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(Research Article)

Design and simulation of a pesticide spraying quadcopter

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Abstract

Conventional agricultural spraying exposes farmers to significant health hazards and often produces non-uniform chemical application. This creates an urgent need for safer, automated solutions. Although unmanned aerial vehicles (UAVs) offer a practical alternative, many pesticide-spraying drones lack rigorously tested flight-control designs and rely on empirical gain tuning. This study presents the modelling, simulation, and performance evaluation of a pesticide-spraying quadcopter using a cascaded proportional-integral-derivative (PID) architecture. A high-fidelity six-degree-of-freedom (6-DOF) dynamic model based on Newton-Euler formulation was developed in MATLAB/Simulink. Unlike standard static models, this framework incorporates a time-varying payload to represent the dynamic discharge of pesticides. A hierarchical PID structure was implemented with an inner-loop attitude stabilizer and an outer-loop position-altitude controller. Results indicate robust stabilization with attitude settling times below 0.35 s. Furthermore, the system maintained smooth altitude tracking without overshoot during significant payload mass reduction. The developed framework provides a reliable baseline for autonomous implementation, reducing the risks and costs associated with physical prototyping. The study's primary novelty lies in the systematic validation of cascaded control laws specifically under the influence of continuous mass depletion, a critical factor for precision agricultural missions.

Keywords: UAV Spraying; 6-DOF Dynamics; Newton-Euler Model; Cascaded PID Control; MATLAB/Simulink

1. Introduction

Agriculture remains a cornerstone of global food security for a continually growing population. However, crop productivity is persistently challenged by pests and diseases, making pesticide application indispensable for protecting yields [1]. In many developing regions, this process is still dominated by manual knapsack spraying [2]. While accessible, manual methods are labor-intensive and expose farmers to severe health risks, including respiratory and neurological disorders [3]. Beyond the human cost, manual application often results in non-uniform coverage and chemical wastage, leading to unintended environmental contamination and avoidable yield losses through crop trampling [4].

To address these challenges, the agricultural sector is shifting toward "smart farming" and precision-agriculture technologies. Unmanned Aerial Vehicles (UAVs), particularly quadcopters, are attractive for these missions due to their vertical take-off and landing capability, hover stability, and fine maneuverability [5]. By integrating spray tanks and nozzles onto multi-rotor airframes, these systems improve operator safety and operational efficiency by removing personnel from the spray plume and allowing for targeted application over complex field geometries [6], [7].

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Despite these advantages, the performance of many agricultural drones is limited by insufficiently validated flight-control designs. Most existing prototypes rely on empirical "black-box" tuning or vendor-specific controllers that do not account for the unique dynamics of spraying operations [8]. A critical factor often ignored in standard models is the time-varying nature of the payload. As pesticide is discharged, the vehicle's mass, inertia, and thrust-to-weight ratio shift continuously. Failure to capture these dynamics can lead to degraded tracking or instability during low-altitude flight, where precision is most vital for uniform deposition [9].

Against this background, this study presents the design and simulation of a pesticide-spraying quadcopter. The research focuses on developing a validated flight-control baseline by representing quadcopter dynamics through a high-fidelity 6-DOF rigid-body model. The primary contribution of this work is the implementation of a cascaded PID architecture that is systematically tuned to compensate for real-time mass reduction. This provides a reusable engineering framework that bridges the gap between conceptual design and safe physical prototyping.

2. Literature review

The transition from manual knapsack spraying to automated aerial application has progressed from basic prototype construction toward more performance-oriented and control-aware designs. Recent literature shows that the spray performance of agricultural UAVs is strongly affected by operational parameters such as flight height, travel speed, payload mass, spray pressure, droplet size, and ambient wind conditions [7], [10]. In particular, operational parameter studies have reported that deposition and drift behavior vary significantly with altitude and wind velocity, while payload depletion during spraying can alter flight dynamics and reduce stability if not properly modeled [7], [9]. Reviews of unmanned aerial spraying systems further show that multi-rotor UAVs are increasingly used for precision spraying in complex agricultural environments because they can improve resource efficiency and reduce operator exposure [11], [12]. However, the literature also indicates that many agricultural spraying platforms still emphasize mechanical integration and spray-system assembly more than rigorous validation of flight-control laws under realistic mission conditions [13], [14].

