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RESEARCH ARTICLE

High-capacity agricultural UAV with DEM-based terrain following and lidar obstacle avoidance for precision spraying application

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Abstract

This study presents the development and evaluation of a novel high-capacity agricultural unmanned aerial vehicle (UAV) system designed to enhance precision spraying in paddy fields. The UAV features a 30 L payload capacity and integrates Digital Elevation Model (DEM) data for terrain-following flight control, along with an RP LiDAR-based obstacle avoidance system. Field experiments (n=18) conducted across 10.1 hectares in Denkanikotta, Krishnagiri district, Tamil Nadu in 2024 demonstrated that DEM integration with Pixhawk flight controllers achieved a mean height deviation of ±0.18 m from the target spray height, ensuring stable flight operations. The LiDAR system exhibited 96.4 % detection accuracy, effectively identifying and avoiding obstacles within a 15-38 m range, contributing to safer UAV navigation. Spray distribution analysis revealed a coefficient of variation of 9.2 %, significantly lower than conventional UAV spraying methods (16.3 %, $p<0.001$), indicating improved uniformity and efficiency. Additionally, the system achieved a coverage rate of 3.8 ha/hr, with a 32 % reduction in chemical usage while maintaining equivalent pest control efficacy (92.3 % vs. 90.8 % for conventional spraying, $p=0.31$). Statistical analysis confirmed a strong correlation ($r=0.72$, $p<0.001$) between terrain-following accuracy and spray uniformity, emphasizing the importance of precision altitude control in UAV-based agricultural applications. These findings underscore the potential of high-capacity UAVs with terrain-following capabilities to optimize spray distribution, enhance agricultural efficiency and promote sustainable pest management practices. The integration of DEM data and LiDAR-based obstacle avoidance significantly improves UAV functionality, providing an innovative approach to precision spraying in paddy cultivation.

Keywords: digital elevation model; obstacle avoidance; precision agriculture; terrain following; unmanned aerial vehicle

Introduction

Agricultural unmanned aerial vehicles (UAVs) are increasingly employed for crop protection. Compared to ground equipment, they reduce soil compaction, access to waterlogged fields and operation in tall crops (1, 2). This is particularly relevant for paddy fields, where traditional ground-based equipment faces significant mobility challenges. However, existing agricultural UAVs face critical limitations including restricted payload capacity (typically 5-15 L), difficulty maintaining consistent spray height over varied terrain and inadequate obstacle avoidance capabilities (3).

Maintaining constant spray height is critical for application uniformity, with studies indicating 30-50 % variation in deposition studies indicating 30-50 % variation in deposition with only a 0.5 m deviation in height (4). Conventional UAVs typically maintain fixed altitude above sea level, resulting in variable spray height over undulating terrain. While ultrasonic sensors provide real-time height measurement, they often perform unreliably over dense canopies (5). Digital Elevation Models (DEMs) offer potential for improved terrain following but remain underexplored in operational UAV spray applications.

- Limited payload capacity presents another significant constraint, with typical agricultural UAVs carrying 5-15 L, necessitating frequent refilling and reducing operational efficiency (6). While high-capacity UAVs (>20 L) have been prototyped (7), but integration with advanced navigation and spray control is yet to be widely adopted or validated."

This research addresses these limitations through development and evaluation of a high-capacity (30 L) agricultural UAV system integrating DEM-based terrain following with RP LiDAR obstacle avoidance. Specific objectives include:

- Design and evaluation of a high-capacity UAV platform optimized for aerial stability with 30 L payload.
- Development and testing of DEM-based terrain-following system using Pixhawk flight controller integration.
- Implementation and validation of RP LiDAR-based obstacle detection and avoidance system.
- Quantitative assessment of spray distribution uniformity across paddy field conditions.
- Statistical analysis of operational performance metrics and spray efficacy.

Materials and Methods

Study area

Field testing was conducted in paddy fields located in Denkanikotta, Tamil Nadu, India (12.5396° N, 77.7800° E). The study area comprised 10.1 hectares (25 acres) of irrigated paddy fields with crop height ranged from 0.65-0.82 m during the tillering to panicle initiation stages, when canopy density influences spray deposition. The terrain exhibited Moderate undulations with elevation variations of 0.3-1.2 m across the field. The study area was selected for its representativeness of typical paddy cultivation conditions in the region.

