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Obstacle Avoidance and Profile Ground Flight Test and Analysis for Plant Protection UAV

Shubo Wang [1,2,3,†], Shaoqing Xu [1,2,3,†], Congwei Yu [1,2,3], Hecheng Wu [1,2,3,4], Qiang Liu [1,2,3,4], Dian Liu [1,2,3,4], Liujian Jin [1,2,3,4], Yi Zheng [1,2,3,4], Jianli Song [1,2,3] and Xiongkui He [1,2,3,*]

[1] Centre for Chemicals Application Technology, China Agricultural University, Beijing 100193, China; wangshubo@cau.edu.cn (S.W.); b20213100722@cau.edu.cn (S.X.); y_ycw@cau.edu.cn (C.Y.); sy20213071465@cau.edu.cn (H.W.); sy20213071448@cau.edu.cn (Q.L.); sy20213071447@cau.edu.cn (D.L.); sy20213071443@cau.edu.cn (L.J.); sy20203071391@cau.edu.cn (Y.Z.); songjianli@cau.edu.cn (J.S.)

[2] College of Agricultural Unmanned System, China Agricultural University, Beijing 100193, China

[3] College of Science, China Agricultural University, Beijing 100193, China

[4] College of Engineering, China Agricultural University, Beijing 100083, China

[*] Correspondence: xiongkui@cau.edu.cn

[†] These authors contributed equally to this work.

Abstract: In recent years, with the further development of agricultural aviation technology, the plant protection UAV has been widely used, especially in some agricultural environments with limited operating conditions due to its advantages of high efficiency, environmental protection and safety guarantee. A plant protection UAV generally flies at low altitude during operation. However, the low altitude operation environment, such as farmland and mountainous areas, is relatively complex, and is faced with many types of obstacles, proposing higher requirements for obstacle avoidance and the profiling system of a plant protection UAV. In order to test the obstacle avoidance and profiling performance of the commercialized plant protection UAV at this stage and explore the performance boundary of obstacle avoidance and profiling of the UAV, EAVISION E-A2021 and XAG P80, the flagship models of the plant protection UAV manufacturer on the market, were hereby selected as the experimental test objects in the paper. Firstly, the obstacle avoidance and profiling test scheme of plant protection UAVs is designed; then, the above two UAVs are adopted for corresponding tests, and the test data are discussed based on the analysis of software and hardware technology; finally, the practical application status of different obstacle avoidance and profiling technologies of plant protection UAVs is clarified, and the shortcomings of obstacle avoidance and profiling technology of plant protection UAVs on the market are summarized, providing a reliable reference for the future development of plant protection UAVs.

Keywords: plant protection UAV; obstacle avoidance; profile ground flight; test and analysis

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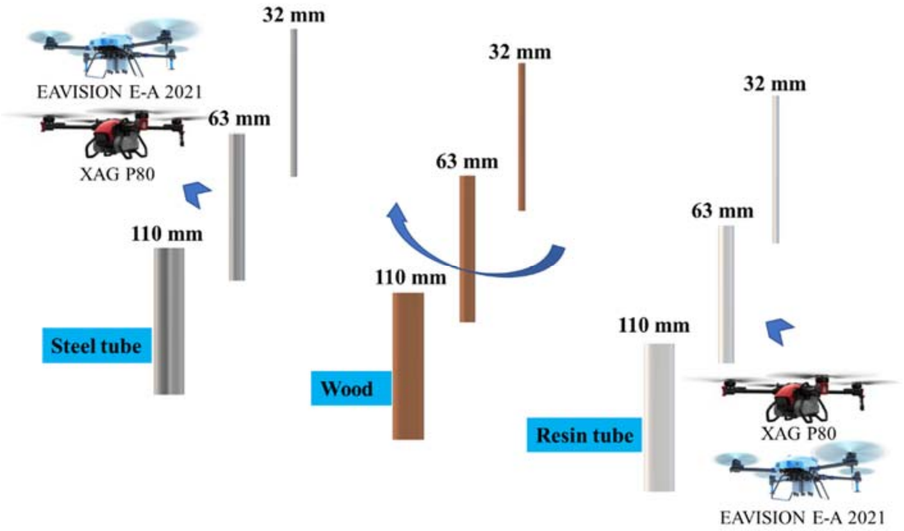
1. Introduction

While carrying out plant protection operations in farmland, plant protection UAVs are required to deal with complex operating environments such as common power equipment towers, wires, nylon nets for agricultural production management, houses, etc., which have greatly increased the risk of plant protection operations [1–5]. In addition, especially to ensure the operation quality, plant protection UAVs usually need to fly at a low altitude of 1.5–3 m from crops or tree crowns, where some prominent branches, trunks, etc., inevitably bring hidden dangers to the safety of aircraft operations [6]. However, the traditional manual remote control operation method still relies heavily on the control by ground personnel and has extremely high requirements for the operation experience and concentration of the personnel. Additionally, once encountering long-distance or large-scale operation in the operation process, obstacles outside the vision field are likely to become operational threats to plant protection UAVs, thus resulting in aircraft accidents [7–9]. At present, in order to improve the operational autonomy of plant protection UAVs and reduce the dependence on manual operations, RTK technology is generally adopted for plant protection UAVs to achieve advance planning of operating routes [10], and complete autonomous operation flights according to planned routes [11,12], which can avoid the interference of some static and large obstacles during the operation to a certain extent [13]. However, for some relatively small or dynamic obstacle targets, the plant protection UAV still needs to rely on an accurate and reliable obstacle avoidance system without human intervention, identify the obstacles to be avoided, and plan a reasonable avoidance path or make other obstacle avoidance decisions, so as to independently complete the obstacle avoidance task of plant protection operations and ensure the flying safety [14].

