Journal of Applied Technology and Downstream Innovation (JATDI)
P-ISSN: xxxx-xxxx | E-ISSN: xxxx-xxxx Website: https://jatdi.id/
Vol. 1, No. 1, July 2026, Page. 1-19 DOI: https://doi.org/10.20884/1.jatdi.1.1.7

Conjugate-Gradient Method for Propulsion Optimization and Flight Stability of an Agricultural Drone Sprayer

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Received: May 19, 2026; Revised: July 12, 2026; Accepted: July 14, 2026; Published: July 31, 2026.

Abstract

Conventional pesticide and liquid fertilizer spraying methods in agriculture remain inefficient because they require intensive labor, long operational time, inconsistent spraying quality, and direct human exposure to agrochemicals. Improving the flight performance of agricultural drone sprayers is therefore essential to achieve accurate, stable, and efficient spraying operations under varying payload conditions. This study presents the design, optimization, realization, and testing of an agricultural drone sprayer for pesticide and liquid fertilizer applications in precision agriculture. The study focused on optimizing the drone's overall flight performance using the conjugate-gradient method. The lifting power analysis considered several parameters, including payload mass, thrust generation, battery efficiency, and aerodynamic resistance. The optimization process was performed iteratively to minimize thrust errors and improve flight stability during low-altitude spraying operations. The simulation results showed that the optimization error decreased from 12.5% to 0.22% after fifteen iterations, while the flight stability index improved from 62% to 98%. These results indicate that the conjugate-gradient method effectively optimized the propulsion configuration, thereby enhancing the drone hovering stability and maneuverability. The developed prototype integrated a quadcopter propulsion system, spraying mechanism, GNSS/GPS-based autonomous navigation, and real-time telemetry monitoring. Experimental testing demonstrated stable flight performance, efficient spraying capability, and reliable operation under varying payload conditions. This study advances agricultural drone optimization by demonstrating the effectiveness of the conjugate-gradient method in improving flight performance, providing a scientific basis for developing more reliable and efficient unmanned aerial systems for precision agriculture.

Keywords: *Aerodynamics, Conjugate-Gradient, Control System, Drone-Sprayer, Optimization.*

1. INTRODUCTION

Conventional pesticide and liquid fertilizer spraying in agricultural fields is generally performed manually using backpack sprayers, resulting in high labor requirements, long operational time, and direct human exposure to agrochemicals that may pose health risks to operators. The application of unmanned aerial vehicles (UAVs) for agricultural spraying has been recognized as an effective alternative, provided that pesticide formulations are compatible with aerial spraying to ensure appropriate droplet atomization, uniform distribution, and effective deposition on crop surfaces [1]. The implementation of agricultural drones has also been shown to improve spraying efficiency by reducing labor requirements, shortening application time, and minimizing direct operator exposure to pesticides during field operations [2]. Furthermore, drone-assisted spraying enables more effective application in large-scale and difficult-to-access agricultural areas, thereby supporting precision agriculture and improving overall field management efficiency [3]. Although these studies have demonstrated the practical advantages of agricultural drones, they have primarily focused on field implementation and spraying applications, with limited attention to optimizing drone flight performance under varying payload conditions. Therefore, this study emphasizes the computational optimization of an agricultural

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drone sprayer to improve lifting capability, flight stability, and operational reliability during low-altitude spraying missions.