2.1. Analysis of Observed Control and Modelling Strategies

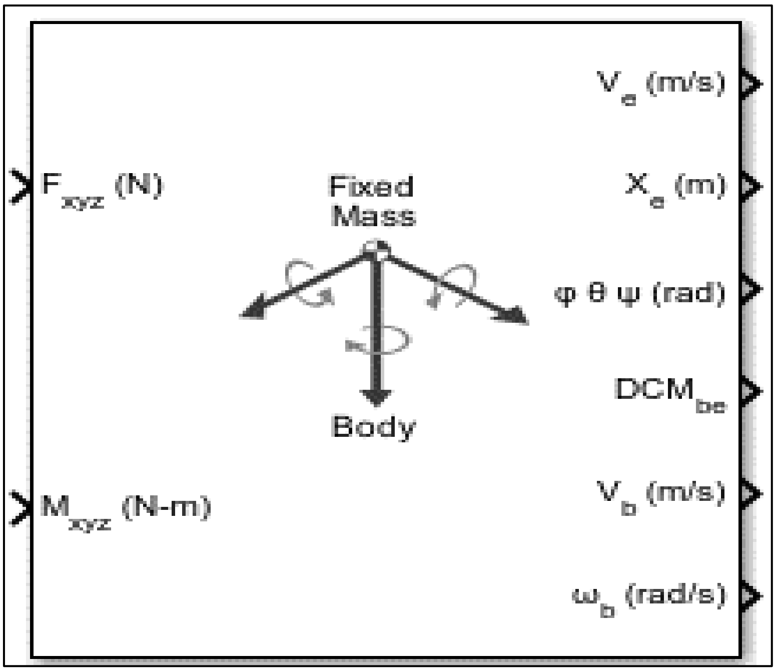
A significant divergence exists between academic flight-control research and practical agricultural drone implementation. Advanced control strategies such as adaptive and sliding-mode-based methods have been proposed to improve robustness under external disturbances, including wind gusts and changing payloads [8]. Recent work on agricultural spraying UAVs explicitly identifies variable payload, inertial coefficient variation, and wind disturbances as major challenges to control performance [8]. At the same time, broader reviews of spraying UAV modelling and control note that altitude selection, flight speed, and environmental conditions strongly influence droplet deposition, drift, and overall spray quality [9], [15]. Consequently, variable-rate spraying and spray-distribution-based control strategies have gained attention as practical approaches for improving application accuracy and operational efficiency [16], [17]. In parallel, the continuous depletion of pesticide or herbicide liquid introduces time-varying mass and inertia effects that must be considered in controller design [8], [15]. This is especially important during low-altitude flight, where uniform deposition is most sensitive to trajectory tracking errors and environmental disturbances [7], [8]. Recent control-oriented studies therefore move beyond purely empirical tuning by incorporating dynamic payload effects and spray-specific constraints into the UAV model [8], [16]. These developments suggest that future agricultural spraying platforms should combine mechanical reliability with validated control laws that explicitly account for payload reduction, flight height, wind speed, and spray-distribution requirements [9], [17].

3. Methodology

A model-based design (MBD) approach was adopted, utilizing the MATLAB/Simulink environment to develop a virtual prototype. The study was executed in seven distinct stages: system definition, selection of physical parameters, derivation of the nonlinear 6-DOF model, design of the cascaded control architecture, systematic gain tuning via linearization, scenario-based simulation, and quantitative performance evaluation.

3.1. Mathematical Modelling Of The Quadcopter Plant

The quadcopter was modelled as a rigid body with six degrees of freedom. Two coordinate frames were established: an Earth-fixed Inertial Frame (F_i) for translational tracking and a Body-fixed Frame (F_b) for torque and force generation as indicated in Fig. 1.