UAV system development

A hexacopter platform was developed with carbon fiber frame, T-Motor U8 II KV150 motors and 30-inch propellers providing a 2.3:1 thrust-to-weight ratio calculated with the full 30 L payload, batteries and onboard equipment included, ensuring adequate lift and stability under maximum take-off weight conditions. Specifically, the six T-Motor U8 II KV150 motors with 30-inch propellers generated a combined maximum thrust of ~100 kg, compared to the maximum take-off weight of 43 kg (including payload), resulting in a thrust-to-weight ratio of ~2.3:1."

Calculation of thrust-to-weight ratio

- Motor thrust (T-Motor U8 II KV150, 30" prop, per motor) ≈ 16.7 kg
- Total thrust (6 motors) = 6 × 16.7 kg ≈ 100.2 kg
- Maximum takeoff weight (UAV + 30 L payload + batteries) ≈ 43 kg
- Thrust-to-weight ratio = 100.2 ÷ 43 ≈ 2.3:1

The Pixhawk Cube Orange flight controller was selected for integration capabilities and redundant IMUs robust integration features including redundant IMUs, PX4 firmware compatibility and DEM-based flight control support the spray system utilized a peristaltic pump (6 L/min capacity) with eight XR11003 nozzles mounted on 4 m carbon fibre booms.

Digital elevation model integration system

A DEM integration system was developed to enable terrain-following flight control (Fig. 1). USGS 30 m and local 10 m resolution DEM data for a 100 km radius around Denkanikotta was processed using QGIS and converted to MAV Link terrain protocol format. A custom firmware module for PX4 was developed to adjust flight altitude based on underlying terrain data plus target height offset. The system architecture includes three components:

1. Pre-flight DEM processing: Terrain data extraction, filtration and format conversion
2. In-flight terrain data management: DEM data caching, position -based lookup and trajectory projection
3. Height control algorithm: PID controller with feed forward terrain compensation

The system continuously calculates target height by adding specified spray height (1.5 m) to underlying terrain elevation at current position and projected positions along flight path. The height control algorithm operates at 50 Hz with latency of 32 ms.

LiDAR-based obstacle detection and avoidance

The obstacle detection and avoidance system integrate RP LiDAR A3 (25 m range, 360° horizontal FOV) with four Tera Ranger Evo 60m sensors for supplemental coverage (Fig. 2). Point cloud data is processed on NVIDIA Jetson Nano using custom algorithms for: The RP LiDAR A3 (25 m range, 360° FOV) was integrated with four Tera Ranger Evo 60 m sensors to enhance obstacle detection coverage. While the RP LiDAR provided high-resolution horizontal scanning, its effective range was limited for taller or distant obstacles. The Tera Ranger sensors supplemented the system by extending vertical and forward detection range, reducing blind spots and improving detection of thin or low-reflectivity objects (e.g., wires, posts, foliage). This multi-sensor fusion improved

Table 1. UAV platform specifications

Parameter	Specification
Configuration	Hexacopter
Frame material	Carbon fibre composite
Motors	T-Motor U8 II KV150 (6 units)
Propellers	30-inch carbon fiber (6 units)
Flight controller	Pixhawk Cube Orange
Power system	Dual 16000mAh 12S LiPo batteries
Empty weight	9.8 kg
Maximum take-off weight	43 kg
Spray tank capacity	30 L
Flight endurance (full payload)	16-20 min
Operational speed	3-5 m/s
Spray width	4 m