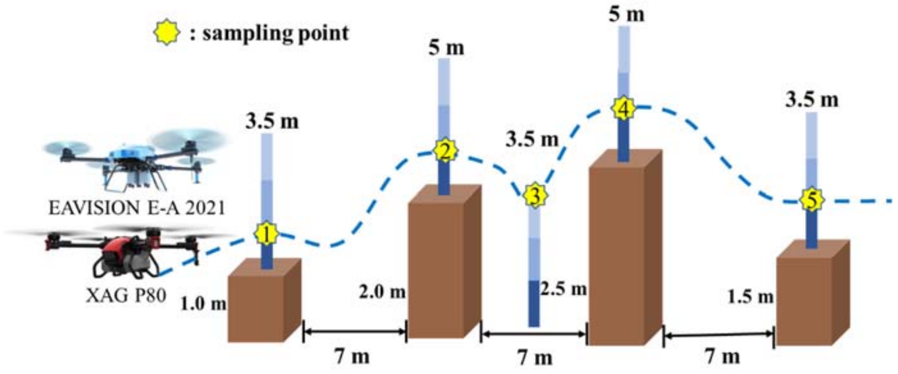
Profile ground flight is another key technology for plant protection UAVs, which means that the UAV can form a fixed flight altitude with the ground, and the operation altitude can be adjusted with the fluctuation of the ground during the flight. Profiling technology has a great impact on the quality of plant protection operations, and the profiling performance of plant protection UAVs is particularly important for the quality and safety of plant protection operations, especially in the uneven working environment of hilly and mountainous areas [15,16]. According to the study, when the flight height of the UAV is too low compared to the relative height of the crop canopy, it will bring about operational safety hazards, and will cause problems such as uneven distribution of fog droplets. The uniformity of the droplets will be optimized when the flight height increases, but a too-high flight height will cause the loss of fog droplets, resulting in adverse effects such as decreased pesticide utilization [17]. It can be concluded from the above research that in the actual operation of the crop protection UAV, the uneven height of the crop canopy or the change in terrain fluctuations will inevitably lead to the change in the relative height between the UAV and the crop canopy, which affects the uniformity of the fog droplet deposition, and even the phenomenon of heavy spraying and leakage, and will also pose a threat to the operation safety [18,19]. Therefore, out of comprehensive consideration, the height of the plant protection UAV relative to the crop canopy or ground should be maintained within a reasonable height range and kept as constant as possible in some undulating terrain or crop canopy in obvious staggered operating areas, so as to ensure the operation safety, better operation quality and operation efficiency. Generally, during the plant protection operation of UAV, the relative height between the aircraft and the crop or ground is about a 1.5–3 m range, and it is extremely difficult to achieve this effect when manually operating the machine to maintain the flight height. Consequently, the UAV is required to carry a stable profiling module to complete the profiling task during the plant protection operation.

However, at this stage, the profiling and obstacle avoidance technology of a plant protection UAV is more complex. Various UAVs mainly use cameras, radars and other sensors as important sensing elements, and its real operation effect is also difficult to evaluate. Therefore, combined with the actual operation, the test site is hereby built and the test scheme for the obstacle avoidance and profiling system of plant protection UAVs is designed, as shown in Figure 1. At the same time, the representative E-A 2021 [20] and P80 [21] plant protection UAVs in the current market are adopted for the test, and different obstacle avoidance and profiling technologies used are compared and analyzed based on the test data. A set of standard test schemes is explored through the test method designed in this paper, which also provides a useful reference for the development of plant protection UAVs in the future.

The remainder of the paper is organized as follows: Section 2 analyzes the hardware systems of two UAVs, including their obstacle sensing and ground imitating sensors; Section 3 conducts obstacle avoidance environment construction and flight test; Section 4 carries out the construction of ground simulation test site and flight test experiment; Section 5 discusses and analyzes the test results of two UAVs; and Section 6 summarizes the paper.



(**a**) Simulation diagram of obstacle setting in obstacle avoidance test



(**b**) Simulation diagram of UAV profiling test scheme

Figure 1. Schematic diagram of testing scene of plant protection UAV.

2. Hardware Analysis of the EAVISION E-A2021 and XAG P80

2.1. Hardware Structure Analysis of the XAG P80

The XAG P80 plant protection UAV has a quadrotor beam symmetrical structure, equipped with several innovative radar matrices, including a dynamic radar at the front of the fuselage, a top-view radar at the upper part of the fuselage and a radar at the bottom of the fuselage. The millimeter-wave radar model RD2436 was selected as the front dynamic radar, whose operating frequency is 24 GHz. The multi-transmitting and multi-receiving antenna are used, which improve the angular resolution of the radar and enables it to detect a smaller angular range, making it possible for the radar to identify the information of obstacle feature more accurately and finely. The front radar provides a viewing angle of 80° horizontally and 90° vertically, and perceives the position, distance, movement direction and relative speed of static obstacles in real time within a distance of 1.5 m to 40 m.

The millimeter-wave radar model UP24S10 was selected as the top-view radar, with a viewing angle range up to 50°, and detects and identifies obstacles from 1 to 10 m above the aircraft. The terrain module adopts the millimeter-wave radar model TR24S100, which enables UAVs to fly at a fixed altitude within the range of 1–30 m and simulates ground flight with the maximum slope of 45° at the maximum speed of 2 m/s. XAG P80 also captures a PSL pilot's perspective image, enabling operators to perform delicate operations in complex environments.

2.2. Hardware Structure Analysis of EAVISION E-A2021

The EAVISION plant protection UAV features a quadrotor structure and gives full play to the ability of three-dimensional environment perception based on binocular vision for autonomous obstacle avoidance. The unique Eagle Eye system of EAVISION E-A2021 (Suzhou, China) uses a binocular camera with dual four-megapixel as the main sensor and provides a 120° obstacle avoidance angle in the horizontal direction. The self-developed online calibration algorithm provides a greater guarantee for the accurate processing of subsequent images. At the same time, the image enhancement algorithm and the neural-network-based stereo vision matching algorithm help overcome the shadow generated by the visual technology in the actual operation and common problems in vision technology, such as light interference and structural deformation. At the same time, in cooperation with the laser lidar and millimeter-wave radar equipped on the front of the fuselage, the multi-sensor fusion technology facilitates large slope profiling with a maximum of 70°, and ultra-low terrain profiling and high-precision simulated canopy autonomous flight with a minimum of 0.7 m and a maximum drop of 10 m.

It can be drawn out according to the above introduction to the sensing hardware and distribution form of the two plant protection UAVs, EAVISION E-A2021 and XAG P80, that although the two UAVs use the same combined obstacle avoidance profiling system, different sensor combinations reflect the differences in UAV information processing and control strategies. Three millimeter-wave radars are applied to the XAG P80 obstacle avoidance profiling system to detect obstacles in front, above and below the flight path, and there is no overlap of the view field between the millimeter-wave radar sensors at different positions. In addition, the acquisition and processing of information is mainly a parallel relationship. The final analysis and decision-making of the detection results of different sensors were carried out in the flight control system based on the labor division and detection of obstacle information in different directions, so as to complete the flight control of the UAV. EAVISION E-A2021 adopts a strategy different from that of XAG P80. Multi-sensor fusion technology is applied to its profiling system, which helps accurately measure the relative height of the obstacles below by fusing the perception data of millimeter-wave radar and lidar. The working environment information in front of the flight path is mainly detected by the binocular camera at the front of the UAV. Based on all this information, the data analysis in the subsequent test chapters can be analyzed and summarized, respectively, corresponding to binocular vision technology, radar technology and multi-sensor fusion technology.