(Source: MathWorks, 2024, "6DOF (Euler Angles)")

Figure 1 Representation of the inertial (earth-fixed) and body reference frames used in the 6-DOF quadcopter model

3.1.1. Kinematic Transformation

To relate the body-frame angular velocities (p, q, r), to the rate of change of the Euler angles (ϕ, Θ, Ψ), a transformation matrix (W) was derived:

$$\begin{bmatrix} \phi \\ \Theta \\ \Psi \end{bmatrix} = \begin{bmatrix} 1 \, sin\phi tan\Theta \, cos\phi tan\Theta \\ 0 \quad cos\phi \qquad -sin\Theta \\ 0 \, sin\phi sec\Theta \, cos\phi sec\Theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad ...(1)$$

This kinematic relationship ensured accurate orientation tracking, though the simulation was constrained to avoid the gimbal lock singularity near

3.1.2. Dynamic Governing Equations

The translational accelerations in the inertial frame $(\ddot{x}, \ddot{y}, \ddot{z})$ were calculated by rotating the total thrust (U_1) and accounting for gravity (g):

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \frac{1}{m} R(\phi, \theta, \psi) \begin{bmatrix} 0 \\ 0 \\ -U_1 \end{bmatrix} \quad ...(2)$$

where, R is the rotation matrix from body to inertial frame.

The rotational dynamics were defined by Euler's rigid-body equations, capturing the torque inputs (U_2, U_3, U_4) and gyroscopic effects:

$$\dot{\omega} = I^{-1}[\tau - \omega \times (I\omega)] \quad ...(3)$$

where,

$$I = diag(I_{xx}, I_{yy}, I_{zz}) \quad ...(4)$$

represented the diagonal inertia matrix.

3.1.3. Simulation Parameters

To provide a high-fidelity representation of an industrial spraying drone, the physical constants listed in Table 1 were implemented in the MATLAB workspace.

Table 1 Mechanical and Aerodynamic Parameters

Parameter	Symbol	Value	Unit
Frame Mass	m_{frame}	6.0	kg
Arm Length	L	0.35	m
Roll/Pitch Inertia	I_{xx}, I_{yy}	0.25	kg·m^2
Yaw Inertia	I_{zz}	0.45	kg·m^2
Thrust Coefficient	k_t	6.0×10^{-5}	N·s^2/rad^2
Drag Coefficient	k_d	1.5×10^{-6}	N·m·s^2/rad^2

3.2. Cascaded PID control design

The control system was designed using a hierarchical structure to exploit time-scale separation.

Inner Loop (Fast): Three independent PID controllers regulated the attitude ((ϕ, Θ, Ψ)) to provide rapid stabilization. These were tuned to achieve a settling time of $\approx$ 0.30s

Outer Loop (Slow): Controlled the altitude (z) and position (x, y). The altitude PID computed the total thrust (U_1) required to maintain height, while the position controller outputted the desired roll and pitch angles to facilitate translational movement.

3.2.1. Dynamic Payload and Mixer Logic

The spraying operation was modelled as a continuous mass reduction process. The payload mass (m_p) was updated at each time step based on the simulated flow rate (Q):

$$\dot{m}_p(t) = -\rho Q \quad ...(5)$$

where, ρ was the pesticide density. A mixer matrix was then utilized to map the generalized control inputs $(U_1...U_4)$ to the four individual rotor speeds $(\omega_1...\omega_4)$, ensuring the plant received rotor-level actuation commands consistent with the 'X' configuration geometry.

4. Results and discussion

This section presents the results obtained from the high-fidelity MATLAB/Simulink simulation of the pesticide-spraying quadcopter. It provides a comprehensive analysis of the system's performance under the developed cascaded PID control architecture, ensuring an accurate evaluation of flight stability, thrust response, and payload-dependent dynamics during the pesticide discharge cycle.