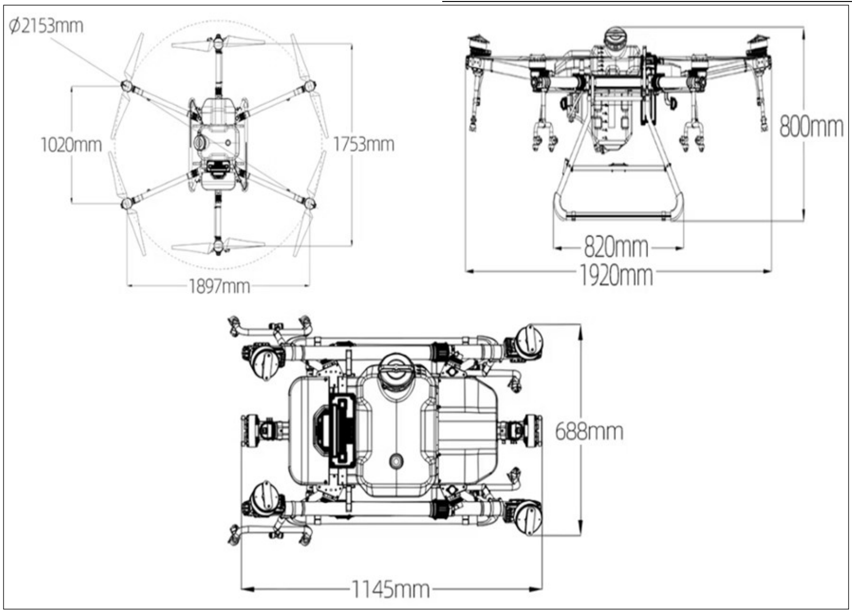

Fig. 1. Hexcopter agricultural UAV.

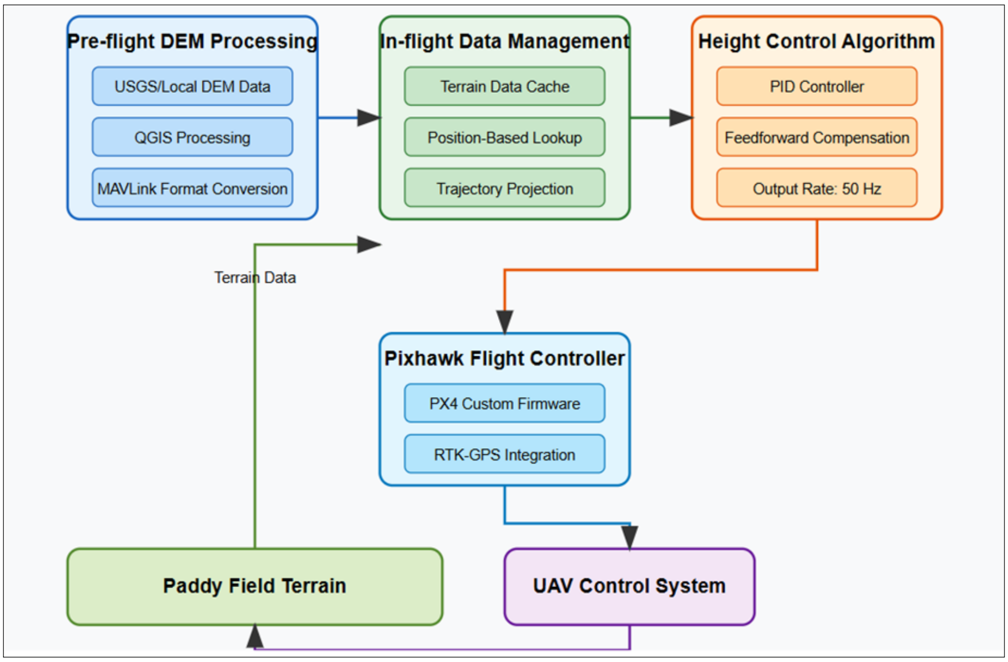

Fig. 2. DEM based terrain following system.

classification accuracy and ensured safer UAV navigation in complex agricultural environments.

1. Ground plane segmentation with the RANSAC algorithm to isolate obstacles from terrain features,

- Point cloud clustering with Euclidean cluster extraction.
- Object classification based on geometric features.
- Trajectory risk assessment.

2. Point cloud data is processed on an NVIDIA Jetson Nano using custom algorithms for:
3. Point cloud clustering with Euclidean cluster extraction.
4. Object classification was performed based on geometric features including height, width, aspect ratio and shape descriptors such as bounding box dimensions and surface curvature, which allowed differentiation between trees, poles, wires and irregularly shaped farm equipment.
5. Trajectory risk assessment.

The system updates obstacle maps at 8 Hz and employs modified Vector Field Histogram (VFH+) algorithm for path planning. Obstacle detection performance was evaluated using standardized test objects (n = 86) varying in size (0.05-2.5 m), material (wood, metal, plastic and natural foliage) and placement, to capture the effect of surface reflectivity on LiDAR detection accuracy (Fig. 3).