3. Obstacle Avoidance Test and Result Analysis

For plant protection UAVs operating in complex environments, it is necessary to divide the obstacles according to the characteristic information such as the position and distance of obstacles in front of the flight path detected by their own sensors. It is advisable to implement different obstacle avoidance strategies for the obstacles in different areas divided according to the distance of obstacles. Specifically, the areas can be classified from far to near as follows: 15 m away is a safe area, where the UAV can fly normally; 5–15 m is an early warning area, bringing an obstacle early warning area, making it necessary to identify and track threatening obstacles; 2.5–5 m is a safe avoidance area, where the UAV needs to perform local path planning to avoid obstacles or hover according to the obstacle information. Generally, the shortest distance between the front-end propeller tip of the plant protection UAV and the obstacle is 2.5 m, which is a normal safe distance, otherwise there will be potential safety hazards. Under special circumstances, when the distance is less than 2.5 m, the UAV must take emergency brakes to hover and avoid the occurrence of a bombing accident.

3.1. Obstacle Avoidance Test Site Construction

During the operation of plant protection UAVs, the operating environment is rather complicated. In farmland and hilly orchards, power equipment such as telephone poles and wires, protective nets, agricultural production equipment for auxiliary management and some prominent tree trunks and branches can be seen everywhere, bringing great hidden dangers to the operation safety of plant protection UAVs and also considerable challenges to the obstacle avoidance performance of plant protection UAVs. According to the different obstacle characteristics such as the shape and size of the obstacle, obstacles can be classified according to the following methods:

Tiny obstacles: common wires, branches and prominent branches in farmland, etc.;

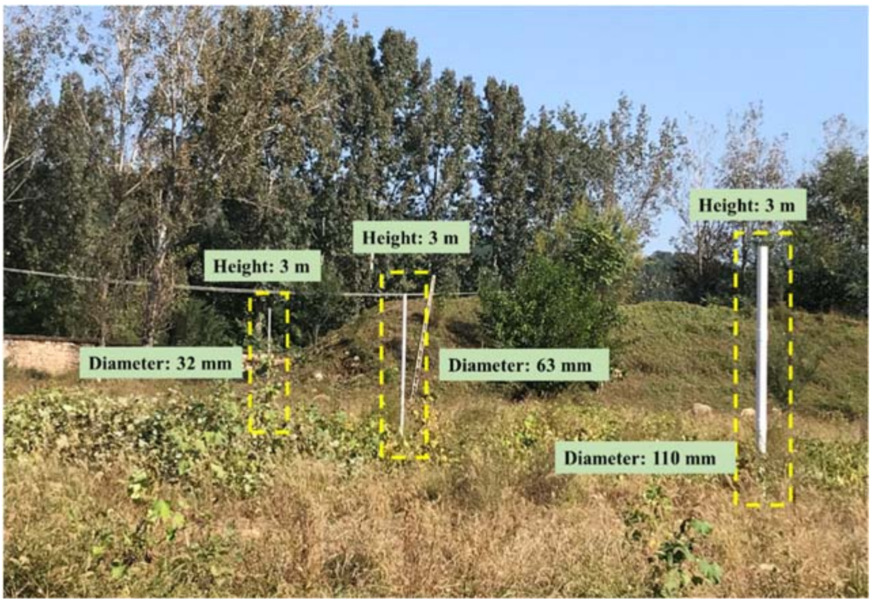
Small and medium obstacles: electrical equipment, scattered trees, haystacks, etc.;

Large obstacles: Shelter Forest, high-voltage towers, houses, etc.

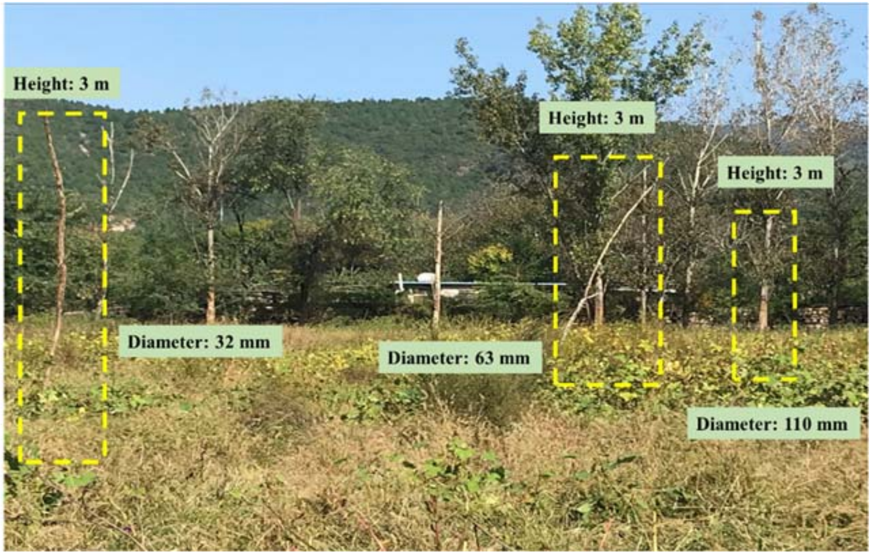
Due to their own characteristics, small and medium-sized and tiny obstacles are not easy to be fully perceived by sensors and make it difficult for plant protection UAVs to fully identify and successfully avoid them in time. In actual plant protection operations, the above two kinds of obstacles are the most important safety hazards, and the detection and avoidance of small and medium-sized obstacles can best demonstrate the obstacle perception and obstacle avoidance performance of plant protection UAVs in actual operations. Therefore, the above two types of obstacles are the main obstacle avoidance targets in this obstacle avoidance test scheme. Some contents of the national specification NY/T 3213-2018 Technical Specification for Quality Evaluation for Crop Protection UAS specify the obstacle avoidance performance test requirements by consulting the data: when operating the plant protection UAV to fly towards some obstacles such as electric poles, trees and haystacks at the speed of 2 m/s, the operator should observe whether the plant protection UAV can avoid collision with obstacles; when operating the plant protection UAV away from obstacles, the operator should measure whether the UAV can be controlled again. The test scheme is designed with reference to the performance test requirements specified in the above specifications.