Drones are classified as Unmanned Aerial Vehicles (UAVs), aircraft capable of operating without an onboard pilot and remotely controlled to perform various civilian and industrial missions [4]. The rapid development of UAV technology has also enabled the design of specialized airframes with improved maneuverability and flight performance for specific operational requirements [5]. Experimental flight tests have further demonstrated that UAVs can achieve reliable flight performance when their structural design and propulsion systems are appropriately integrated [6]. Among the various UAV configurations, the quadcopter has become one of the most widely used platforms because its four independent propellers provide excellent maneuverability and vertical take-off and landing capabilities, while maintaining stable attitude and altitude through an appropriate flight control system [7], [10]. In addition, communication and navigation technologies have significantly enhanced the operational reliability of quadcopters during autonomous and remote missions [8]. The unique aerodynamic characteristics of rotating propellers have also supported the development of detection and monitoring techniques for UAV operations, reflecting the increasing sophistication of quadcopter technology [9]. These technological advances have encouraged the adoption of drones in agriculture, where optimized airframe structures improve payload capacity and operational efficiency for spraying applications [11]. Furthermore, drone technology has expanded beyond agricultural spraying to other practical applications, such as autonomous package delivery, demonstrating the versatility and adaptability of UAV platforms [12]. Despite these developments, most agricultural drone sprayers still employ sophisticated control systems and complex onboard instrumentation, resulting in relatively high manufacturing costs and operational complexity. For routine agricultural spraying, many of these advanced control features are unnecessary and may reduce usability for farmers. Therefore, this study proposes a simplified agricultural drone sprayer with an optimized propulsion system and an efficient control architecture to reduce production costs while maintaining reliable flight performance during low-altitude spraying operations.

Improving the performance of agricultural drone sprayers requires a comprehensive evaluation of all major subsystems because flight performance is determined by the interaction among the control system, propulsion system, energy source, airframe, payload, and aerodynamic characteristics rather than by a single component alone. The flight control system is responsible for maintaining attitude stability, trajectory tracking, and autonomous flight performance under varying operational conditions, while recent developments have also demonstrated the advantages of integrating communication and computing technologies to enhance the reliability of drone control systems [13], [14]. The propulsion system represents another critical subsystem because rotor aerodynamic interactions directly influence thrust generation, hovering capability, and flight efficiency, whereas precise speed regulation of brushless DC motors is essential for maintaining thrust balance and stable maneuverability during flight [15], [16]. Flight endurance and operational reliability are also highly dependent on battery capacity and intelligent energy management, while the structural design of the airframe must simultaneously satisfy the requirements for lightweight construction, mechanical strength, and payload-carrying capability [17], [18]. For agricultural applications, the payload configuration and spray platform design significantly affect spraying effectiveness, whereas the aerodynamic disturbances generated by quadrotor downwash strongly influence droplet distribution and spraying uniformity under different flight conditions [19], [20]. Furthermore, quadcopter platforms have been successfully implemented in various autonomous applications, including package delivery and automatic pesticide spraying, demonstrating the flexibility and practicality of UAV technology for carrying different payloads and performing autonomous missions [21], [23]. Although these studies have substantially advanced individual aspects of drone technology, they have generally focused on optimizing specific subsystems independently, with limited consideration of the integrated optimization of flight performance through

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the coordinated selection of the control system, propulsion system, battery, airframe, and payload configuration. Therefore, this study adopts an integrated optimization approach to develop a simplified agricultural drone sprayer with improved flight performance, stable hovering capability, and efficient payload operation while maintaining a practical and cost-effective design for precision agriculture.

Among the major subsystems of an agricultural drone sprayer, particular attention should be given to the frame, payload, and aerodynamic system because these components directly influence payload capacity, flight stability, and operational efficiency. The structural frame should provide sufficient mechanical strength while remaining lightweight, enabling the drone to safely carry the required payload without significantly degrading flight performance [18]. The payload system generally consists of a liquid storage tank integrated with a spraying mechanism and control module, where the tank capacity, payload distribution, and spraying platform configuration must be carefully designed to ensure efficient pesticide or liquid fertilizer application while maintaining stable flight performance [19], [23]. In addition to the structural and payload configurations, the aerodynamic system plays a fundamental role in determining the drone's lifting capability and maneuverability, as aerodynamic performance depends on the interaction among the airframe, propulsion system, propellers, battery capacity, and total operating weight [21], [22]. These interdependent characteristics indicate that the frame, payload, and aerodynamic system should not be designed independently but rather optimized as an integrated engineering system to achieve reliable flight performance under varying payload conditions. Therefore, this study simultaneously evaluates and optimizes these subsystems to develop an agricultural drone sprayer that is lightweight, aerodynamically efficient, capable of carrying relatively heavy liquid payloads, and suitable for stable low-altitude spraying operations.