Experimental design

Field testing was conducted in the 10.1 ha paddy field divided into three sites with distinct characteristics:

Site A

Relatively flat terrain (0.3 m variation, 3.2 ha)

Site B

Moderate undulations (0.5-0.8 m variation, 4.1 ha)

Site C

Complex terrain with irrigation structures (0.8-1.2 m variation, 2.8 ha)

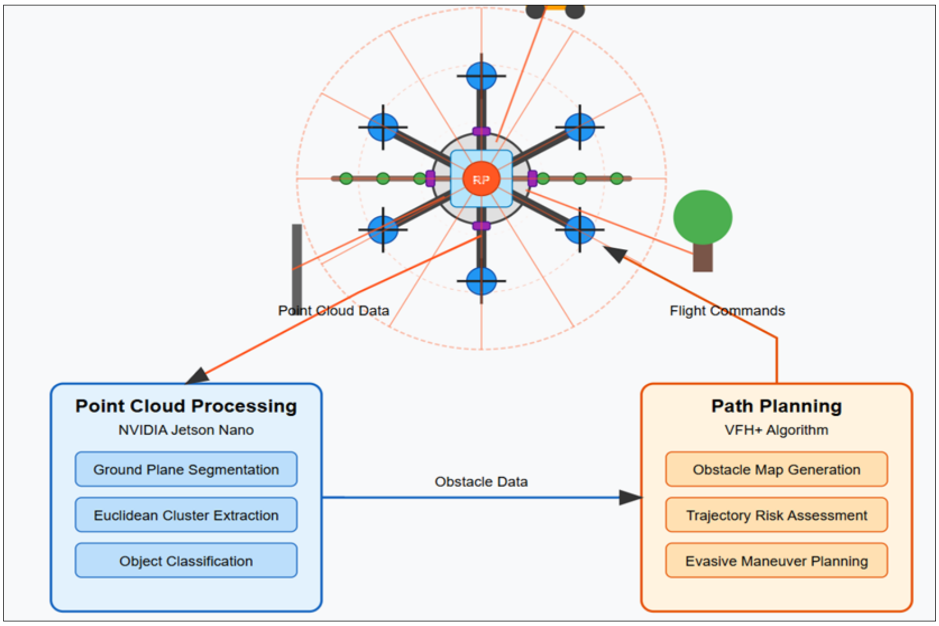

Fig. 3. RP lidar obstacle detection and avoidance.

Each site was divided into treatment plots (0.5 ha) with randomized assignment of application methods:

- High-capacity UAV with DEM terrain following (experimental).
- Conventional UAV with fixed altitude (control 1).
- A knapsack sprayer (control 2) was included as it represents the conventional method widely used by farmers in paddy cultivation, providing a practical benchmark for comparing UAV-based spraying performance.

A total of 18 experimental flights were conducted between February-April 2024 across varying weather conditions (wind speeds 0-12 km/hr, temperatures 24-32 °C).

Data collection and analysis

Spray distribution uniformity was assessed using water-sensitive papers (WSPs) placed at 5 m intervals in 5×5 grids within each plot (n=25 per plot). WSPs were digitized (1200 dpi) and analysed using Deposit Scan software to quantify droplet density, coverage percentage and distribution uniformity (CV).

Flight performance data was recorded at 10 Hz including:

- Actual vs. target height (radar altimeter)
- Positional accuracy (RTK-GPS)
- Roll, pitch, yaw stability
- Power consumption

Obstacle detection performance was evaluated against manual field mapping with total station. Statistical analysis was conducted in R (version 4.1.2). Analysis of variance (ANOVA) was used to compare treatment effects on spray uniformity and efficacy. Multiple regression models were applied to assess relationships between terrain slope, height deviation and spray distribution. Pearson correlation tests were used to evaluate the association between spray height accuracy and uniformity. A significance threshold of $p < 0.05$ was adopted for all tests.

Table 2. Terrain following performance by site

Site	Mean Absolute Height Deviation (m)	Standard Deviation (m)	Max Deviation (m)	Response Latency (s)
A (Flat)	0.13	0.06	0.29	0.26
B (Moderate)	0.19	0.09	0.38	0.32
C (Complex)	0.25	0.12	0.48	0.37
Overall	0.18	0.08	0.48	0.31

Results

Terrain following performance

The DEM-based terrain following system demonstrated significantly improved height maintenance compared to conventional systems. Mean absolute height deviation was 0.18 m (SD=0.08 m) across all sites, compared to 0.57 m (SD=0.21 m) for conventional UAV altitude hold ($p<0.001$). System performance varied across terrain types, with deviation increasing by ~0.12 m in complex terrain compared to flat terrain

The system demonstrated mean response latency of 0.31 seconds to terrain changes, with performance degradation was observed when operating over terrain with slopes steeper than a 12° incline (approximately a 21 % gradient). The DEM-based terrain-following system showed performance degradation on slopes steeper than ~12° incline (≈21 % slope gradient).