Based on the above analysis, a test plan was formulated. The data of the common obstacle size in the agricultural environment (wires and twigs, tree branches, telephone poles and production equipment, etc.) were collected and sorted according to the variable size of the obstacle, and the final plan was determined, where three scales with diameter of 110 mm, diameter of 63 mm and diameter of 32 mm were, respectively, set, and the material variable was set according to the characteristics of the obstacles of each set of scales. Three materials of wood, metal and resin were used to simulate obstacles that might appear in actual operation, and hybrid obstacles were composed of two kinds of obstacles of small size resin and steel pipe. At the same time, according to the analysis, the best and most commonly used speed of plant protection UAVs during operation is 2–6 m/s. Therefore, the test speed of the plant protection UAV was selected from the lowest speed, the highest speed and the average speed in the optimal speed range, i.e., set to 2 m/s, 4 m/s and 6 m/s, respectively. In addition, PVC pipes, wood and metal with different diameters were used to build the test site, where the three UAVs would take off at a fixed height of two meters, five meters away from the first row of obstacles. The UAV conducted continuous flight tests at the above three flight speeds for different obstacle scales, and the test data were recorded. In the obstacle avoidance test, the plant protection UAV flew at a constant height and speed under the settings of professional operators to better simulate the real operation situation of the plant protection UAV and test the initial state, and during the flight, the spray system remained in working order. At the same time, in order to fully verify the autonomous obstacle avoidance performance of the UAV, the operator should not operate it manually after the UAV took off, unless there was an emergency.

PVC pipes, wood and metal with different diameters were prepared according to the test scheme, which were three meters high and grouped according to the scale. The actual environment of agricultural operation was analyzed. As shown in Figure 2, PVC pipes, wood and metal were arranged linearly in the experimental site according to the distance of 10 m in each group, and three groups of obstacles with different scales were arranged at an interval of 5 m. The environment and construction of the test site are shown in the following pictures. The vegetation on the ground can better simulate the agricultural crops in the operation, and it can be matched with the built obstacles to fully verify the obstacle avoidance performance of the plant protection UAV.

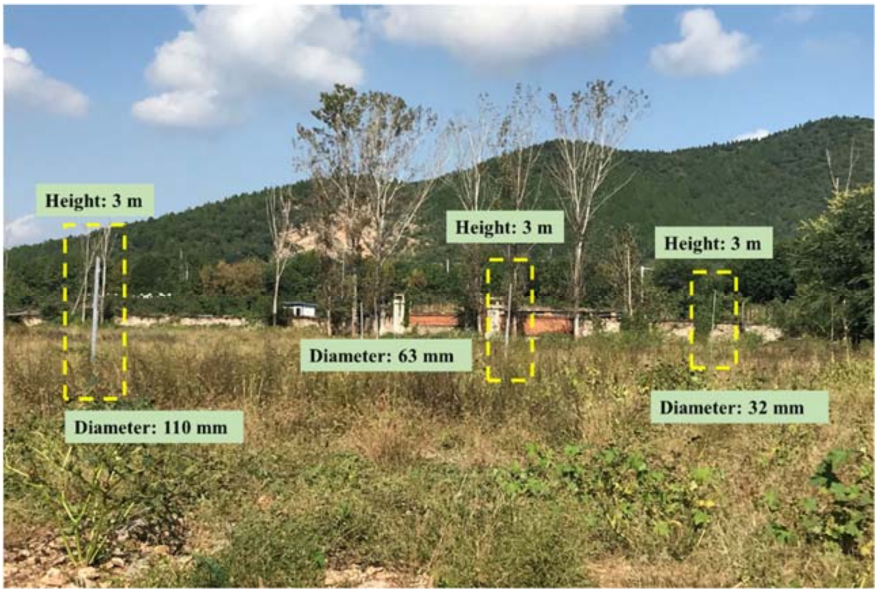


(**a**) Field construction drawing of PVC pipe group for UAV obstacle avoidance test

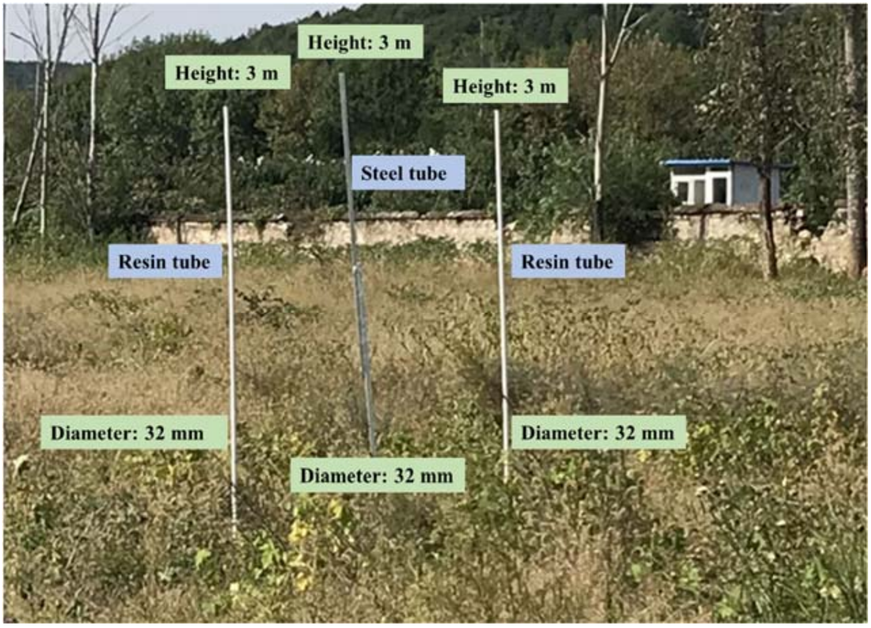


(**b**) Field construction drawing of wood group for UAV obstacle avoidance test

Figure 2. *Cont.*



(**c**) Field construction drawing of steel group for UAV obstacle avoidance test



(**d**) Field construction drawing of plant protection UAV mixed obstacle group

Figure 2. Different obstacle avoidance test scenarios.

3.2. Obstacle Avoidance Test and Result Analysis

3.2.1. Large-Scale Obstacle Avoidance Test Data

In the large-scale obstacle avoidance test, the test results of the three UAVs are shown in Table 1.

