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A VISION–CONTROLLED TEST STAND FOR AUTONOMOUS HERBICIDE SPRAYING DRONES

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Abstract: This article presents the design, functionality, and future development directions of a laboratory test stand specifically built to simulate herbicide spraying operations performed by unmanned aerial vehicles (UAVs). As precision agriculture evolves, the need for controlled environments to evaluate UAV–based spraying systems has become critical for ensuring application accuracy, system reliability, and environmental safety. The proposed test stand is a modular, scalable platform that enables researchers to simulate the UAV spraying process under reproducible conditions. It includes a suspended drone mounting system, a motorized conveyor for target motion, and a vision–based detection and control system. The spraying actuation sequence is triggered based on real–time image processing using a ZED X stereo camera and processed by a ZED Box AI unit, with actuation commands managed through an Arduino microcontroller. Though actual herbicide was not applied in this testing phase, the full control and perception chain was successfully simulated and validated. The results confirm that the system is fully operational and capable of emulating key aspects of a UAV spraying mission—target detection, spray triggering, and data logging—without the complexity of field conditions. The platform offers excellent flexibility for integrating new technologies such as nozzle types, AI control algorithms, or canopy simulation modules. The discussion outlines multiple future enhancements, including wind field simulation, droplet spectrometry, multi–UAV coordination, and digital twin integration. As a research and training tool, the test stand can serve academia and industry in developing smarter, safer, and more efficient aerial application systems. In conclusion, the stand provides a robust foundation for testing herbicide spraying subsystems, bridging the gap between conceptual development and field readiness, while supporting sustainability and innovation in precision agriculture.
Keywords: Precision agriculture; UAV spraying; Laboratory simulation; Droplet analysis; Agricultural robotics

1. INTRODUCTION

The global shift toward sustainable agriculture and smart farming technologies has ushered in a new era of innovation in pesticide and herbicide application. Among these innovations, unmanned aerial vehicles (UAVs), commonly known as drones, have become increasingly prominent tools in precision agriculture. Their ability to perform low–altitude, high–precision spraying makes them highly effective for applying agrochemicals, especially in challenging terrains or smallholder farming systems where conventional ground machinery is either impractical or inefficient [1,2].

Recent studies have highlighted the critical role of spray deposition uniformity and droplet behavior in achieving effective and environmentally responsible weed control. Droplet size, distribution, and spray pattern directly influence herbicide efficacy, drift potential, and the impact on non–target vegetation [3,4]. Consequently, accurate assessment of UAV spray performance is paramount, not only for optimizing drone configurations but also for meeting regulatory standards. To ensure such precision, the deployment of dedicated test stands for herbicide spraying drones has become increasingly important.

Test stands—controlled experimental platforms for replicating aerial spraying operations—allow for the measurement of various spray characteristics in a consistent, reproducible environment. They bridge the gap between theoretical modeling, laboratory testing, and field implementation. These stands support a wide range of research goals, including nozzle optimization [9], variable–rate spraying validation [7], drift analysis [14], and spray deposition accuracy [5,6].

Droplet Deposition and Detection Methods

Numerous recent investigations have focused on quantifying spray droplet deposition using various sensors and analytical tools. The combination of chemical colorants and water–sensitive papers (WSPs) has proven to be a reliable method for mapping droplet distribution, particularly when corrected through fluorescence–based techniques [1]. These techniques provide enhanced sensitivity and visibility, enabling the detection of smaller droplets and more accurate estimates of herbicide coverage.

Advanced image processing methods, including artificial intelligence (AI)–based computer vision algorithms, are also being employed to assess spray quality on WSPs. These methods demonstrate a higher level of precision in detecting droplet boundaries and estimating droplet sizes compared to classical thresholding methods [2]. Furthermore, the influence of nozzle type, application rate, and environmental variables such as wind speed on droplet dispersion and coverage has been thoroughly documented [3,12,13].

