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Evaluating stability and range performance of precision agri-drone spraying systems

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Abstract

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are revolutionizing precision agriculture by enhancing critical operations such as crop monitoring, pesticide spraying, and field mapping. This study focuses on evaluating the performance of a UAV-based spraying system, leveraging flight logs to assess key parameters including battery usage, navigation accuracy, environmental impact, and overall system health. The trial was conducted at a farmer's field near Kanchipuram District, Tamil Nadu, during the Rabi season of 2024, providing real-world insights into the system's operational efficiency under typical agricultural conditions. The results highlight the UAV's exceptional performance, particularly in terms of altitude control, positional consistency, and environmental adaptability. The system demonstrated precise altitude control, with a Root Mean Square Error (RMSE) of 0.195 meters, and maintained minimal deviation from the target altitude, as indicated by an Altitude Stability Index of 1.95%. Furthermore, the UAV exhibited high positional consistency, achieving a Range Consistency Index of 0.583%, which underscores its ability to maintain a stable flight path during spraying operations. Environmental factors such as wind speed were also evaluated, with the UAV showing strong resistance to wind interference. At a wind speed of 5 meters per second, the system recorded only a 0.031-meter variation in altitude, highlighting its robustness in challenging conditions. Additionally, the UAV maintained stable hover performance, with a minor horizontal drift of 5 meters over a 10-second interval. Landing accuracy was another key metric, with the UAV achieving a precision margin of ± 0.5 meters, further emphasizing its reliability. These findings underscore the UAV's potential to enhance precision agriculture by offering a reliable, efficient, and environmentally adaptable solution for crop spraying and monitoring. The study provides valuable insights for optimizing UAV performance in agricultural applications, particularly, where precision farming can significantly improve crop yields and resource efficiency.

Keywords: Flight logs, EKF, UAV stability, altitude, range, navigation

Introduction

Agriculture is the backbone of global food security, and with the ever-increasing population, the demand for sustainable and efficient farming practices has never been more critical. Traditional agricultural methods, while effective in the past, are increasingly challenged by issues such as labour shortages, resource inefficiency, and environmental degradation. In this context, precision agriculture has emerged as a transformative approach, leveraging advanced technologies to optimize crop production while minimizing environmental impact. Among these technologies, Unmanned Aerial Vehicles (UAVs), or drones, have gained significant attention for their ability to enhance precision farming practices, particularly in crop monitoring, spraying, and mapping (Zhang and Kovacs 2012) ^[12]. This study focuses on evaluating the stability and range performance of precision agri-drone spraying systems, with a specific emphasis on their operational efficiency and reliability in real-world agricultural settings.

The adoption of UAVs in agriculture has been driven by their ability to perform tasks with high precision, efficiency, and minimal human intervention. Unlike traditional ground-based machinery, drones can access difficult terrains, reduce chemical usage, and provide real-time data for decision-making (Shafi *et al.*, 2019) ^[7]. Spraying pesticides and fertilizers using drones has become particularly popular due to its potential to reduce chemical wastage, improve coverage, and minimize human exposure to harmful substances. However, the effectiveness of drone-based spraying systems depends heavily on their stability, navigation accuracy, and ability

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to withstand environmental factors such as wind and temperature variations (Xiongkui *et al.*, 2017) ^[10]. These factors directly influence the uniformity of chemical distribution, which is critical for achieving optimal crop protection and yield.

One of the key challenges in deploying UAVs for agricultural spraying is ensuring stable flight performance under varying environmental conditions. Stability, in this context, refers to the drone's ability to maintain a consistent altitude, position, and orientation during flight. This is particularly important for spraying applications, as even minor deviations can lead to uneven chemical distribution, resulting in over-application in some areas and under-application in others (Giles & Billing, 2015) ^[4]. Range performance, on the other hand, refers to the drone's ability to cover a specified area efficiently while maintaining operational parameters such as battery life and payload capacity. Both stability and range performance are critical for ensuring the economic viability and environmental sustainability of drone-based spraying systems.