It can be seen from the data recorded in Table 1 that in the large-scale obstacle avoidance test, at the speeds of 2 m/s and 4 m/s, the EAVISION E-A2021 UAV successfully realized obstacle recognition and obstacle avoidance and flew around obstacles of the three different materials in Figure 3; the XAG P80 UAV could also achieve obstacle avoidance flight well at the speed of 2 m/s, but at the speed of 4 m/s, the UAV only completed obstacle avoidance flight when facing resin obstacles, and only made hovering response when facing metal and wood obstacles, suggesting that it could not complete obstacle avoidance flight autonomously; at a speed of 6 m/s, both UAVs failed the obstacle avoidance test in this group.

Table 1. Large-scale obstacle avoidance results of plant protection UAVs.

		XAG P80			**EAVISION E-A2021**		
		Metal	**Wood**	**PVC**	**Metal**	**Wood**	**PVC**
2 m/s	Flying around			√	√	√	√
	Hover	√	√				
	Collision						
4 m/s	Flying around	√	√	√			√
	Hover					√	
	Collision				√		
6 m/s	Flying around	–	–	–	–	–	–
	Hover	–	–	–	–	–	–
	Collision	–	–	–	–	–	–

(**a**) Obstacle avoidance test of large-sized PVC pipe of XAG P80 (4 m/s)

(**b**) Obstacle avoidance test of large-sized PVC pipe of EAVISION E-A2021 (2 m/s)

Figure 3. *Cont.*

(**c**) Obstacle avoidance test of large-sized wood of EAVISION E-A2021 (4 m/s)

Figure 3. Flight examples of different UAV types under large obstacles.

3.2.2. Obstacle Avoidance Test Data at Mesoscale

In the mesoscale obstacle avoidance test, the test results of the three UAVs are shown in Table 2.

Table 2. Results of obstacle avoidance test of plant protection UAV under mesoscale obstacles.

		XAG P80			**EAVISION E-A2021**		
		Metal	**Wood**	**PVC**	**Metal**	**Wood**	**PVC**
2 m/s	Flying around			√	√	√	√
	Hover	√	√				
	Collision						
4 m/s	Flying around	√	√	√			√
	Hover					√	
	Collision				√		
6 m/s	Flying around	–	–	–	–	–	–
	Hover	–	–	–	–	–	–
	Collision	–	–	–	–	–	–

In the mesoscale obstacle avoidance test, as shown in Figure 4, the EAVISION UAV successfully identified and avoided the three kinds of obstacles at the speed of 2 m/s, but the XAG UAV only hovered during the identification of metal and wood obstacles, and failed to achieve complete planning for obstacle avoidance when tested at the speed of 2 m/s; at the speed of 4 m/s, the XAG P80 plant protection UAV successfully achieved the identification of obstacles and the planned action of obstacle avoidance, but the EAVISION UAV was not able to accurately identify the characteristics of the obstacle during the wood obstacle test and only achieved hovering to avoidance the obstacle. In addition, the front of UAV collided with the top of the metal obstacle, resulting in damage to the propeller in the metal obstacle test; at the speed of 6 m/s, all three UAVs failed the obstacle avoidance test in this group.

(**a**) Obstacle avoidance test of EAVISION E-A2021 in medium-sized PVC pipe (2 m/s)

(**b**) Obstacle avoidance test of XAG P80 in medium-sized PVC pipe (2 m/s)

Figure 4. Flight examples of different UAV types under mesoscale obstacles.

3.2.3. Small-Scale Obstacle Avoidance Test Data

In the small-scale obstacle avoidance test, the test results of the three UAVs are shown in Table 3.

In the small-scale obstacle avoidance test, the EAVISION UAV could detect the existence of obstacles at the speed of 2 m/s, and it also completed an obstacle avoidance fly-around in the test against an obstacle made of resin, but only achieved hovering in the obstacle avoidance test of metal and wood materials; at the speed of 4 m/s, all three obstacles were not identified by the EAVISION UAV, and a collision occurred. However, the XAG UAV identified all three kinds of obstacles at both speeds, but only bypassed obstacles in front of the wood obstacles and hovered to avoid all other obstacles; at the speed of 6 m/s, both UAVs failed the obstacle avoidance test in this group.

Table 3. Results of obstacle avoidance test of plant protection UAV under small-scale obstacles.

		XAG P80			**EAVISION E-A2021**		
		Metal	**Wood**	**PVC**	**Metal**	**Wood**	**PVC**
2 m/s	Flying around			√			√
	Hover	√	√		√	√	
	Collision						
4 m/s	Flying around			√			
	Hover	√	√				
	Collision				√	√	√
6 m/s	Flying around	–	–	–	–	–	–
	Hover	–	–	–	–	–	–
	Collision	–	–	–	–	–	–

3.2.4. Mixed Obstacle Avoidance Test Data

In the mixed obstacle avoidance test, the results of the three plant protection UAVs are shown in Table 4.

Table 4. Test results of mixed obstacle avoidance of plant protection UAV.

		XAG P80	**EAVISION E-A2021**
2 m/s	Flying around		
	Hover	√	√
	Collision		
4 m/s	Flying around		
	Hover	√	√
	Collision		
6 m/s	Flying around	–	–
	Hover	–	–
	Collision	–	–

In the mixed obstacle avoidance test, both XAG P80 and EAVISION E-A2021 failed to identify and bypass obstacles at the speeds of 2 m/s and 4 m/s, but both UAVs could sense the presence of obstacles ahead and hovered within the specified safe distance. However, at the speed of 6 m/s, both UAVs failed the obstacle avoidance test in this group.

3.3. Analysis and Discussion of Obstacle Avoidance Test

It can be seen based on the summary of the EAVISION E-A2021 plant protection UAV obstacle avoidance test data that in large-scale, mesoscale and mixed obstacle avoidance tests, EAVISION E-A2021 could effectively sense the obstacles ahead in most cases, thus hovering or bypassing the obstacles. However, a collision accident occurred in the test of small-scale obstacles at the speed of 4 m/s. Combined with the analysis of the obstacle avoidance flight process, the plant protection UAV did not make any obstacle avoidance response within the safe distance, but only attitude adjustment when it was about to collide. Consequently, it can be reasonably judged that the main reason for the collision accident of EAVISION UAV was that the obstacle avoidance system failed to sense the existence of small obstacles within a safe distance. In combined results from four sets of obstacle avoidance tests, the EAVISION E-A2021 obstacle avoidance system, which used binocular vision as the main sense technology, presented excellent obstacle avoidance performance when the obstacle features were obvious. However, with the increase in flight speed and the reduction in obstacle size, the success rate of obstacle identification of EAVISION E-A2021 decreased, and even collision accidents might occur. Current binocular vision technology is therefore proven not accurate enough to identify small obstacles in complex environments. Especially in practical operation, meteorological conditions such as light and other environmental targets such as ground crops will greatly interfere with the core links such as stereo matching of binocular vision technology. Therefore, it is the key to the development of binocular vision technology to eliminate noise interference in the core link of binocular vision technology and improve the accuracy of image processing.