The optimization of an agricultural drone sprayer requires careful consideration of the frame, payload, and aerodynamic system because these subsystems collectively determine payload capacity, flight stability, and operational efficiency. The structural frame should be sufficiently strong while maintaining a lightweight configuration to support the required payload without compromising flight performance, making lightweight materials such as aluminum alloys highly suitable for agricultural drone applications [18]. The payload system generally consists of a liquid storage tank integrated with a spraying mechanism and control module, where the tank capacity, payload distribution, and spraying platform configuration directly influence spraying effectiveness and the dynamic stability of the drone during flight [19], [23]. In addition to the structural and payload subsystems, the aerodynamic characteristics of the drone must be evaluated together with the propulsion system because the overall flight performance depends on the interaction among the rotor configuration, battery capacity, propeller characteristics, total operating weight, and flight control strategy [21], [22]. From an aerodynamic perspective, the propeller of a quadcopter operates on the same fundamental principle as a helicopter rotor by generating lift through the rotation of airfoil-shaped blades, enabling both vertical take-off and hovering flight [24]. During operation, each propeller blade produces lift perpendicular to its surface to support the total weight of the drone, while aerodynamic drag is simultaneously generated parallel to the blade surface as a consequence of airflow resistance and friction [25], [26]. Since lift and drag are the primary aerodynamic forces governing thrust generation and flight stability, optimizing these forces is essential for achieving reliable hovering performance and efficient payload transportation in agricultural spraying operations. Therefore, this study emphasizes the integrated optimization of the frame, payload, propulsion, and aerodynamic systems to improve the flight performance of an agricultural drone sprayer under varying payload conditions.

The aerodynamic performance of a quadcopter is primarily determined by the capability of its propellers to generate sufficient lift while minimizing aerodynamic drag to maintain stable and efficient flight under varying operating conditions. Therefore, airfoil analysis is essential for evaluating the aerodynamic forces and moments, including lift, drag, and pitching moment, which collectively determine the thrust generated by the propulsion system. Recent studies have demonstrated that

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optimizing blade geometry, airfoil configuration, and other aerodynamic parameters can significantly improve thrust generation, propulsion efficiency, and lifting capability, although these efforts have mainly concentrated on propeller design optimization rather than on enhancing the overall flight performance of the drone [25]. In addition to aerodynamic studies, advances in drone technology have also been achieved through radar-based signal processing techniques capable of improving the detection and classification of UAVs using micro-Doppler signatures, thereby expanding the application of drones in surveillance and monitoring systems rather than in flight performance optimization [26]. Furthermore, drone platforms have been successfully integrated with computer vision techniques to improve image stitching accuracy and inspection reliability for infrastructure monitoring applications, demonstrating the versatility of UAV technology in remote sensing and industrial inspection [27]. Although these studies have significantly advanced propeller aerodynamics, drone detection, and vision-based inspection technologies, they have primarily focused on optimizing individual application domains, with limited attention devoted to computational optimization of the propulsion system to improve lifting capability and flight stability under varying payload conditions. Therefore, this study employs the conjugate-gradient method as a numerical optimization approach to optimize the propulsion system by simultaneously considering thrust generation, payload variation, battery performance, and aerodynamic resistance, thereby improving the overall flight performance of an agricultural drone sprayer.

These previous studies demonstrate that current research has primarily concentrated on propeller aerodynamic design, drone detection, and vision-based inspection systems. Despite these advances, limited attention has been paid to computational optimization methods for improving the propulsion system and achieving higher lift capability and better flight stability under varying payload conditions. Therefore, this study proposes the conjugate-gradient method as a numerical optimization technique to optimize the overall flight performance of an agricultural quadcopter. The proposed approach iteratively minimizes thrust errors by optimizing propulsion parameters, thereby improving hovering stability, maneuverability, and operational efficiency during low-altitude spraying missions. This computational optimization strategy represents the primary novelty of the present work and extends the current state of the art in agricultural drone performance optimization.