Recent advancements in UAV technology have led to significant improvements in flight stability and range performance. Modern drones are equipped with advanced sensors, GPS modules, and autonomous navigation systems that enable precise control over flight parameters (Torres-Sánchez *et al.*, 2015) ^[9]. For instance, real-time kinematic (RTK) GPS systems provide centimeter-level positioning accuracy, while inertial measurement units (IMUs) ensure stable flight even in windy conditions. Additionally, advancements in battery technology have extended the flight duration of drones, allowing them to cover larger areas in a single mission (Yallappa *et al.*, 2017) ^[11]. Despite these advancements, there is a lack of comprehensive studies evaluating

Materials and Methods

Experimental Setup and UAV Specifications

The study was conducted at a farmer's field near Kanchipuram District, Tamil Nadu, during the Rabi season of 2024. The UAV used in this study was a hexacopter equipped with advanced flight control systems and precision spraying payloads. The key specifications of the UAV are as follows:

- **Frame:** Enhanced Frame Technology (EFT)
- **Motors:** Hobbywing X6 Hexacopter Motors
- **Payload Capacity:** 10 kg
- **Battery:** Tattu and Grepow 22Ah LiPo, 6S configuration (two modules)
- **Battery Voltage:** 50V nominal, dropping to 44V after 1-acre coverage
- **Endurance:** 7 to 8 minutes per flight
- **Speed:** 5.2 m/s
- **Flight Mode:** Autonomous flight controlled via ArduPilot
- **Autopilot:** Pixhawk Cube Orange

The UAV was equipped with a real-time kinematic (RTK) GPS module, an inertial measurement unit (IMU), and a barometer for precise altitude and position control. The spraying system included a 10-liter tank and a precision nozzle for uniform chemical distribution.

I. Flight Log Collection and Analysis

Flight logs were collected from multiple UAV missions conducted during the Rabi season. These logs contained detailed data on GPS coordinates, altitude, battery voltage, speed, sensor performance, and operational status. The analysis was conducted in the following steps:

1. Collection of Flight Logs

Flight logs were obtained from UAV missions focused on precision spraying tasks. Each log included timestamped data on altitude, position, battery status, and environmental conditions.

2. Segmentation of Flight Phases

Each flight was divided into distinct phases: take-off, navigation, spraying, hovering, and landing. This segmentation allowed for a detailed analysis of UAV performance during each operational stage.

3. Analysis of Flight Parameters

Key metrics such as battery consumption, GPS accuracy, altitude stability, wind resistance, and spraying consistency were evaluated for each flight phase.

II. Flight Stability Analysis

Flight stability was assessed using two primary metrics: altitude stability and range consistency.

1. Altitude Stability Evaluation

• Root Mean Square Error (RMSE)

The RMSE was calculated to quantify the deviation between the target altitude (10 meters) and the actual altitude maintained by the UAV. The formula used was:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (H_{target} - H_{actual})^2}$$

• Altitude Stability Index (ASI)

The ASI was calculated as:

$$ASI = \left(\frac{RMSE}{H_{target}} \right) \times 100$$

2. Wind Influence on Altitude

The impact of wind on altitude was evaluated using the following formula:

$$\Delta h = \frac{F_{wind} \cdot g \cdot t^2}{m}$$

Where:

$$F_{wind} = 0.5 \cdot C_d \cdot \rho \cdot A \cdot v_{wind}^2$$

$$C_d = 1.2, \quad \rho = 1.225 \text{ [kg/m}^3\text{]},$$

$$A = 0.5 \text{ m}^2, \quad v_{wind} = 5 \text{ m/s}$$

$$m = 24 \text{ kg}, \quad g = 9.81 \text{ [m/s}^2\text{]}, \quad t = 2 \text{ s}$$

III. Range Performance Evaluation

Range performance was assessed using the following metrics:

1. Range Error

The range error was calculated using the Euclidean distance formula:

$$R_{error} = \sqrt{(X_{target} - X_{actual})^2 + (Y_{target} - Y_{actual})^2}$$

2. Range Consistency Index (RCI)

The RCI was calculated as:

$$RCI = \left(\frac{\text{Mean Range Error}}{\text{Target Range}} \right) \times 100$$

IV. Ground Stability Metrics

1. Horizontal Drift During Hover

The horizontal drift was calculated as:

Formula

$$D_{\text{drift}} = V_g \cdot \cos(\phi) \cdot t$$

Where:

$$V_g = 0.5 \text{ m/s}, \quad \phi = 0^\circ, \quad t = 10 \text{ s}$$

$$D_{\text{drift}} = 0.5 \cdot \cos(0^\circ) \cdot 10 = 5 \text{ m}$$

Meaning: The UAV drifts horizontally by 5 meters in a 10-second hover under mild wind. Tuning the PID controller can further improve stability.

2. Landing Accuracy

The UAV demonstrated a landing deviation of ± 0.5 meters, reflecting strong positional control during descent.

V. Battery Performance Analysis

Battery performance was evaluated using the energy consumption model:

$$E = V \times I \times t$$

Where:

- $V=50 \text{ V}$ (nominal voltage)
- $I=44 \text{ Ah}$ (total battery capacity)
- $t=420 \text{ s}$ (flight time)

The energy consumption per meter was calculated as:

$$\text{Energy per meter} = 264 \text{ Wh}/2184, \quad m=0.121 \text{ Wh/m}$$

VI. Extended Kalman Filter (EKF) Analysis

The EKF was used for state estimation during autonomous flights. The algorithm combined data from the IMU, GPS, and barometer to estimate the UAV's position, velocity, and altitude. The EKF status was evaluated using flight log data, with key parameters including altitude deviation (< 0.2 meters), position error (0.518 meters), and velocity consistency ($< 0.5 \text{ m/s}$).

VII. Statistical and Mathematical Tools

All calculations and analyses were performed using Python and MATLAB. Statistical tools such as RMSE and RCI were used to quantify performance metrics, while the EKF algorithm was implemented using Ardu Pilot's open-source libraries.

Results

EKF Error Evaluation and Performance Analysis

The performance of the Extended Kalman Filter (EKF) was evaluated using log data from the UAV mission. The results demonstrate the EKF's effectiveness in maintaining accurate altitude, position, velocity, and battery consumption estimates.

Altitude Monitoring

The EKF successfully monitored altitude with minimal error. The maximum altitude deviation observed during the mission was 0.2 meters, calculated as the difference between the target altitude (10 meters) and the measured altitude (9.8 meters). This

deviation is within acceptable limits, indicating robust altitude tracking (Fig 1). Similar findings have been reported in studies evaluating EKF performance in UAV altitude control, where deviations below 0.5 meters are considered acceptable for precision agriculture applications (Smith *et al.*, 2020)^[8].



Fig 1: 3D Flight Path Trajectory (Altitude & Range) illustrates the UAV's flight path and altitude consistency.

Position Tracking (GPS-based)

The EKF integrated data from the GPS, accelerometer, and magnetometer to track horizontal position. For a target position of (3640, 0) meters, the actual GPS position at the mission's end was (3640.5, 0.2) meters. The position error, calculated using the Euclidean distance formula, was 0.518 meters. This error margin confirms the EKF's reliability in maintaining accurate positional data. Comparable results have been observed in UAV navigation systems, where EKF-based GPS integration achieves sub-meter accuracy in horizontal positioning (Johnson & Lee, 2019)^[5].

Velocity Monitoring

The velocity was consistently maintained at 5.2 m/s, with minor fluctuations attributed to air resistance and control adjustments. The EKF effectively compensated for external disturbances, as evidenced by the velocity error remaining below 0.5 m/s throughout the mission (Fig 2). This aligns with previous research demonstrating the EKF's ability to mitigate velocity drift in dynamic environments (Zhang *et al.*, 2021)^[13].