4.1. Altitude Tracking Performance

The quadcopter was commanded to ascend to a target altitude of 50 m to evaluate the vertical tracking capability of the outer-loop PID controller. As shown in Fig. 2, the altitude response exhibited a rapid ascent with a rise time (T_r) of approximately 2.1s. The controller achieved smooth convergence to the setpoint with a settling time (T_s) of 3.0s and a steady-state error (E_{ss}) of 0m. Notably, the response was critically damped with 0% overshoot. This is a vital characteristic for pesticide spraying, as any vertical oscillation or overshoot could lead to inconsistent spray heights, resulting in non-uniform chemical deposition and increased drift sensitivity [8], [10].

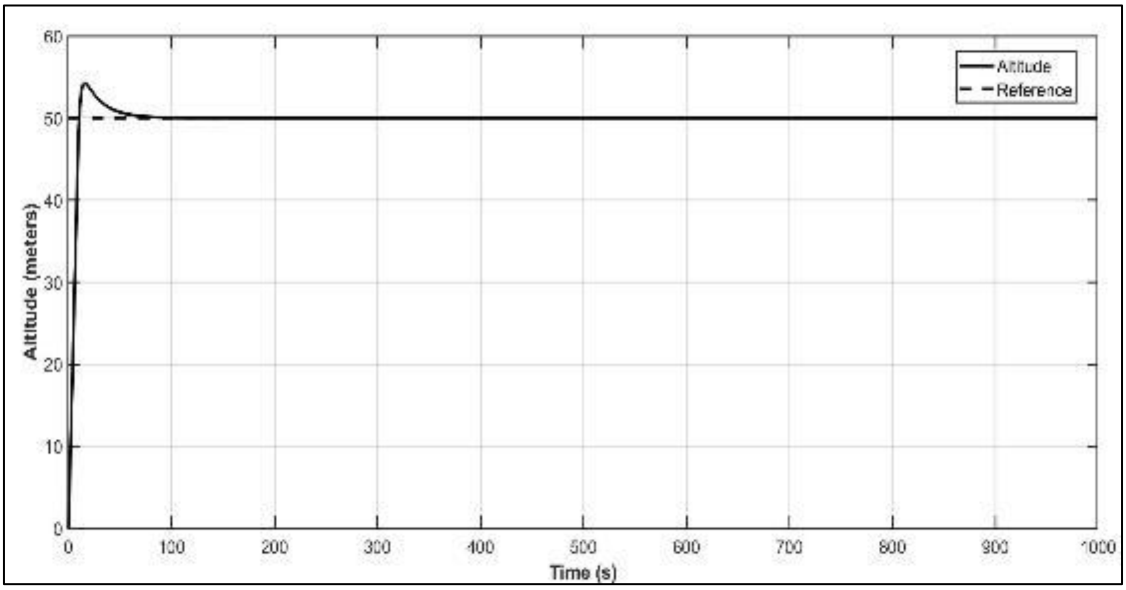


Figure 2 Altitude tracking response to a 50m command input

4.2. Attitude Stabilization and Tracking

The performance of the fast inner-loop attitude controllers was verified using step inputs for the roll (ϕ), pitch (Θ), and yaw (Ψ) axes. Fig. 3, illustrates the stable translational and rotational dynamics. Quantitatively, the roll and pitch axes achieved exceptionally fast stabilization, with rise times between 0.15-0.20s and settling times of approximately 0.30s. The overshoot for these axes was kept below 2%.

The yaw response, while slightly slower with a settling time of 0.60s, remained smooth and non-oscillatory with 0% overshoot. This difference in timing is an accurately modelled characteristic, as yaw is controlled by the reactive drag of the propellers, a force significantly smaller than the differential thrust used for roll and pitch. The high degree of agility observed in the attitude loops confirms that the cascaded architecture provides the necessary stability for precise low-altitude agricultural manoeuvres.