In light of these factors, test stands play a vital role in isolating and controlling environmental variables, allowing researchers to evaluate the interplay between UAV parameters (e.g., altitude, speed, rotor–induced wind) and deposition performance. For instance, Lee et al. [5] examined how flight altitude and collector height affect spray deposition using food dye tracers and emphasized the need for consistent, calibrated conditions to interpret UAV spraying efficacy.

The Need for Controlled Testing Environments

Real–world agricultural settings present multiple uncontrollable variables—wind turbulence, crop canopy variability, and topographical differences—that can distort deposition outcomes. Test stands offer a solution by providing a semi–automated or fully controlled space in which UAV systems can be tested under simulated field conditions. Researchers such as Dai et al. [6] have developed online measurement systems for real–time monitoring of spray deposition, which can be integrated into these test stands to enable dynamic feedback and system calibration.

Moreover, canopy–related complexities such as porosity, volume, and leaf architecture further affect droplet penetration and deposition. Canopy–sensitive variable–rate spraying algorithms, tested in orchards [7,20], demonstrate the importance of fine–tuning drone spraying systems in accordance with plant morphology. Test stands that simulate crop canopies or allow for modular canopy setups can be instrumental in validating these algorithms and mechanical adaptations such as electrostatic spray enhancement [8,9,16].

Technological Innovations in UAV Spraying Systems

The evolution of UAV spraying systems has gone hand in hand with innovations in nozzle design, electrostatic charging, PWM (pulse–width modulation), and real–time environmental sensing. Zhang et al. [9] introduced a novel air–assisted electrostatic nozzle that enhances droplet attraction to the plant surface, increasing application efficiency and reducing drift. Similarly, PWM–controlled staggered–phase spray systems have been shown to reduce inhomogeneity in droplet distribution [17].

Test stands provide the optimal environment for testing these novel systems under controlled conditions. Spray distribution sensors, high–speed imaging, and automated data acquisition tools can be integrated into these platforms to yield comprehensive datasets on nozzle performance and droplet behavior. Researchers like Li et al. [18] and Jing & Wei [22] have proposed mechanized boom sprayers and canopy–opening devices for ground applications—many of which can inspire hybrid designs or complementary tools for UAV–based spraying systems.

Flight Dynamics and Spray Pattern Interaction

Flight parameters—including altitude, speed, and rotor–induced turbulence—significantly influence spray deposition characteristics. Liu et al. [19] developed a wind vortex control model for multirotor UAVs, which underscores the critical interaction between downwash effects and droplet trajectory. Other studies have modeled droplet movement in flat spray nozzles [15] and the impact of fluroxypyr drift on sensitive crops like soybeans [14], reinforcing the importance of understanding aerodynamic dynamics during spraying.

Test stands allow for these interactions to be observed and measured in a controlled environment using sensors, cameras, and tracer dyes. In particular, using stereo vision systems such as the ZED X camera enables 3D mapping of droplet clouds and airflow behavior. When integrated with onboard processors like the ZED Box and Arduino–based controllers, these platforms can simulate variable spraying conditions and evaluate the real–time response of the UAV system.

UAV Swarms and Collaborative Spraying

The advancement of UAV swarm technology—where multiple drones operate in formation—introduces new opportunities and challenges for precision spraying. Chen et al. [24] conducted preliminary evaluations of multiple UAVs in close formation spraying, revealing the complex interactions between overlapping downwash zones and droplet drift. Dedicated test stands offer a safe and measurable environment to explore these dynamics, allowing researchers to refine algorithms for cooperative navigation and synchronized spraying.

Toward Standardization and Regulatory Compliance

As UAV spraying becomes more prevalent, the need for standardized testing protocols and performance metrics becomes more pressing. Test stands can support the development of such standards by providing reproducible testing conditions and enabling cross–validation of results between different research teams and drone platforms.

Furthermore, these platforms can help identify safety thresholds and optimize herbicide application rates to minimize phytotoxicity risks, such as those observed in soybean crops exposed to drift [14]. With increasing regulatory scrutiny of pesticide use, demonstrating controlled and accurate deposition via validated test procedures is essential.