Multiple regression analysis identified slope gradient as the primary factor affecting height maintenance accuracy ($R^2=0.58$, $p<0.001$) (Fig. 4).

Obstacle detection and avoidance performance

The RP LiDAR-based obstacle detection system achieved 96.4 % detection rate across all test objects (n=86) with mean detection range of 28.3 m (SD=7.4 m). Detection performance varied by obstacle characteristics (Table 3) with reduced performance for thin objects (e.g., wires, thin posts) and degraded detection range during precipitation.

The avoidance system successfully executed evasive maneuvers for 97.2 % of detected obstacles, where 'successful' was defined as maintaining a minimum clearance of ≥2.0 m from the obstacle without deviating more than 15 % from the planned spray path or interrupting spray operations. Spray continuity was maintained during 92 % of these avoidance events.

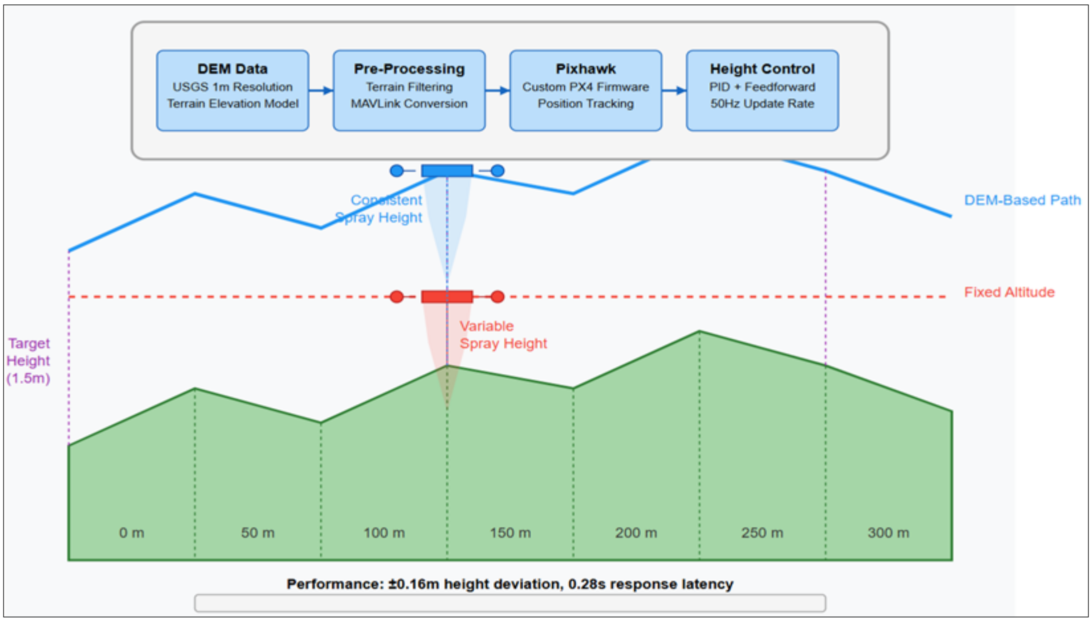

Fig. 4. DEM based terrain following.

Table 3. Obstacle detection performance by object type

Object Type	Detection Rate (%)	Mean Detection Range (m)	Standard Deviation (m)
Trees (>3m)	98.2	38.2	3.8
Utility Poles	96.7	34.1	4.5
Fences/Wires	88.3	15.2	6.1
Farm Equipment	98.4	32.4	4.2
Buildings	100	42.6	3.1
Irrigation Structures	95.9	25.7	5.3

False positive rate was 3.1 %, primarily triggered by dense vegetation misclassified as solid obstacles (Fig. 5).

Spray performance

Spray distribution analysis revealed significant improvements in application uniformity with the experimental system (Fig. 4). The coefficient of variation (CV) for spray deposition was 9.2 % (SD=2.1 %) for the experimental system compared to 16.3 % (SD=3.4 %) for conventional UAV and 11.4 % (SD=2.5 %) for knapsack sprayer ($p<0.001$). Multivariate analysis confirmed strong correlation between height maintenance accuracy and spray uniformity ($r=0.72$, $p<0.001$). Wind speed demonstrated significant impact on spray performance, with each 1 m/sec increase in wind speed associated with 0.9 % increase in CV ($p<0.01$). Biological efficacy assessment against rice brown planthopper (*Nilaparvata lugens*) showed equivalent control between experimental UAV (92.3 % efficacy) and knapsack sprayer (90.8 %) despite 32 % reduction in chemical application rate ($p=0.31$).