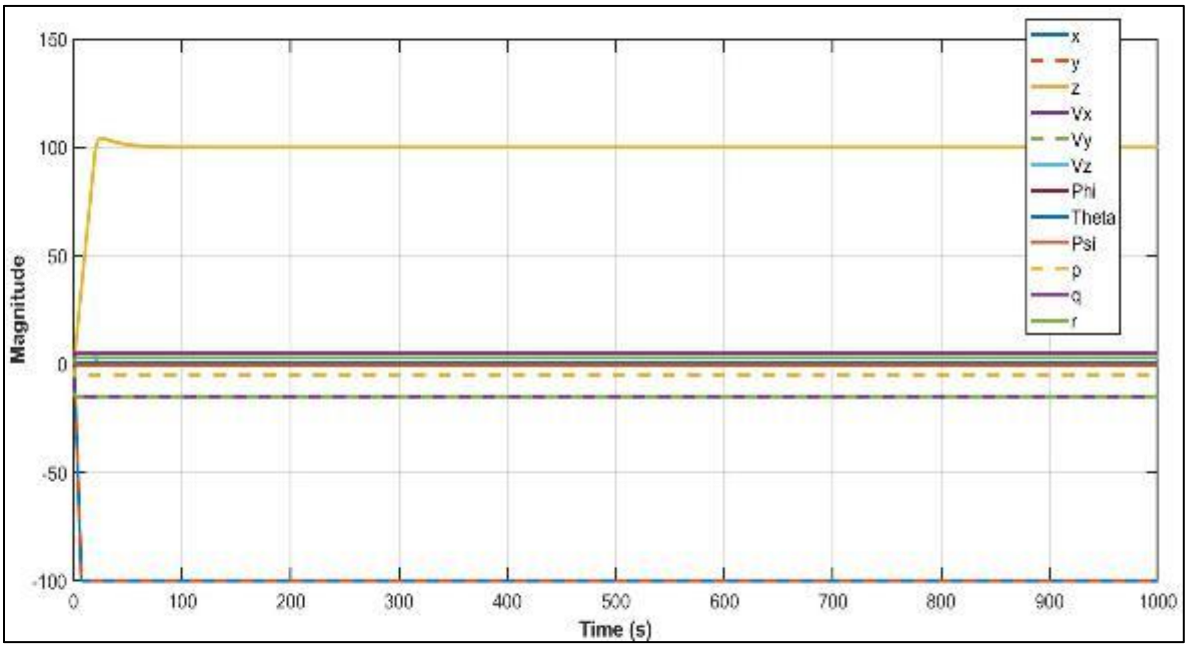


Figure 3 System dynamics showing position and attitude evolution during flight.

4.3. Propulsion Response and Payload Variation Effects

A primary contribution of this study was the evaluation of the controller's robustness during active spraying. Fig. 4 shows the total thrust profile generated by the PID controller. At the initiation of flight ($t = 0$), a sharp rise in thrust was observed to overcome gravity and facilitate the 50m climb. Once the target altitude was reached, the thrust settled to a hover level.

As the pesticide discharge progressed (modelled in Fig. 5 as a linear decline from 15L to 0L), the total thrust required to maintain a hover gradually decreased. The simulation confirmed that the cascaded PID architecture successfully compensated for this mass depletion in real-time unlike empirical tuning methods which may struggle with significant mass shifts. The systematically tuned controllers in this study maintained stable flight and constant altitude throughout the entire spraying cycle.

