application showing the potential for commercial deployment of unmanned vehicles for specialty crops. Qiu et al.[86] studied the relationship between spray deposition characteristics and flight height and velocity of small unmanned helicopter (CD-10, Wuxi Hanhe Aviation Technology Co., Ltd) and developed a model of the relationship between droplet deposition distribution and the two factors of flight height and velocity. Qin et al.[87] explored the effect of spray droplet deposition from applications using a UAV (N-3, Nanjing Research Institute for Agricultural Mechanization Ministry of Agriculture) on late season maize at different application heights and effective spraying swath width and showed that 7 meters in the working height and 7 meters in the spraying swath should be chosen as reference of spraying pesticides. Chen et al.[88] used a single-rotor, small unmanned helicopter (HY-B-10L, Shenzhen Hi-tech New Agriculture Technologies Co., Ltd) with different flight parameters of 1-3 m in the working height and showed that the droplet deposition in the target area decreased with the increase of the flight height in the 3 trials. Gao et al.[89,90] examined spray droplet distribution and efficacy from aerial applications using the UAV (Af-811, Aviation Industry Corporation of China) for control of corn borer and wheat midge, demonstrating 80.7% and 81.6% mortality, respectively. Qin et al.[91] demonstrated the influence of spray parameters, such as Droplets of 480 g/L chlorpyrifos·(Regent EC) (at a dose of 432 g a.i/hm^2 spray volume rate of approximately 15 L/hm^2, the flight height of 0.8 m and 1.5 m, the flight velocity of 3 m/s and 5 m/s) of the UAV on spray deposition in a rice canopy for control of plant hoppers showing that low volume applications of concentrated spray solution enhanced the efficacy duration. Similarly, as listed in Table 1, for UAV operating parameters optimization, various UAV models have been tested under different flight parameter settings to find more suitable flight altitudes and speeds that could achieve optimum spray droplet deposition for UAV spraying on many crops (Table 1 is a summary of optimal operating parameters obtained by spraying test). And in order to avoid pesticide damage of the surrounding crops and environmental pollution caused by drift of the liquid, some tests were carried out to find the security buffer area of different types of UAVs under different operating parameters and wind speeds (Table 2 is a summary of the security buffer area of different types of UAVs).

Table 1 Optimal operating parameters of different types of UAVs from literatures

UAV type	Crop	Flight altitudes tested/m	Optimal flight altitude/m	Flight speeds tested/m·s^{-1}	Optimal flight speed/m·s^{-1}	Source
WPH642 helicopter	Rice	1, 2, 3, 4	2	1.5, 2.0, 2.5	1.5	[92]
HY-B-10L helicopter	Rice	1, 2, 3	2	2~5	2~3	[88]
N-3 helicopter	Maize	5, 7, 9	7	3	N/A	[87]
P-20 Quad-rotor UAV	N/A	1-3	2	2-6	3.7	[93]
3W-LWS-Q60S Quad-rotor UAV	Citrus	0.5, 1, 1.5	1	1	N/A	[94]

Table 2 Security buffer area of different types of UAVs from literatures

UAV type	Flight altitudes tested/m	Flight speeds tested/m·s^{-1}	Wind speeds tested/m·s^{-1}	Security buffer area/m	Source
3WQF80-10	1.5-3	2.4-5	0.76-5.5	≥15	[95]
HY-B-10L helicopter	1.3-3.2	2.2-4.5	1-2	≥7	[88]
N-3 helicopter	6	3	1-3	8-10	[96]
Z-3 UAV	5	3	3	≥8	[97]

Further supporting and enhancing the effectiveness of UAV-based aerial spraying technologies, the precision agricultural aviation team from South China Agricultural University has carried out a number of research projects in various crops such as orange trees, rice, cotton and wheat in Yunnan, Hunan, Xinjiang, Henan and other provinces. The National Aviation Plant Protection Science and Technology Innovation Alliance was established in 2016 by Anyang Quanfeng Aviation Plant Protection Technology Co., LTD and South China Agricultural University organizing more than 60 groups concerned with agricultural UAVs and has become an important landmark for the application and development of UAV-based aerial spraying technologies in China. The alliance has organized a number of enterprises to carry out wheat aphid control and cotton defoliant spraying tests in May, July and September of 2016. In August 2016, over 20 000 hectares were impacted by the outbreak of mythimnaseparata walker disease in Shaanxi Province. The alliance organized a number of member units and mobilized hundreds of UAV for emergency prevention and relief work. This was the first cooperation for UAV-based aerial spraying in China which established an operational model for the use of UAV for large-scale pest control moving forward.