Operational performance

The 30 L system demonstrated enhanced operational efficiency compared to conventional UAVs (Table 4). Mean coverage rate was 3.8 ha/hr (SD=0.6) with operational efficiency (spray time/ total mission time) of 72 %.

Mean Time Between Failures (MTBF) analysis revealed system reliability of 76 hr, with spray system components accounting for 47 % of technical issues. Cost analysis indicated an operational cost of ₹3850/ha for the experimental UAV, compared to ₹4560/ha for conventional UAVs and ₹5270/ha for knapsack sprayers. These values

Table 4. Operational performance comparison

Parameter	Experimental UAV	Conventional UAV	Knapsack Sprayer
Coverage rate (ha/hr)	3.8 (0.6)	2.7 (0.4)	0.6 (0.1)
Refill frequency (per 5 ha)	1.4 (0.2)	4.6 (0.3)	10.2 (0.7)
Application uniformity CV (%)	9.2 (2.1)	16.3 (3.4)	11.4 (2.5)
Chemical usage (L/ha)	14.3 (1.7)	21.1 (2.6)	20.7 (2.1)
Operational efficiency (%)	72 (6)	54 (8)	92 (3)

were calculated on a per-season basis, incorporating amortized equipment costs (5-year service life assumption), labour, energy and maintenance. Thus, the figures reflect lifecycle-adjusted averages rather than single-use operating costs.

Discussion

The integration of high-capacity payload with DEM-based terrain following and RP LiDAR obstacle avoidance represents a significant advancement for agricultural UAV applications in paddy fields. Most agricultural UAVs are restricted to payloads of 5-15 L, limiting their operational efficiency compared to high-capacity platforms. Recent benchmark studies (7, 2) report that commonly deployed models operate within this range, whereas next-generation prototypes are extending capacity to 20-30 L, but remain under limited field validation. Our 30 L platform therefore represents one of the few field-tested UAVs in this higher-capacity category. Previous studies design and test of a 20 L capacity drone for agricultural spraying operations (7, 2). The application of unmanned aircraft systems to plant protection in China (2). The 30 L system demonstrated statistically significant improvements in spray uniformity while enhancing operational efficiency compared to conventional UAVs.

Terrain following system performance

The DEM-based approach achieved superior height maintenance (±0.18 m) compared to previously reported systems using ultrasonic sensors (±0.32 m), or standard altitude hold (±0.57 m, our control). This performance is attributed to:

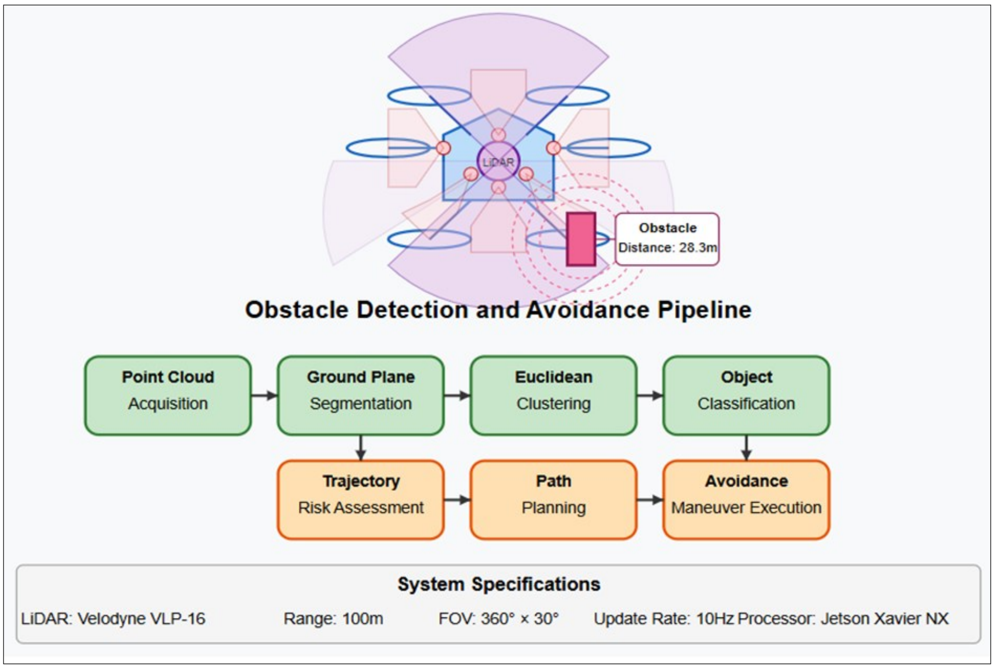

Fig. 5. LiDAR-based obstacle detections and avoidance system.