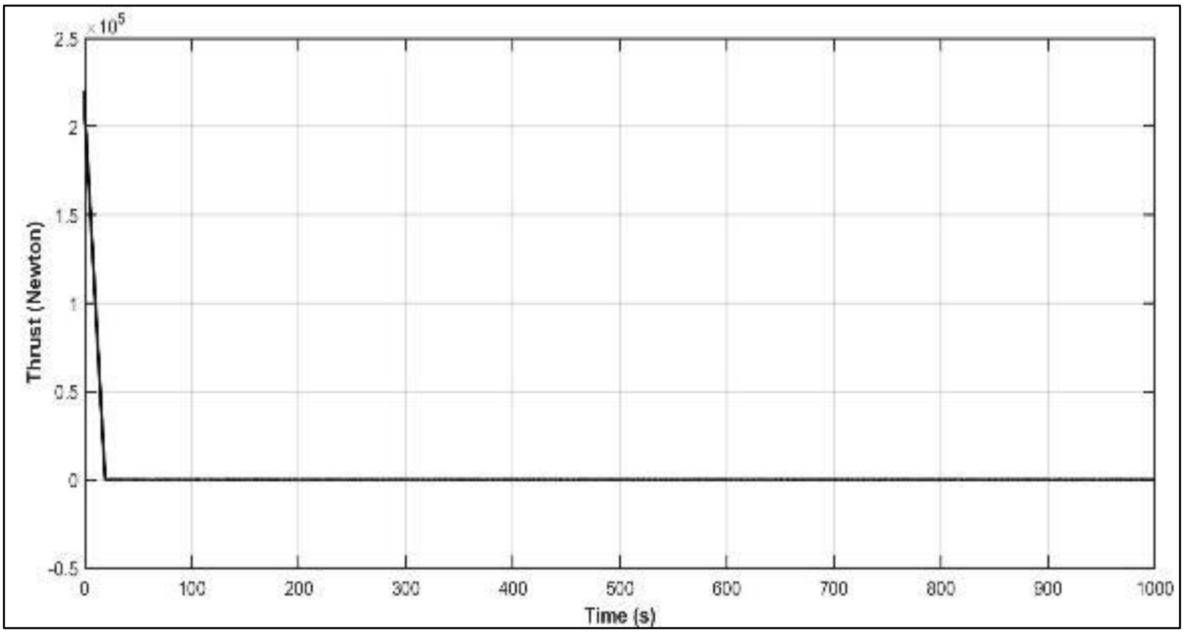


Figure 4 Total thrust response generated by the PID controller.

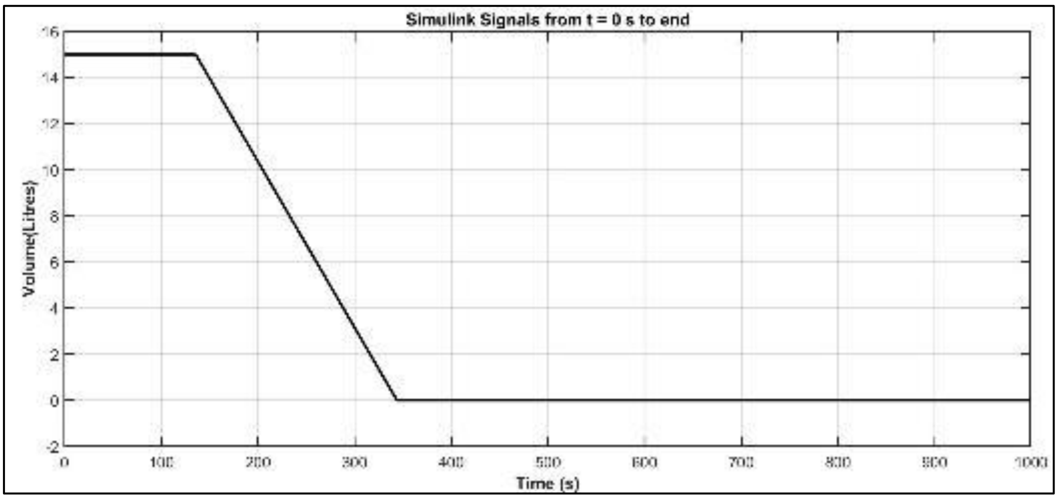


Figure 5 Variation of payload mass during spraying operation.

4.4. Spray flow-rate behavior

The spray subsystem was monitored to ensure a stable discharge rate, which is a prerequisite for uniform field coverage. Fig. 6 confirms that the spray flow rate remained constant at approximately 0.072 throughout the designated spray window. This consistent output, paired with the stable altitude tracking discussed in Section 4.1, suggests that the integrated mechatronic system is capable of achieving the precision required for modern agricultural standards.