The XAG P80 plant protection UAV uses millimeter-wave radar to sense obstacle information. The dynamic radar arranged in front of the fuselage mainly detects the obstacle information in front of the flight route in real time. It can be found by comprehensively comparing and analyzing the performance of XAG P80 in this four-group UAV autonomous obstacle avoidance experiment that the XAG P80 plant protection UAV was able to effectively identify obstacles of three different scales and materials—large, medium and small—as well as mixed obstacles in this test, and there was no dangerous situation of collision with simulated obstacles. Even in the more rigorous small-sized group obstacle avoidance test, XAG P80 could still identify and bypass obstacles in the face of PVC pipe obstacles. For the wood and metal obstacles, although XAG P80 failed to complete the flight around the obstacle, it still sensed the existence of obstacles and made timely hovering response within a safe distance to avoid danger, which ensured the flight safety of the plant protection UAV to a certain extent.

Based on the summary and analysis of the test data of XAG P80 and EAVISION E-A2021 UAVs, their success rate of obstacle identification and obstacle avoidance fluctuated significantly with the change in conditions, regardless of flight speed, obstacle size and material. Especially in the high-speed flight state of 6 m/s, both UAVs failed to complete the experimental test. However, in a comprehensive comparison, the success rate of obstacle avoidance of XAG P80 was high, and there was no collision accident in the whole test. By analyzing the hovering working state, it was found that the EAVISION E-A2021 plant protection UAV could identify the existence of obstacles in front of it only when it flew into the dangerous area within two meters of the radius of obstacles, even within a distance of 1 m from the obstacle in some emergency situations, so as to implement emergency braking hovering. Such a performance is seriously inconsistent with the safe braking distance of 2.5 m between the front wing of the UAV and the obstacle specified by the obstacle avoidance performance and will bring great risks to the operation safety of the plant protection UAV in a complex environment. At the same time, emergency braking hovering will produce a large vertical inclination, which will affect the flight safety of the UAV. When the hovering strategy was implemented, the flight state of XAG P80 was relatively stable, especially in the case of small obstacles when the UAV could hover around the safe distance range without excessive inclination, which provides a reliable guarantee for the flight safety of UAV.

4. Profile Ground Flight Test and Result Analysis

4.1. Construction of Profile Ground Flight Test Site

In daily plant protection operations, the UAV should generally maintain the height of 1.5–3 m above the crop. Meanwhile, according to the requirements of the advanced assessment criteria for the multi-rotor plant protection UAVs published in 2019, the plant protection UAV should be able to follow the terrain in the operation scene with a maximum slope of 30°, while maintaining the relative height to the crop unchanged when operating in mountainous areas. The present profiling test simulates the setting of canopy with different heights according to the above requirements, and the simulated canopy should be provided with a certain width. At the same time, in order to simulate the real operation state of the UAV better and test the profiling ability of the UAV more accurately, the variable of flight speed is correspondingly set to test the performance of the profiling system of the plant protection UAV at different flight speeds.

Combined with the terrain changes detected by the profiling sensor, different profiling control strategies are adopted for different areas. The flight areas of the plant protection

UAV are divided into the following order: within 3 m is the advance sensing area, where the UAV can detect the change in the terrain height in advance, so as to adjust its attitude correspondingly. The range of this area can be adjusted appropriately with the flying speed of the plant protection UAV. The second is the real time profiling area, where the UAV will adjust its flight height in real time according to the change in terrain or the height of the crop canopy. At present, in the profiling operation state, the plant protection UAV mostly uses the sensor to detect the relative height information with obstacles in real time, and the flight control system completes the height adjustment according to the information, which requires the plant protection UAV to have sufficient sensor accuracy and the response speed of the flight control system.

In this profiling test scheme, as shown in Figure 5, four simulated canopies with different heights of 1 m, 1.5 m, 2 m and 2.5 m, respectively, were set up to reproduce the fluctuation of terrain or canopy in the real working environment. At the same time, in order to measure and calculate the relative height between the UAV and the simulated canopy more intuitively, the simulated canopy is spliced with 1 m long cartons. In this way, a two-meter-long platform is formed on the upper part of the canopy, to better observe the relative height between the plant protection UAV and the simulated canopy, thus reducing the difficulty of data acquisition and the data error and ensuring the accuracy of test data. Five five-meter-long rulers were prepared as the main measurement tools to measure the flying height of the UAV during the operation. Similar to the obstacle avoidance test, in order to truly simulate the actual operation situation, the three UAVs were set with two different flight speeds of 1.5 m/s and 3 m/s and a flying height of 1.5 m during the flight test. At the same time, the spray system needs to be in working state during the flight test and fly at the constant height and the constant speed under the operation of professional operators. In the whole profiling test process, five high-definition cameras were used to record the flight trajectories of five sampling points, which will benefit subsequent data processing.

Figure 5. Profile ground flight test site.

Different from the obstacle avoidance test, in order to avoid the interference of some vegetation on the ground, the profiling test was conducted on the open ground. The simulated canopies with four heights were arranged in the order of 1 m, 2 m, 2.5 m and 1.5 m, respectively, with a distance of 7 m. At the same time, according to the current agronomic standards, the centers of the four simulated canopies were kept on a horizontal line, so as to better simulate the working environment. The four rulers corresponded to the four different heights of the simulated canopy center, and the fifth ruler was placed in the middle of the simulated canopy with a height of 2 m and 5 m. Meanwhile, the ruler should also be arranged in parallel with the simulated canopy and the bottom of the two should be at the same level to reduce the error of data measurement. In addition, there should be a safety distance of 3 m to prevent the ruler from interfering with the flight test of the UAV.