4 Ground verification technology for PAA

As an important part of PAAT, ground verification technology (GVT) is indispensable for obtaining droplet deposition data following aerial spray applications and is used to optimize spraying system setups and operational parameters. Droplet trajectories and depositional distributions are difficult to predict aerial spray applications as a result of the complexity of the operational environment and the variability of operating parameters. GVT are used to measured and examine droplet deposition patterns and explore the influence of the UAV and spray system operating parameters to provide improved operational guidance and spray system setups. GVTs used in precision agricultural aerial spray applications include theoretical models and measurement of spray deposition.

4.1 Theoretical model verification technology for PAA

The theoretical modelling of droplet deposition and drift is an important tool in the regulation and the decision management of aerial applications[98], with decades spent in the development of the models used. Since the late 1970s and early 1980s, the US Forest Service began to develop and use the FSCBG (Forest Service Cramer Barry Grim) model to analyze and predict droplet drift and deposition in aerial spray applications[99-102]. Through the efforts of researchers such as Bilanin and Teske et al.[103-105], FSCBG was expanded into the AGDISP (Agricultural Dispersion) model. AGDISP models aircraft wake effects (vortices, propellers, and jet engines) and evaporation. The AGDISP is the regulatory model of choice in the United States, Canada, and New Zealand. Further development and refinement by the Spray Drift Task Force (SDTF) led to a regulatory version, AgDRIFT. Further, efforts by the New Zealand Forest Research led to the development of SpraySafe Manager, efforts of the USDA Forest Service led to an ArcView/GPS version GypsES Spray Advisor[106-108]. Teske et al.[109-114] made further improvements to the model using the methods of the steady state Gaussian model, the Gaussian pull model, analyzing the aircraft wake in the physical angle, atmospheric turbulence interaction and the N-S equation, extending the effective forecast range of the model to 20 km. Hewitt et al.[115] introduced the geographic information system (GIS) into the model optimizing spray decision making using real-time wind speed to reduce pesticide drift loss in non-target areas. Ru et al.[116] analyzed related factors which influence spray drift behavior, and set up the equations of motion for droplets in a three-dimensional coordinate system to develop a prediction model of droplet drift under a crosswind to predict droplet drift distance. Zhang et al.[96] proposed a computational fluid dynamics (CFD) simulation to analyze the drift of sprays from aerial spraying using a N-3 UAV. The model was verified through field evaluations and is being used to provide guidance for the actual spraying operations.

4.2 Sensor verification technology for PAA

At present, the development and use of droplet deposition imaging systems are of great interest. Compared with traditional GVT, such as fluorescent tracers or stain analysis methods, these near-real time methods shorten the verification cycle and simplify processing. Zhu et al.[117] developed a custom-designed software package entitled “DepositScan” for evaluating the droplet deposition distribution allowing for determination of individual droplet sizes, overall distributions, total droplet number, droplet density, spray deposit volume and percent coverage from the exposed card. Jiao et al.[118] demonstrated a new method for real-time evaluation of pesticide drift using infrared thermal imaging technology to detect the differences before and after spraying to measure the size range and deposit concentration of droplets. Infrared thermal imaging combined with infrared image processing algorithms can be used to monitor real-time measurement of pesticide drift in aerial spray applications. Zheng et al.[119] established a detection method that uses the reflective wave of laser radars. Positional information for applied droplets was recognized and extracted and the coordinate was transformed, and the sample time that could describe the droplets distribution was analyzed and determined. In addition, the dynamic proportion was used to eliminate the drift droplets and the effective distribution range was determined. Zhang et al.[120] analyzed the relationship between droplet deposition applied from a M-18B aircraft and vegetation indices calculated from satellite imagery of the test area. The results showed that the single phase spectral feature and the temporal change characteristic can be used to determine the aerial spraying effects in the field on a large scale. Zhang et al.[121] developed a sensor with a variable dielectric capacitor and network system to measure deposition volume in near real-time. The results of testing showed that compared to water sensitive paper image analysis, the degree of fit for the distribution curve is 0.9146 with relative measurement errors of 10%-50% . The precision agriculture aviation team of South China Agricultural University designed a sensor for real-time detection of the effect of droplet deposition in aerial spraying application based on the principle of common-plane plug-in capacitor, with measurement accuracy of 0.1 μg/cm and single point measurement speed of 10 μs. The sensor not only can measure the amount of droplet deposition, but also observe the whole process of droplet evaporation.

5 Future development of PAATs

As precision agriculture continues to grow, and demand for food and ecological security will continue to rise and more operators will become familiar with these technologies to meet this growing demand. Research continues to be conducted to enhance these technologies and create new technologies for accuracy and efficiency.