The evaluation and optimization of the primary aerodynamic parameters, namely lift, drag, and pitching moment, require an efficient numerical method capable of solving complex engineering problems with high computational accuracy and reliable convergence. A generalized conjugate-gradient algorithm has been developed to improve the convergence characteristics of conventional optimization methods for differentiable objective functions, demonstrating its effectiveness for solving large-scale optimization problems through iterative computation [28]. Further developments have introduced nonlinear and hybrid conjugate-gradient formulations that provide faster convergence, greater numerical stability, and improved computational efficiency for unconstrained optimization problems, making the method increasingly suitable for engineering applications involving complex nonlinear systems [29], [30]. Beyond theoretical algorithm development, the conjugate-gradient method has also been successfully applied to practical engineering problems, including the optimization of automotive exhaust muffler designs to improve emission and noise characteristics and the analysis of low-frequency electrical generator performance to determine optimal operating conditions through iterative numerical computation [31], [32]. The capability of the conjugate-gradient method has also been demonstrated in optimizing the thrust force of pico-hydropower systems, confirming its effectiveness in improving mechanical performance while minimizing computational errors and maintaining solution stability [33]. Although previous studies have established the robustness of the conjugate-gradient method in mathematical optimization and various engineering applications, its implementation for the integrated optimization of agricultural drone flight performance has received relatively limited attention. In particular, few studies have employed this numerical optimization approach to simultaneously evaluate the interactions among thrust generation, payload variation, battery performance, and aerodynamic

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resistance in multirotor UAVs. Therefore, this study applies the conjugate-gradient method as a computational optimization framework to improve the overall flight performance of an agricultural drone sprayer by enhancing lifting capability, hovering stability, and propulsion efficiency under varying payload conditions.

Although the conjugate-gradient method has been successfully applied to structural design optimization, electrical system analysis, and hydropower performance optimization, its application to optimizing the flight performance of agricultural quadcopters remains rarely reported. In particular, few studies have employed the conjugate-gradient method to optimize propulsion parameters while simultaneously accounting for payload variation, thrust generation, battery efficiency, and aerodynamic resistance in low-altitude spraying operations. Therefore, this study proposes the conjugate-gradient method as a computational optimization framework to improve the overall flight performance of an agricultural drone sprayer. The proposed approach aims to enhance hovering stability, maneuverability, and lifting capability by iteratively optimizing the propulsion system, thereby extending the use of the conjugate-gradient method to the optimization of agricultural unmanned aerial vehicles.

2. METHOD

The research methodology consisted of two main stages: (1) lifting power analysis of the drone sprayer and (2) prototype fabrication followed by preliminary flight testing. The lifting power analysis was performed using the conjugate-gradient optimization method to evaluate the drone's aerodynamic performance and determine the optimal lifting capability. The optimization process involved calculating the optimization error, the required total thrust, and the Flight Stability Index (FSI) to assess the feasibility of the proposed design under different payload conditions. Based on the analytical results, a drone sprayer prototype was fabricated by integrating the frame structure, propulsion system, flight controller, and spraying mechanism. The fabricated prototype was subsequently subjected to preliminary flight tests to verify the lifting power analysis and to confirm the system's basic flight capability. This study was limited to validating the lifting power analysis through prototype fabrication and initial flight testing; comprehensive performance evaluations, including detailed flight dynamics, spraying efficiency, and long-term operational analyses, were beyond the scope of the present work. The overall research workflow is illustrated in Figure 1.