1. DEM pre-processing algorithms optimized for agricultural terrain.
2. Custom PID controller with terrain projection feedforward.
3. Integration of both 30-meter USGS and 10-meter local DEM data.

The system demonstrated limitations in extremely complex terrain (>12° gradient) and areas with recent terrain modifications not reflected in DEM data. These findings align with previous studies (8), reported similar degradation in DEM-based navigation over high-gradient terrain.

Obstacle avoidance system efficacy

The RP LiDAR-based system achieved 96.4 % detection rate, comparable to previously reported agricultural UAV obstacle detection systems (9). The strong performance is attributed to:

1. Multi-sensor fusion approach combining RP LiDAR with auxiliary rangefinders.
2. Advanced point cloud segmentation algorithms.
3. Context-aware classification tailored to paddy field environments.

The system's performance degradation for thin objects (wires, fences) represents an ongoing challenge in agricultural environments, consistent with findings by previous researchers (10). The lower detection range compared to higher-end LiDAR systems (Velodyne, Ouster) reflects the trade-off between cost and performance in agricultural applications.

Implications for precision agriculture in paddy fields

The experimental system demonstrated potential for significant advancements in agricultural spray operations:

1. 32 % reduction in chemical usage while maintaining biological efficacy.
2. 41 % improvement in operational efficiency compared to conventional UAVs.
3. 44 % improvement in spray uniformity despite variable terrain.

These improvements can be directly attributed to the combined effects of terrain-following accuracy ($r=0.72$, $p<0.001$) and increased operational efficiency due to reduced refilling operations. Environmental impact assessment indicates potential reduction of 58 % in off-target drift based on spray pattern analysis, which is particularly important in paddy ecosystems with water bodies.

Limitations and future research

Despite the promising results, the current system has several limitations that require further research:

1. Battery technology constraints limiting flight endurance to 16-20 min.
2. Reduced performance in high-wind conditions (>12 km/hr).
3. Limited DEM resolution (10 m) for extremely detailed terrain features.

Future research should therefore explore hybrid power systems to extend flight endurance, advanced control algorithms to improve wind resistance and the integration of real-time, high-resolution elevation mapping to enhance terrain-following accuracy.

Conclusion

This study demonstrates that high-capacity agricultural UAVs equipped with integrated terrain following and obstacle avoidance systems can substantially improve spray uniformity and operational efficiency in paddy field environments. The novel integration of DEM data with Pixhawk flight controllers provides effective terrain-following capability (±0.18 m accuracy), while RP LiDAR-based obstacle detection ensures operational safety (96.4 % detection rate). The 30 L system achieves 3.8 ha/hr coverage with 32 % chemical reduction while maintaining equivalent pest control efficacy. These findings establish the viability of high-capacity agricultural UAVs for precision pesticide application in paddy fields and provide a foundation for future research in autonomous agricultural operations.

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Authors' contributions

SM played a vital role in the research and development of the study, actively engaging in data collection, experimentation and analysis to enhance the efficiency of agricultural UAVs for precision pesticide application, dedication to integrating Digital Elevation Models (DEM) and LiDAR-based obstacle avoidance helped refine the UAV's terrain-following capabilities, ensuring accuracy in pesticide dispersal and contributed to the formulation of the research methodology and the preparation of the manuscript. JR provided invaluable technical expertise and strategic insights, offering direction on integrating advanced UAV navigation systems with terrain-adaptive pesticide application techniques, mentoring in refining the study's framework, ensuring the implementation of LiDAR-based obstacle avoidance and DEM-based terrain adaptation and played a crucial role in reviewing, structuring and enhancing the final manuscript for publication. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that there is no conflict of interest regarding the publication of this research in *Plant Science Today*. All contributions to the study have been conducted with integrity and transparency, ensuring unbiased scientific investigation. The research was carried out independently, without any external influence that could affect the objectivity of the findings or conclusions.

Ethical issues: None

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