5.1 Real time image processing

Real time image processing is needed to bridge the gap between remote sensing and variable-rate aerial application. Data analysis and interpretation is one of the most important parts of precision aerial application. Whether collected from airborne images, ground-based sensors and instrumentation systems, human observations, or laboratory samples, data must be analyzed properly to understand cause-and-effect relationships. To develop appropriate prescription maps for variable-rate aerial application, the findings from hyperspectral or multispectral remote sensing images in near real time has been a challenge. The ultimate goal is to develop a user-friendly image processing software system, aiming to analyze the data rapidly from aerial images so that variable-rate spraying can occur immediately after data acquisition.

5.2 Variable-rate technology

Variable-rate spay technology is the core of precision aerial spraying. There is limited application for turn-key commercial Variable-rate technology (VRT) devices due to their perceived high cost and operational difficulty. An economical and user-oriented system is needed that could process spatially distributed information, and apply only the necessary amounts of pesticide to the infested area efficiently and to minimize environmental damage. Additionally, nozzles are designed to produce optimal droplet size spectra for mitigation of off-target drift and to provide maximum application efficacy. These desired size ranges require the nozzles to operate within proper boundaries of their design pressure. Variable rates called for by the aerial application system might operate these nozzles outside their optimal pressure ranges making their valid use questionable if a wide range of flow rate is required. This would not be a problem for “on-off” variable control.

5.3 Multisensor data fusion technology

A key step in successful precision system development is creation of accurate prescription maps for aerial application. Creation of these maps can be assisted by multisensor, multispectral, multitemporal and even multi-resolution data fusion utilizing GIS techniques. The data fusion will be based on new methods for the fusion of heterogeneous data: numerical or measurable (radiometric, multispectral, and spatial information) and symbolic (thematic, human interpretation and ground truth) data. The multisensor data fusion scheme needs to be fully integrated into the system through GIS.

5.4 RTK positioning technology

GPS is one of the most important parts of agricultural aircraft. Inertial navigation provided only by inertial measurement unit (IMU), is unable to provide hover and route planning accurately. The hover and route planning of agricultural aircraft (or UAV) is essential for precision aerial spraying operations, not only saving labor costs to a large extent, but also improving the accuracy and efficiency of spraying operations. At present, the RTK positioning technology and product has not really applied in agricultural aircraft (or UAV) due to its high price for aerial spraying operation, which will result in the safety and accuracy of aerial spraying difficult to ensure. Therefore, with the rapid development of micro-electronic technology, RTK technology costs will gradually decline, and RTK technology will be one of the most important technologies in the field of agricultural aviation in the future.

5.5 Multi-aircraft cooperative technology

With the extensive implementation of precision agricultural aviation applications, information detection and pesticide spraying of aircraft have different requirements, and single aircraft is difficult to effectively accomplish various tasks at the same time[122]. In order to make up for the shortcomings of single-aircraft operations, researchers have begun to follow with interest the multi-aircraft cooperative technology. Multi-aircraft cooperative operation is based on single-aircraft operation, to achieve intelligent networking of multi aircrafts. Each single aircraft is required to be able to coordinate the task for the whole so as to effectively cover a large area and conduct information interaction and collaboration. With technological advances in Internet of Things (IoT) and big data, multi-aircraft cooperative operation will be a greater extent to save labor costs and improve the efficiency of precision aviation operations.

5.6 Supporting technologies for UAV-based aerial spraying

In recent years, UAV-based aerial spraying operation has become one of the most important components of agricultural aviation applications as its large-scale application. As UAV-based aerial spraying application with high-degree atomization of spray liquid, droplets easy to drift and other characteristics, in order to ensure the effective application of UAV-based aerial spraying, supporting technologies for UAV-based aerial spraying such as R&D technologies for nozzle, chemical agent and adjuvant, etc., which have a huge research potential. In which, these nozzles may include the electrostatic nozzle, the adjustable spray nozzle for droplet size and spray flow and others, chemical agent for aerial spraying by UAV may include the ultra-low-volume liquid, the nano-biological agent and others, chemical adjuvant for aerial spraying by UAV may include the modified vegetable-oil adjuvant, the organosilicone adjuvant and others. The development and application of these technologies will provide a strong guarantee for precision agricultural aviation application by effectively reducing drift and loss of droplets and promoting the absorption of the active ingredients in crop.

6 Summary

PAAT will result in more judicious use of pesticides while maintaining efficacious application and protecting the environment from adverse impacts. Large farms will benefit greatly from the use of these technologies. Small farmers could use precision agriculture technologies using a cooperative system to deal with urgent areawide pest management issues. PAAT will also allow for the targeting inputs to specific areas of fields, enabling farmers to remain successful in an increasingly competitive industry. Furthermore, it is anticipated that within the next 5-10 years, a number of breakthroughs will be made expanding the basic theories of PAAT and related equipment research such as real-time image processing and VRT, along with agricultural aviation policy. This will lead to increased guidance and support for PAATs and an increase in the number of alliances and associations related to agricultural aviation pushing PAAT into the future to support the needs of modern agricultural production.

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