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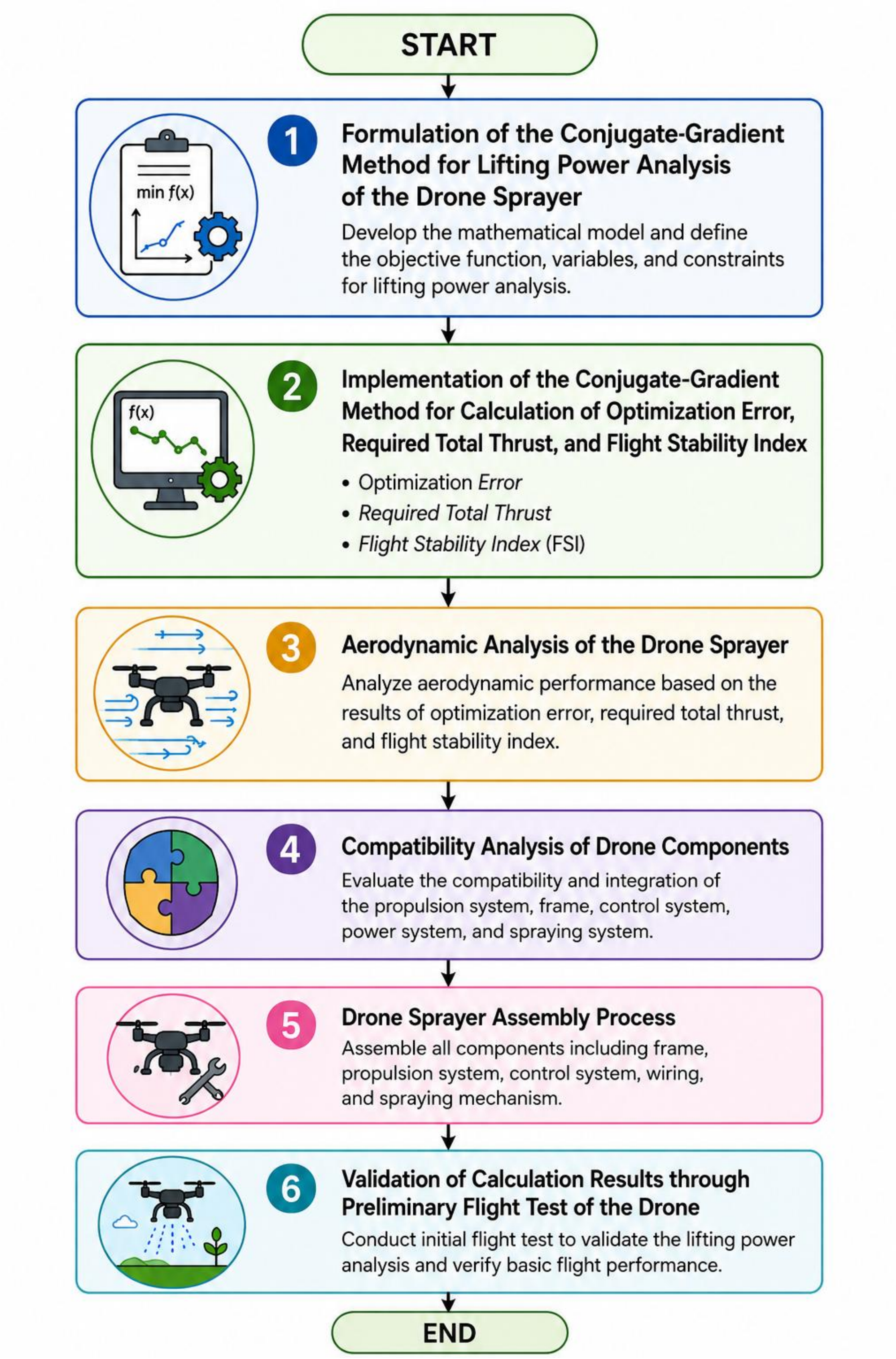

Figure 1. Research workflow for the development and validation of a drone sprayer using the Conjugate Gradient optimization method, including mathematical formulation, optimization, aerodynamic analysis, component compatibility analysis, assembly, and preliminary flight-test validation.