Fig 2: Velocity dDP highlights the velocity stability and minor fluctuations.

Battery Usage:

The EKF dynamically estimated battery consumption based on voltage readings and an energy model (Fig 3). At the mission's conclusion, the battery voltage dropped to 44V, corresponding to a total energy consumption of 968 Wh (calculated as $44\text{V} \times 22\text{Ah}$). This demonstrates the EKF's capability to accurately predict power usage. Such energy estimation models are critical

for optimizing UAV mission planning and ensuring operational efficiency (Brown *et al.*, 2018)^[2].



Fig 3: Battery Voltage and Current Graph (Without payload) demonstrates the battery consumption trend.

EKF Status Indicators

The EKF status flags indicated stable performance during the mission:

1. **EKF 3D Position:** Green (valid).
2. **EKF Horizontal Position:** Green.
3. **EKF Vertical Position:** Yellow (minor drift).
4. **EKF Velocity:** Green (stable).

These indicators confirm that the EKF operated within acceptable limits, with only minor vertical drift observed. Similar status-based evaluations have been used in UAV systems to ensure real-time monitoring and fault detection (Garcia *et al.*, 2022 and Bogue, 2019)^[3, 1].

Altitude Stability and Wind Resistance

The UAV exhibited exceptional altitude stability, with a Root Mean Square Error (RMSE) of 0.195 meters and an Altitude Stability Index (ASI) of 1.95%. These metrics indicate minimal deviation from the target altitude, showcasing robust altitude control. Under a wind speed of 5 m/s, the UAV maintained strong wind resistance, with an altitude variation of only 0.031 meters. Such performance is critical for precision agriculture applications, where stable altitude control is necessary for accurate data collection and operations (Smith *et al.*, 2020)^[8].

Range Performance and Positional Consistency

The UAV achieved a range error of 5.83 meters over a 1-kilometer flight, resulting in a Range Consistency Index (RCI) of 0.583%. This highlights the UAV's high positional consistency during flight. During hovering, the UAV showed minor horizontal drift, moving 5 meters over a 10-second period, while maintaining precise landing accuracy within a margin of ± 0.5 meters. These results align with studies emphasizing the importance of range accuracy and landing precision in agricultural UAVs (Johnson & Lee, 2019)^[5].

Battery Performance and Energy Efficiency

Battery performance analysis revealed an energy consumption of 264 Wh for 1-acre coverage, with an energy consumption rate of 0.121 Wh per meter. This demonstrates the UAV's energy efficiency, which is essential for extended mission durations in large-scale agricultural operations. Comparable energy consumption rates have been reported in UAVs optimized for precision agriculture (Brown *et al.*, 2018)^[2].

EKF Performance in Flight Stability

The Extended Kalman Filter (EKF) ensured stable flight performance, with an altitude deviation of 0.2 meters, a position error of 0.518 meters, and velocity consistency maintained below 0.5 m/s. These metrics confirm the EKF's effectiveness in compensating for external disturbances and maintaining flight stability. Similar findings have been reported in studies evaluating EKF-based navigation systems for UAVs (Zhang *et al.*, 2021)^[13].

Discussion

The results demonstrate the UAV's exceptional performance in precision agriculture applications. The low RMSE and ASI values indicate excellent altitude stability, while the RCI highlights strong positional consistency. The UAV's ability to maintain stable flight under wind influence and achieve precise landing accuracy further underscores its reliability. The EKF's role in ensuring accurate state estimation is critical for autonomous operations, as evidenced by the minimal deviations in altitude, position, and velocity. These findings suggest that the UAV is well-suited for precision spraying tasks, with potential for further optimization in battery usage and flight path planning.

Conclusion

This study evaluated the stability and range performance of a precision agri-drone spraying system using flight logs and EKF analysis. The UAV demonstrated excellent altitude control, wind resistance, and positional accuracy, making it a reliable tool for precision agriculture. Future work will focus on optimizing battery performance and flight paths to extend mission durations and improve operational efficiency.

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