4.2. Profile Ground Flight Test and Results

The profiling test data of three plant protection UAVs were summarized and analyzed. Limited by conditions, 10 cm was the minimum unit for reading the flight altitude data of the plant protection UAVs. After later analysis and research, data of the overall trend and the flight status were found relatively accurate, although there existed small errors.

In the flight process of this profile ground flight test, as shown in Figure 6, both XAG P80 and EAVISION E-A2021 plant protection UAVs could adjust their flight attitude according to the simulated canopy height changes, and successfully completed the profiling test. It can be seen from the profiling test data recorded in Tables 5 and 6 that there were certain profiling errors in the five sampling points of the two plant protection UAVs. However, on the whole, EAVISION E-A2021 presented higher profiling accuracy and better profiling system performance compared with XAG P80.

(**a**) EAVISION E-A2021 profiling test

(**b**) XAG P80 profiling test

Figure 6. Flight examples of different UAV types in profile ground flight.

Table 5. EAVISION E-A2021 flight data in profile ground flight.

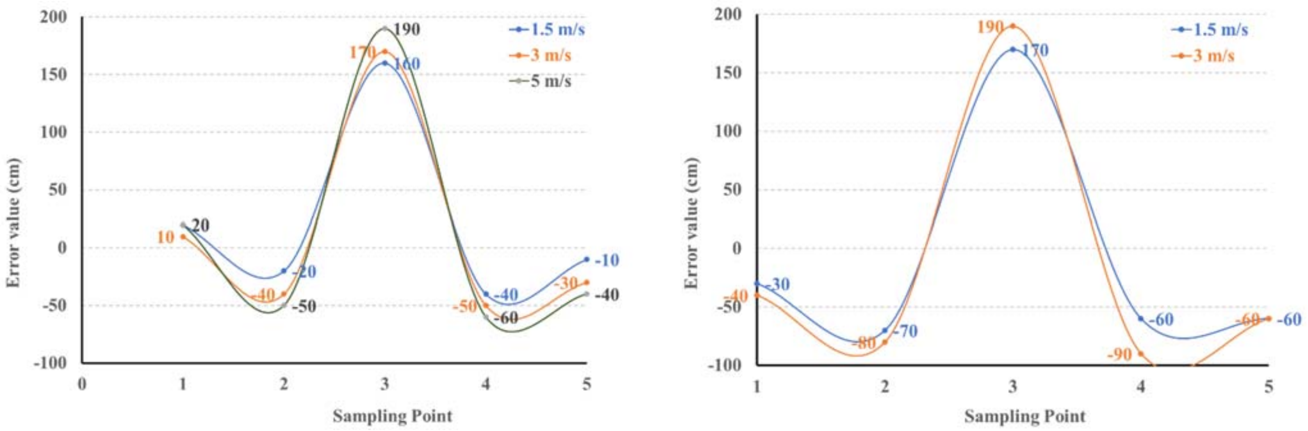
Speed	Sampling Point Number	Sampling Point Height (cm)	Preset Flight Altitude (cm)	Actual Flight Altitude (cm)
1.5 m/s	1	100	150	270
	2	200	150	330
	3	0	150	310
	4	250	150	360
	5	150	150	290
3 m/s	1	100	150	260
	2	200	150	310
	3	0	150	320
	4	250	150	350
	5	150	150	270
5 m/s	1	100	150	270
	2	200	150	300
	3	0	150	340
	4	250	150	340
	5	150	150	260

Table 6. XAG P80 flight data in profile ground flight.

Speed	Sampling Point Number	Sampling Point Height (cm)	Preset Flight Altitude (cm)	Actual Flight Altitude (cm)
1.5 m/s	1	100	150	220
	2	200	150	280
	3	0	150	320
	4	250	150	340
	5	150	150	240
3 m/s	1	100	150	210
	2	200	150	270
	3	0	150	340
	4	250	150	310
	5	150	150	240

4.3. Analysis and Discussion of Profile Ground Flight

The profiling test data of EAVISION E-A2021 and XAG P80 plant protection UAVs were processed and analyzed, and the error of each sampling point was calculated based on the preset flight height of 1.5 m. The results are shown as follows in Figure 7.



(**a**) Error diagram of EAVISION profiling test (**b**) Error diagram of XAG profiling test

Figure 7. Error diagram of different UAVs in profile ground flight.

On the whole, it can be clearly seen by analyzing the profiling test data of EAVISION E-A 2021 and XAG P80 UAVs that the relative height of the two plant protection UAVs at the four simulated canopy layers was generally lower than the preset flight height (Figure 8). At the same time, with the improvement of the test speed, the profiling error continued to increase, and the highest error occurred in the 3 m/s profiling test of EAVISION, with a fluctuation range of 60%. Change in the above data indicate the gradual decrease in the relative height between the plant protection UAV and the simulated canopy, which would affect the operation safety of the plant protection UAV to a certain extent. Combined with the profiling test flight process and the profiling strategy analysis described in Section 2, the main reason for the above problems was that the UAV failed to accurately identify the height change in the front simulated canopy in the advance sensing area. The relative height of the simulated canopy could be accurately identified only when it was about to be above the simulated canopy. At the same time, the UAV profiling system was subject to a certain response lag. As a result, the UAV was still in the climbing state, and the highest point of its attitude change exceeded the range of the simulated canopy when the UAV flew above the simulated canopy, which would have a great impact on the continuous profiling operation of the plant protection UAV. It can also be clearly noticed based on the data in the figure that the two UAVs produced great profiling error at sampling point 3, which mainly resulted from the lag of attitude adjustment of the above UAV and was affected by the forward obstacle avoidance system of the UAV.

(**a**) Attitude adjustment points of EAVISION E-A202 at different speeds

(**b**) Attitude adjustment points of XAG P80 at different speeds

Figure 8. Side view of key points in profile ground flight.

According to the overall analysis on the profiling test data, the plant protection UAV should meet the following two requirements to exhibit better profiling operation ability: firstly, the obstacle sensing system of the plant protection UAV should be capable of sensing the change in obstacle height in advance within an appropriate distance; and secondly, the UAV flight control system should have high response speed, so that the UAV can make timely attitude adjustment at different flight speeds, and ensure the profiling performance of the plant protection UAV.

5. Discussion

Binocular vision technology can obtain more accurate depth information than monocular vision, and richer specific obstacle feature information than the radar. The laser radar and millimeter-wave radar would be more accurate in ranging accuracy measuring. In particular, the millimeter-wave radar can avoid the influence of meteorological condition, maintain high awareness under the condition of bad environment and enable plant protection UAVs to deal with complicated outdoor work environments, which also explains why millimeter-wave radar is more widely used than vision and laser radar.