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2.1. Drone sprayer lifting power formulation

The research methodology began with developing an agricultural quadcopter drone sprayer based on the fundamental configuration of an Unmanned Aerial Vehicle (UAV), which employs four independently driven propellers to enable vertical take-off, hovering, and stable flight through an integrated flight control system [4], [7]. The selection of the quadcopter configuration was based on its proven maneuverability, payload-carrying capability, and operational flexibility for low-altitude agricultural applications [5], [10]. To accommodate pesticide and liquid fertilizer spraying, the baseline drone platform was modified by integrating a liquid storage tank, spraying mechanism, and supporting structural components while maintaining stable flight performance under varying payload conditions [19], [23]. The overall prototype developed in this study is presented in Figure 2. In addition, the flight control system was implemented using a modified remote-control module adapted from previously established quadcopter control architectures to provide reliable manual operation during prototype testing and performance evaluation [7], [22]. The configuration of the modified remote-control system is illustrated in Figure 3 and served as the primary interface for flight control throughout the experimental investigations.

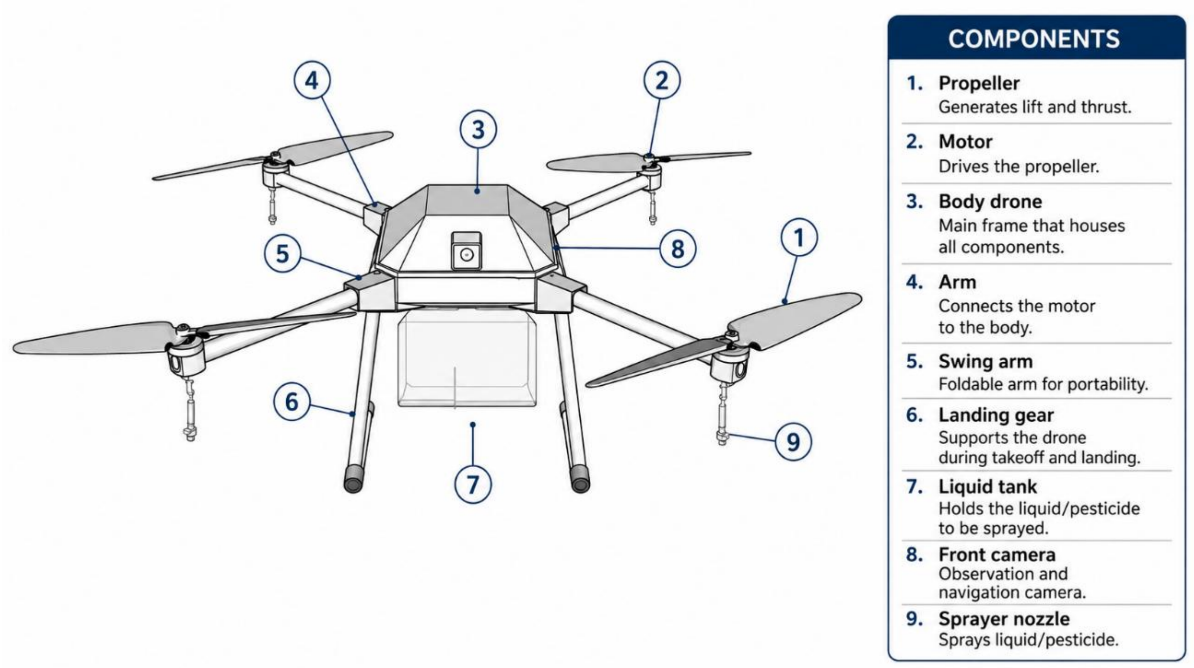

Figure 2. The main components of the drone sprayer are modified from reference [23].

For the aerodynamic analysis, the agricultural drone sprayer was modeled as a conventional quadcopter consisting of four identical propellers arranged symmetrically around the center of mass, with each rotor generating thrust perpendicular to the horizontal plane [7], [10]. This configuration was selected because it provides stable hovering, balanced thrust distribution, and sufficient maneuverability for low-altitude agricultural spraying operations [8], [9]. To simplify the analytical model, all four propulsion units were assumed to have identical geometric characteristics, equal thrust-generating capability, and equal radial distances from the center of mass, resulting in a symmetric distribution of aerodynamic forces and moments during flight [15]. Under these assumptions, stable take-off and hovering can be achieved when the total lift generated by the four propellers exceeds the combined gravitational and aerodynamic drag forces acting on the drone.