2. MATERIALS AND METHODS

Design Principles and Purpose of the Test Stand

The increasing reliance on unmanned aerial vehicles (UAVs) for herbicide application in precision agriculture calls for reliable methods to assess and calibrate spraying performance under controlled conditions. Field testing is often hindered by environmental variability, logistical constraints, and regulatory limitations. In response, a dedicated laboratory test stand was conceived as a scalable, modular infrastructure for simulating aerial spraying conditions.

The primary purpose of this stand is not to replicate all aspects of field spraying, but rather to create a controlled, flexible, and reproducible environment where hardware components, control algorithms, and detection systems can be verified, compared, and refined prior to field deployment. The test stand is also intended to support educational and demonstration activities, providing a tangible framework for training engineers, agronomists, and students in UAV spraying technologies. The stand serves as a development and integration platform, offering a space where engineering and agronomic research intersect. Key functions envisioned include:

- Evaluation of real–time spray actuation mechanisms;
- Validation of vision–based detection and triggering systems;
- Compatibility testing with different nozzle types and UAV configurations;
- Benchmarking of system performance for further optimization.

Structural Components of the Test Stand

The stand is built around a robust aluminum frame with an approximate footprint of 3.0×2.5 meters and a height clearance of up to 3 meters. It is structured to support the following modular systems:

- Drone Suspension and Positioning System: A hydraulic lift table provides vertical adjustability for mounting UAVs at fixed heights, simulating various spraying altitudes. This system allows for easy manual or remote adjustment of the UAV platform, maintaining positional stability during simulated spraying.
- Target Transport System: A motorized chain conveyor runs along the length of the test platform. It is designed to carry potted plants or artificial targets through the UAV's spray zone at constant,

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configurable speeds (default: 33 m/min). This mechanism simulates relative movement between drone and crops during actual flight operations, without requiring the UAV to fly indoors.

— Interchangeable Target Surfaces: The stand accommodates multiple types of targets:

≡ Live potted plants for simulating natural canopy;

≡ Panels with water–sensitive paper (WSP) for future spray visualization;

≡ Custom trays for potential granular material or seed collection (applicable to other subsystems).

— Support Infrastructure: The frame includes attachment rails for lights, cameras, sensors, and side barriers to reduce external airflow and improve reproducibility.

Actuation and Control System

At the heart of the stand is an integrated control and perception system designed to simulate the complete detection–decision–actuation pipeline of an autonomous spraying drone. This system replicates the essential logic of an autonomous spraying UAV, where visual input triggers a responsive actuation within milliseconds. Importantly, all systems are mounted statically for now, but are compatible with drone integration for future testing. The main elements include:

— ZED X Stereo Camera (Stereolabs): This high–performance RGB–D camera provides real–time 3D perception, used for plant or target detection. It offers millimeter–scale depth resolution and a wide field of view, making it suitable for canopy detection, height estimation, and obstacle avoidance logic prototyping.

— ZED Box AI Processing Unit: Serving as the central onboard computer, the ZED Box handles image acquisition and analysis using embedded deep learning models or custom algorithms. Its computational power allows it to simulate in–flight decisions such as object classification, distance estimation, and spray triggering.

— Arduino UNO Microcontroller: Acting as the low–level interface between the processing unit and actuation hardware, the Arduino board receives commands via serial connection and controls the 12V stainless steel electrovalves, enabling precise activation of the spray nozzle.

— Liquid Spraying System: Although not used in real spraying tests for this article, the nozzle system includes standard agricultural flat–fan nozzles connected to a small–capacity pressurized tank. The electrovalve controls liquid flow, and nozzle characteristics (angle, flow rate) can be easily swapped for different configurations.