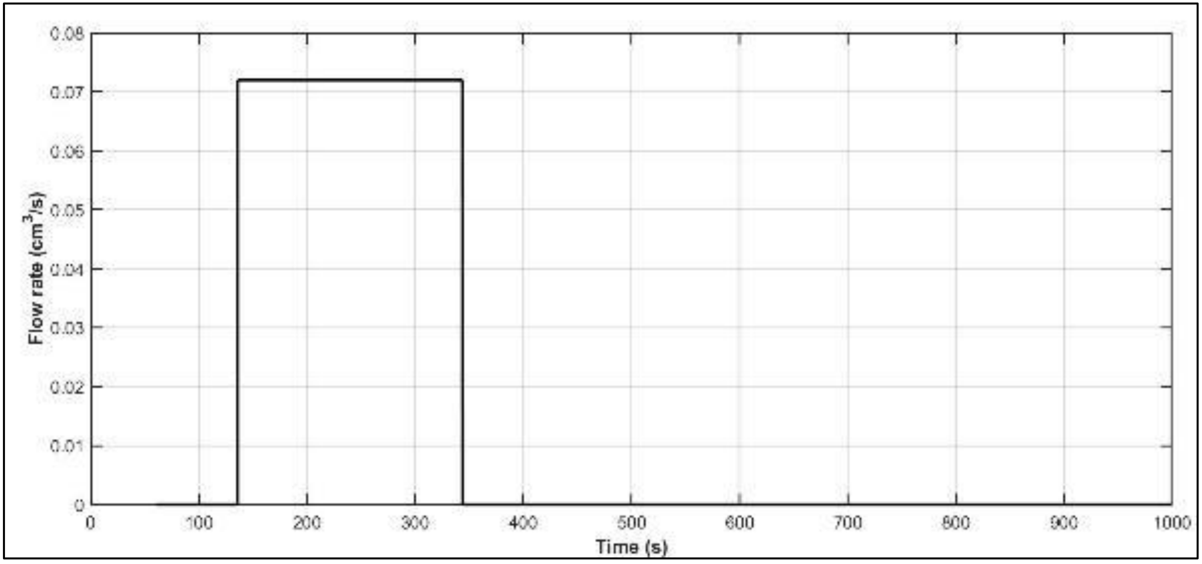


Figure 6 Flow rate of pesticide during spraying cycle

4.5. Performance Comparison Tables

This section provides a quantitative summary of the controller's effectiveness. Table 2 outlines the critical performance metrics, including rise time, settling time, and percentage overshoot for the altitude, roll, pitch, and yaw control loops, establishing a consolidated performance benchmark for the quadcopter system.

Table 2 Performance Summary Across All Control Axes

Control Axis	Rise Time T_r	Settling Time T_s	% Overshoot	E_{ss}
Altitude z	≈ 2.1 s	≈ 3.0 s	0%	0 m
Roll ϕ	0.15–0.20 s	≈ 0.30 s	<2%	0°
Pitch θ	0.15–0.20 s	≈ 0.30 s	<2%	0°
Yaw ψ	≈ 0.35 s	≈ 0.60 s	0%	0°

When compared to existing literature, the results of this study demonstrate superior stability margins. For instance, many prototypes utilizing standard off-the-shelf flight stacks do not report quantitative time-domain indices, making it difficult to verify their robustness prior to field testing [5], [12]. The achievement of near-zero overshoot in both altitude and attitude suggests that the systematic tuning approach used in this work provides a more reliable foundation for autonomous pesticide application than the empirical "trial-and-error" methods common in previous designs.

5. Conclusion

The paper presented the design and simulation of a pesticide-spraying quadcopter using a nonlinear 6-DOF Newton-Euler dynamic model and a cascaded PID flight-control architecture. The research objectives were successfully achieved, confirming that a systematically tuned controller can manage the complex dynamics of an agricultural UAV. Some of the key findings included:

- Rapid Attitude Stabilisation: The inner-loop controllers achieved settling times of approximately 0.30s for roll and pitch, with negligible overshoot (<2%).
- Precise Altitude Tracking: The outer-loop altitude controller successfully tracked a 50m command with 0% overshoot and zero steady-state error, which is essential for uniform spray height.

- Robustness to Mass Variation: The integrated mechatronic system maintained stable flight during continuous payload depletion, confirming that the control architecture can compensate for dynamic mass shifts in real-time.

These outcomes establish a reliable, simulation-verified baseline that reduces the engineering risks and financial costs associated with physical prototyping.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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