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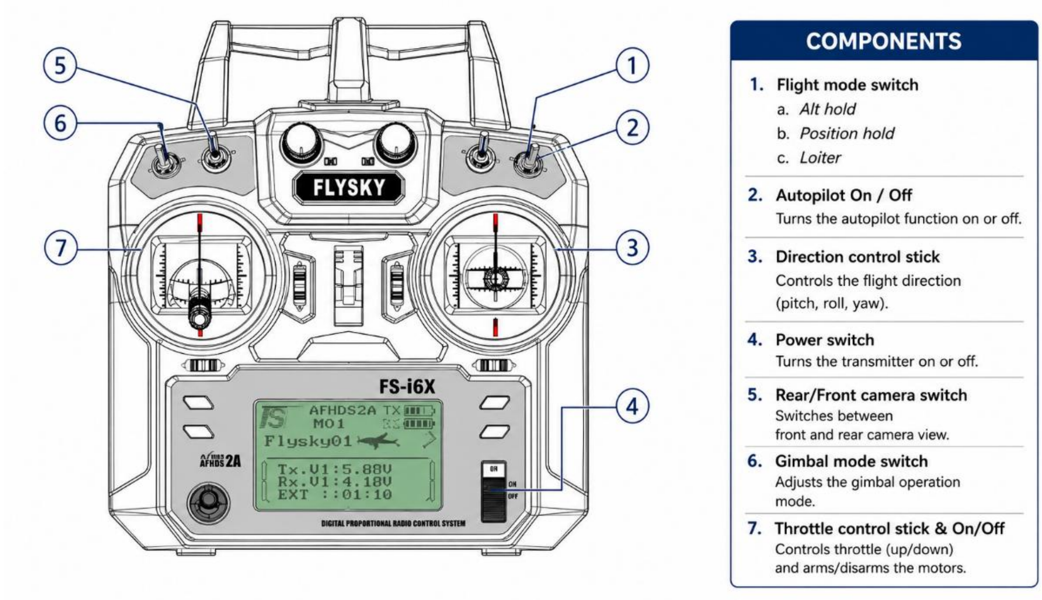

Figure 3. A modified main part of the remote drone sprayer from references [7] and [22].

Furthermore, the propulsion system was designed to satisfy the commonly adopted engineering criterion that the maximum total thrust should be approximately four times the overall take-off weight, thereby providing sufficient thrust margin to ensure stable flight, payload-carrying capability, and maneuverability during agricultural spraying operations [25], [27]. These aerodynamic assumptions served as the basis for the subsequent propulsion analysis and numerical optimization performed in this study.