Simulated Functionality and Workflow

While no actual spraying or deposition measurements were performed in this phase, the stand was fully set up to simulate the operational sequence of a UAV herbicide–spraying mission. This simulated functionality offers a safe and replicable method to evaluate the software–hardware interaction, latency, and logic correctness of the spraying system. The workflow is as follows:

— Target detection: The ZED X stereo camera scans the conveyor path and identifies the presence of a plant or pre–defined marker using 3D image processing.

— Trigger logic: Based on detection parameters (e.g., object height, area, or spatial coordinates), the ZED Box sends a command to the Arduino UNO to activate the spray system.

— Actuation event: The electrovalve is activated for a preset duration (e.g., 2 seconds), mimicking the UAV's spray burst over the detected target.

— Data logging: The system can be configured to record image frames before, during, and after actuation, which would support future droplet analysis using NI Vision Builder AI or custom Python scripts.

Software Architecture and Analytical Tools

Data is saved in structured formats (CSV, JSON) and can be analyzed using spreadsheet tools or statistical software. The platform also allows for integration with MATLAB or LabVIEW for advanced automation or feedback control development. The software architecture of the test stand includes:

— ZED SDK for camera calibration, depth map processing, and real–time object tracking;

— Custom Python scripts for command parsing, image capture, and parameter logging;
— Arduino IDE with C++ routines for electrovalve and servo control;
— NI Vision Builder AI for future integration of droplet detection workflows on water–sensitive paper.

Current Limitations and Modular Upgrade Potential

Although the test stand is fully functional in simulating herbicide spray triggering, several enhancements are proposed to expand its research capabilities:

— Wind and Downwash Simulation: Integrating variable–speed fans to emulate rotor–induced turbulence and crosswind scenarios would allow testing of drift control algorithms.
— Rotational Targeting System: Adding a tilting platform for target plants could help assess performance on sloped or non–horizontal surfaces, simulating real crop topography.
— Multi–UAV Synchronization Module: Expanding the platform for coordinated testing of two or more UAVs could facilitate swarm spraying studies and collision avoidance testing.
— Real–Time Droplet Sensing: Incorporating inline droplet sensors (e.g., laser diffraction or imaging–based spectrometry) could allow instant feedback on spray quality and volume.
— Wireless Communication Testing: Simulating field conditions where drone–ground communication is intermittent could help evaluate system resilience and autonomous fallback behavior.

The modular nature of the stand ensures that these upgrades can be implemented without overhauling the core infrastructure.

3. RESULTS

The implementation of the modular test stand demonstrated the feasibility of simulating UAV–based herbicide application processes under laboratory conditions. Although no quantitative spraying trials were performed at this stage, a comprehensive functional evaluation of the stand's architecture, control logic, and system integration was carried out.

Initial verification confirmed the compatibility between the ZED X stereo vision system and the target detection tasks required for autonomous spraying scenarios. The camera successfully captured depth information and recognized three–dimensional structures resembling plant canopies. The ZED Box processing unit, configured with custom detection algorithms, responded consistently to the presence of targets and generated actuation commands in real time.

The actuation chain—from visual recognition to electro valve triggering—functioned as intended. The Arduino–based control board demonstrated reliable execution of spray commands, with low latency and consistent behavior across multiple simulated runs. Although liquid flow was not activated for safety reasons during this phase, the electro valve and nozzle assembly were mechanically and electronically validated, confirming readiness for future experimental deployment.

The conveyor system, designed to simulate relative motion between drone and crop, operated at a stable, repeatable speed. This allowed for the synchronized passage of target pots through the spray zone and validated the system's ability to maintain a realistic flight–ground dynamic without requiring actual UAV flight indoors.

The structural design of the test stand also proved to be mechanically robust and flexible. Its modular frame supported interchangeable target surfaces, and the adjustable drone suspension mechanism allowed for precise height calibration. These elements create favorable conditions for future testing under variable configurations (nozzle types, actuation timings, target geometries).

Importantly, the platform demonstrated high interoperability among its hardware and software components. The integration of commercial vision systems (ZED X), open–source microcontrollers (Arduino), and proprietary image analysis software (NI Vision Builder) enabled a scalable and cost–effective experimental infrastructure.