However, some shortcomings of binocular vision technology were also reflected in the test of EAVISION E-A2021 plant protection UAV. It can be seen from the test results of the EAVISION obstacle avoidance experiment in Section 3 that in the process of obstacle size changing from large to small and speed changing from low to high, the obstacle recognition success rate of the EAVISION plant protection UAV decreased gradually, especially for tiny obstacles. Binocular vision technology could not accurately detect the characteristic information of obstacles or even perceive the existence of obstacles, which led to the operation safety risk of plant protection UAVs. Combined with the relevant analysis in the first subsection of this section, binocular vision technology increased the difficulty of obstacle feature recognition in the face of a series of inevitable factors such as light intensity and complex environmental interference, resulting in unstable performance of the recognition system and reduction in detection accuracy. The front dynamic millimeter-wave radar applied to XAG also presented unstable performance in the obstacle avoidance test. Although the millimeter-wave radar model could perceive the existence of obstacles in the face of small obstacles and ensure the operation safety of the plant protection UAV to a certain extent, its perceiving ability for the details of small obstacles was still insufficient, and the obstacle avoidance flight could not be completed.

Binocular vision and radar technology have their own advantages, but given the limitations of different aspects such as the sensor itself or the performance of the algorithm, single perception technology also exerts an adverse impact on the obstacle recognition system at the same time. According to the obstacle avoidance test in Section 3, merely relying on a single sensor could not fully perceive the effective characteristic information of obstacles, and the performance of the obstacle detection system was unstable, especially in the face of tiny obstacles. However, multi-sensor fusion technology can effectively integrate multiple identical or different sensors to achieve effective complementarity in performance, and obstacle features can be more comprehensively perceived based on a large amount of redundant and complementary information. As a result, multi-sensor fusion technology possesses certain advantages. In the test experiment, EAVISION E-A2021 adopted the method of multi-sensor fusion to realize the profiling operation of a plant protection UAV. According to the test results in Section 4, compared with the single millimeter-wave radar profiling system of the P80 plant protection UAV, EAVISION integrated the profiling module of millimeter-wave radar and lidar, and was therefore endowed with a larger sensing range and could more accurately perceive the relative height changes in obstacles. However, there were still some errors in both of the above two profiling technologies, whose real-time performance and accuracy were greatly reduced at high speed.

To sum up, for current obstacle perception technology, the perception system with a single technology cannot accurately perceive the obstacle characteristic information, and the stability and environmental adaptability of the perception system are poor. Moreover, the perception algorithm has disadvantages in the case of real-time performance and accuracy. To better satisfy the work needs of plant protection UAVs in complex environments and further improve the intelligence of plant protection UAVs, the following issues still need further exploration.

Firstly, there will be various meteorological conditions and simple or complex working environments in actual farmland working environments, which will cause problems such as image blur and noise for binocular vision technology and will bring considerable trouble to the processing and stereo matching of the algorithm. For radar point cloud information processing, noise interference in complex environments also causes difficulty with the algorithm. Therefore, the adaptability and accuracy of the algorithm should be improved to meet the information processing requirements under different environmental conditions, especially in complex environments. Conducting in-dept algorithm learning is a research direction of great value in improving perceptual accuracy.

Secondly, multi-sensor fusion technology can be used to fuse the richer information perception ability of binocular vision and millimeter-wave radar for obstacle detection in complex environments, which can meet the adaptability requirement under more complex environmental conditions. However, the diverse structural levels of multi-sensors will increase the complexity of the system. At the same time, multiple sensors will produce a large amount of information data mixed with different noise interference, which increases the amount of data processing. Therefore, the multi-sensor fusion system should be optimized as a whole.

Thirdly, the current binocular stereo matching algorithm, radar point cloud processing algorithm and multi-sensor fusion algorithm are all subject to relative contradiction between speed and accuracy. Generally speaking, the relative accuracy of the algorithm with good real-time performance will be reduced while improving the accuracy will correspondingly increase the amount of calculation, thus slowing down the real-time processing speed of the system. Therefore, a lot of research and verification are still needed on how to take into account the contradiction between performance and efficiency or find a relatively balanced fit between the two for the plant protection operation environment.

6. Conclusions

With their advantages of safety, environmental protection and no terrain restrictions, plant protection UAVs have gradually developed and been widely used. In order to cope with the complex operating environment of plant protection UAVs and ensure the operating safety and efficiency, obstacle avoidance and profiling technology of plant protection UAVs have become a hot research topic. In order to fully study current obstacle avoidance and profiling technology of plant protection UAVs and their practical application performance, obstacle avoidance and profiling experimental tests were designed in this paper for the three plant protection UAVs taking up the highest proportion on the market, and different obstacle identification technologies were combined for further analysis and verification, desiring to provide new vision for the research direction and hot spots related to obstacle avoidance and profiling technology of future plant protection UAVs.

In the obstacle avoidance test, the UAVs conducted obstacle avoidance tests at a speed of 2 m, 4 m and 6 m for simulated obstacles of different scales: large, medium and small. The analysis results show that the XAG P80 and the EAVISION E-A2021 plant protection UAVs witnessed a low success rate for high-speed operation and small obstacle avoidance of the millimeter-wave radar and binocular vision technology, and the performance of the two UAVs revealed the higher-level stability and safety performance of the millimeter-wave radar in obstacle avoidance.

At speeds of 1.5 and 3 m, the plant protection UAVs carried out profiling flights for obstacles at different heights. Comprehensive analysis shows that the XAG P80 relied on the lower millimeter-wave radar to complete the profiling test, but the reaction delay was too obvious. The EAVISION E-A2021 relied on the fusion of millimeter-wave radar and

LIDAR, which could perceive the relative height change in obstacles more accurately. In addition, multi-sensor fusion was proven to possess certain advantages over single sensors.

This paper mainly analyzed the main application performance of obstacle avoidance technology through analysis on obstacle avoidance and profiling of two mainstream plant protection UAVs, i.e., EAVISION E-A2021 and XAG P80. At the same time, it analyzed and studied the main technologies, compared and verified the above two parts of the content and comprehensively analyzed and proposed the future development prospects of plant protection UAV obstacle avoidance technology, aiming to provide a technical reference for the development of future plant protection UAVs. However, it is noteworthy that the simulation operation settings of the UAV test in this study are more stringent, and the actual application performance may be slightly different.

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