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In terms of usability, the system was found to be easy to operate and reconfigure, requiring minimal time to adjust between test setups. This user–friendly aspect is essential for supporting rapid iteration in future development cycles, especially when evaluating alternative nozzle designs, actuation mechanisms, or AI–based spray control strategies.

Though experimental metrics such as droplet coverage, density, or drift were not collected, the stand's current capabilities demonstrate strong potential for supporting such measurements in upcoming phases. The simulated workflows—target detection, control signal generation, actuation triggering, and image acquisition—were all validated and ready to be paired with data acquisition tools in the next research stages.

Collectively, the results of this functional assessment confirm that the test stand fulfills its intended purpose: providing a safe, controlled, and adaptable environment for validating key subsystems involved in drone–based herbicide application. It establishes a solid foundation for future experimental research, performance benchmarking, and design optimization of intelligent agricultural UAVs.

In order to simulate realistic herbicide application scenarios in the laboratory environment, two major crops—maize and sunflower—were selected as reference models. These crops are representative for large–scale farming in Eastern Europe and are often associated with intensive phytosanitary interventions. To recreate biologically plausible conditions within the test stand, artificial plant pots were used to mimic the crop structure at specific phenological stages.

As a foundation for system calibration and future experimental validation, estimated treatment calendars were compiled based on agronomic practice. These include standard timings for herbicide application, phytosanitary interventions, and solid fertilization, structured according to the growth stages of each crop. The information serves as both a technical reference and a guideline for defining test conditions on the motorized conveyor stand.

The tables below provide an overview of the agronomic timelines for maize and sunflower, highlighting critical intervention points from sowing to maturity. These data were used to inform the selection of relevant growth stages (30– and 60–days post–sowing), at which drone spraying simulations were conceptually planned.

By aligning test conditions with real–world crop management schedules, the platform ensures that future UAV spraying scenarios can be evaluated in a meaningful, crop–specific context. This approach also supports the development of adaptive spraying algorithms that take into account crop phenology, canopy density, and operational timing for optimized treatment delivery.

This contextual information is essential not only for simulating crop conditions but also for evaluating the timing and suitability of UAV interventions under dynamic field conditions. By referencing phenological development, the system can be adjusted to account for differences in canopy height, leaf structure, and potential pest or weed pressure. These parameters influence droplet retention, spray drift, and penetration, making them critical variables in the design of spraying strategies. Ultimately, aligning test stand operations with actual agricultural timelines increases the relevance and transferability of future results, bridging the gap between laboratory testing and practical field implementation.

4. ESTIMATED TREATMENT, HERBICIDE, AND FERTILIZATION SCHEDULE

The experimental testing of the intelligent systems will be carried out on the laboratory test stand equipped with a motorized conveyor and artificial potted plants representing corn and sunflower crops. The first two systems will be evaluated at two phenological stages (30 and 60 days). Each system was assessed at three conveyor travel speeds, with three repetitions per speed:

- V1 = 6,17 m/min
- V2 = 6,93 m/min
- V3 = 7,82 m/min

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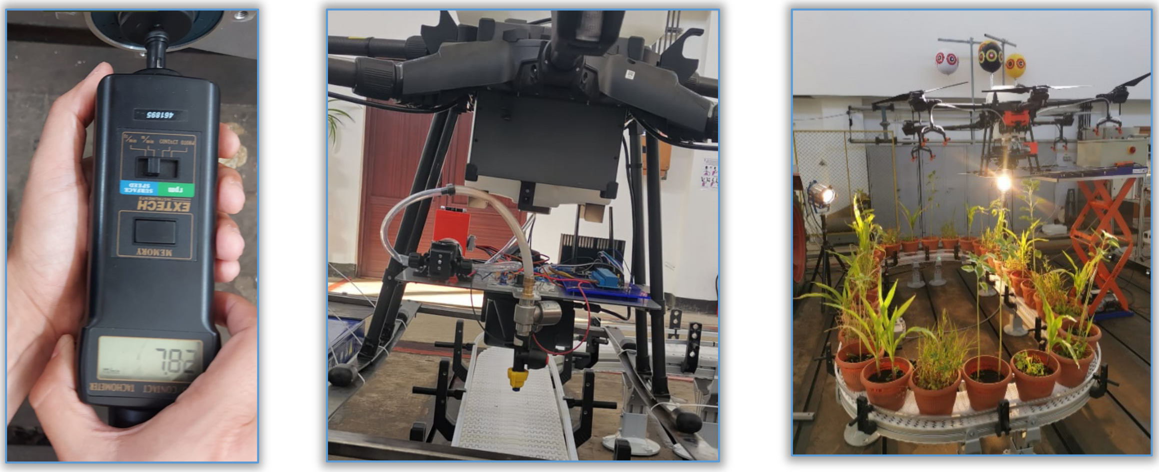
Table 1 Maize – Estimated Schedule

Time from Sowing	Growth Stage	Phytosanitary Treatments	Herbicides	Solid Fertilization (NPK)
0 days (sowing)	—	Seed treatment (fungicide + insecticide)	Pre–emergent: S–metolachlor, terbuthylazine	NPK 15:15:15 – 200–300 kg/ha in soil
10–15 days	Emergence (BBCH 09)	Pest monitoring	Weed monitoring	—
20–30 days	2–4 leaves (BBCH 12–14)	Insecticide (wireworm, if present)	Post–emergent: nicosulfuron, dicamba	Ammonium nitrate – 100 kg/ha
30–45 days	5–8 leaves (BBCH 15–18)	Fungicide (Helminthosporium, if present)	Corrective (persistent perennial weeds)	Urea – 100 kg/ha (optional)
50–60 days	Tasseling – Flowering	Insecticide (European corn borer), Fungicide	No more herbicide applications	—
80–100 days	Grain filling – Maturity	Monitoring; generally, no treatments	—	—

1.1. Table 2. Sunflower – Estimated Schedule

Time from Sowing	Growth Stage	Phytosanitary Treatments	Herbicides	Solid Fertilization (NPK)
0 days (sowing)	—	Seed treatment (fungicide + insecticide)	Pre–emergent: pendimethalin, acetochlor	NPK 16:16:16 – 200 kg/ha
10–15 days	Emergence (BBCH 09)	Downy mildew monitoring	Weed monitoring	—
20–30 days	2–4 leaves (BBCH 12–14)	Insecticide (wireworm, if present)	Post–emergent: imazamox (Clearfield), tribenuron–methyl (ExpressSun)	Ammonium sulfate – 80–100 kg/ha
30–45 days	6–8 leaves (BBCH 16–18)	Fungicide (Alternaria, Phoma, downy mildew)	Corrective for persistent weeds	—
50–60 days	Bud – Flowering (BBCH 50–65)	Insecticide (Helicoverpa); Fungicide	No more herbicide applications	—
70–90 days	Seed filling – Maturity	Monitoring	—	—



a) b) c)

Figure 1. Preparation of the systems and test stand for laboratory testing and system calibration

5. DISCUSSION

As precision agriculture technologies advance, there is an increasing need for reliable, adaptable platforms that allow controlled testing and development of unmanned aerial spraying systems. The current test stand offers a functional basis for simulating UAV–based herbicide application under laboratory conditions, but several opportunities for improvement and expansion have been identified to support broader research, innovation, and pre–commercial validation.

One of the most significant future developments involves the integration of environmental simulation capabilities. Replicating the effects of wind, turbulence, and drone rotor downwash is essential for understanding how droplet behavior is altered in real operating conditions. The installation of axial fans and controlled airflow generators within the stand would allow for reproducible wind field experiments. Similarly, controlling temperature and humidity could help researchers evaluate how climatic variables influence droplet evaporation, drift, and canopy penetration.

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In parallel, the introduction of a modular canopy simulation platform would greatly enhance the biological realism of testing scenarios. Adjustable artificial vegetation structures could be used to simulate crop–specific conditions such as height variation, leaf density, and canopy porosity. This would allow the platform to evaluate how herbicide deposition is influenced by different plant morphologies, paving the way for crop–specific UAV spray system optimization.
To increase measurement accuracy and diagnostic capability, advanced droplet characterization technologies are also being considered. The integration of laser diffraction sensors, high–speed imaging systems, and fluorescence–based imaging techniques would enable real–time or near–real–time assessment of droplet size distribution, spray plume geometry, and surface coverage. These tools would complement traditional methods based on water–sensitive paper and provide a richer dataset for analysis and modeling.
Another promising direction involves enabling the test stand to support multi–UAV scenarios. As swarm spraying becomes more viable in large–scale farming operations, there is a growing need to understand drone coordination, overlap management, and collision avoidance strategies. The test stand could be upgraded to host multiple UAVs, each with independent vision and control systems, allowing for studies on cooperative spraying, inter–drone communication, and distributed control architectures.
Automation and artificial intelligence integration represent additional frontiers for stand enhancement. Automating the target movement system, data acquisition routines, and analysis workflows would allow for continuous operation and reduce manual intervention. Machine learning models could be trained to detect anomalies in spray patterns, predict system faults, or recommend nozzle configurations based on specific canopy features. Coupling the physical test stand with digital twin environments would enable hybrid experimentation and accelerated development cycles.
In terms of long–term applicability and scalability, the stand is designed to accommodate various UAV sizes and spraying mechanisms. Its modular construction allows it to be reconfigured or extended with minimal effort. Moreover, sustainability is an integral consideration in the stand's evolution, with emphasis on energy–efficient components, biodegradable testing materials, and design for disassembly and reuse.
Beyond its technical value, the test stand holds potential as a national or international research infrastructure. It can support collaborative projects with universities, research institutes, and private industry. It may also be used to develop standardized testing protocols, contribute to regulatory certification efforts, and serve as a training tool for students and agricultural professionals exploring drone–based technologies.
The test stand thus functions not only as a research asset, but also as a bridge between experimental development and real–world deployment of intelligent spraying systems. Its future development directions reflect both the challenges and the aspirations of modern agriculture: to be more efficient, more targeted, and more sustainable in every input delivered to the field.

6. CONCLUSIONS

The development of a modular and multifunctional test stand for UAV–based herbicide spraying represents a significant step toward bridging the gap between laboratory research and real–world agricultural applications. Designed with adaptability and scalability in mind, the platform enables controlled simulation of aerial spraying processes, facilitating the testing of perception systems, actuation mechanisms, and control algorithms without the constraints imposed by field conditions. While the stand has not yet been used for quantitative spraying tests, its architecture supports the integration of advanced sensing technologies and real–time control frameworks. This provides a versatile environment for iterative development, prototyping, and future experimentation. By focusing on the functional behavior of the spraying subsystem—particularly the detection–

actuation cycle—the stand serves as a valuable tool for evaluating UAV performance under reproducible conditions.

The emphasis on modularity ensures that the stand can evolve in line with emerging research needs. From wind simulation and canopy modeling to droplet spectrometry and multi–agent coordination, a wide range of enhancements are already envisioned. These future directions underscore the stand's potential as a dynamic, open–ended research platform capable of supporting innovation in precision agriculture.

Beyond its technical role, the stand also has strategic value as a hub for interdisciplinary collaboration, education, and technology transfer. As agriculture increasingly adopts robotic and data–driven solutions, such infrastructures will be essential in ensuring the safe, efficient, and effective integration of UAV systems into mainstream crop protection practices.

In conclusion, the presented test stand is not an endpoint, but a foundation—one that can support the continuous advancement of intelligent spraying technologies while contributing to the broader goals of sustainability, productivity, and environmental stewardship in modern agriculture.

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