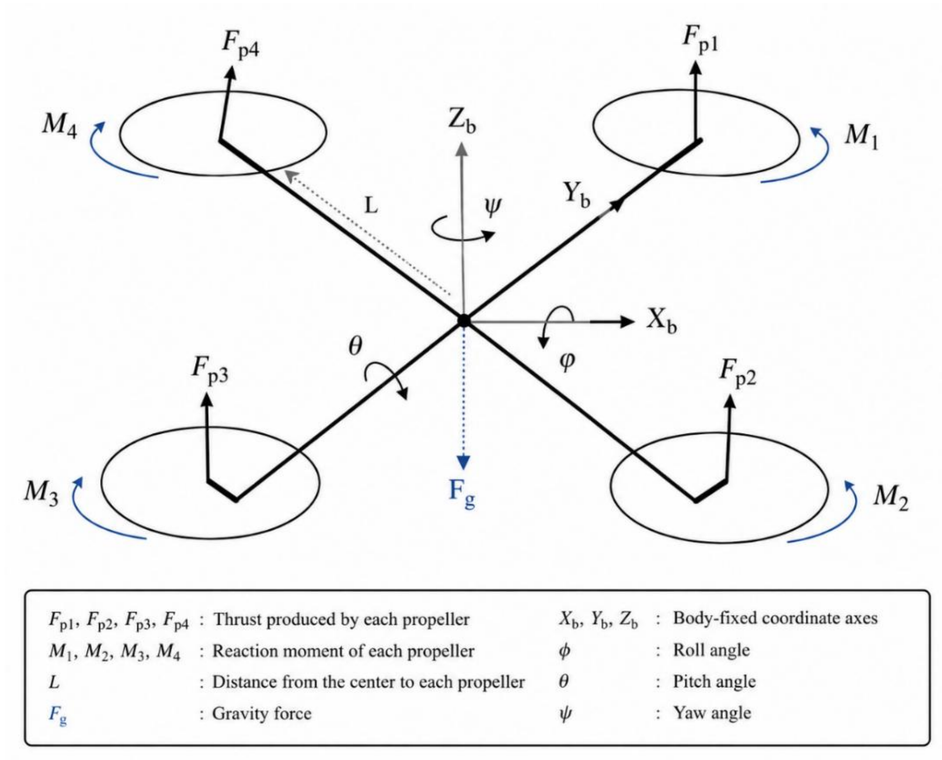

Figure 4. An illustration of the aerodynamic system of a drone sprayer.

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An illustration of the forces acting on each rotor is presented in Figure 4. The rotation of each propeller blade generates an aerodynamic thrust force (F_p)directed upward, which is proportional to the square of the rotor angular velocity (ω_p). This relationship can be expressed as:

$$F_p = k_f \omega_p^2 \tag{1}$$

where k_f is a constant determined experimentally and numerically. An increase in rotor rotational speed results in a greater lifting force. Each propeller produces an upward thrust perpendicular to the drone body frame (z_b), while the gravitational force (F_g)acts in the opposite direction $-z_g$. By defining $\vec{r}$ as the position vector and m as the drone mass, the translational motion of the drone can be represented through the rotation matrix R formulation.

$$m \frac{d^2\vec{r}}{dt^2} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + R \begin{bmatrix} 0 \\ 0 \\ \sum F_p \end{bmatrix} \tag{2}$$

The difference in the upward thrust generated by each rotor produces rotational motion about the center point O, located at a distance $L$from each rotor. The resulting forces and torques can be expressed as follows

$$\vec{F}_{res\theta} = \vec{F}_{p4} - \vec{F}_{p2} \tag{3}$$

$$\vec{\tau}_{res\theta} = \vec{L} \times \vec{F}_{res\theta} \tag{4}$$

$$\vec{F}_{res\phi} = \vec{F}_{p1} - \vec{F}_{p3} \tag{5}$$

$$\vec{\tau}_{res\phi} = \vec{L} \times \vec{F}_{res\phi} \tag{6}$$

where $\vec{\tau}_{res\theta}$ and $\vec{\tau}_{res\phi}$ represent the torques acting along the θ (roll) and ϕ (pitch) axes, respectively. Based on Newton Third Law of Motion, a reaction moment M is generated on each rotor in the direction opposite to the propeller rotation. This moment is directly proportional to the square of the rotor angular velocity (ω_p), and can be expressed as

$$M = k_m \omega^2 \tag{7}$$

where k_m is a proportionality constant determined experimentally or through numerical analysis. By adjusting the combination of roll and pitch angles, a resultant force can be generated in various directions, enabling the drone to maneuver freely in three-dimensional space [20], [25].

2.2. The Conjugate-Gradient Method in Lift Analysis

Analysis of lift, drag, and moment magnitudes, which are the primary factors affecting drone stability and maneuverability in all directions, can be conducted using the conjugate gradient method. This method has been widely used to obtain numerical solutions to linear systems with symmetric, positive-definite matrices [29], [30]. Mathematically, the method is formulated as the following optimization problem

$$\min\{f(x): x \in \mathbb{R}^n\} \tag{8}$$

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Here, $f(x): \mathbb{R}^n \rightarrow \mathbb{R}$ is a differentiable and bounded function. To solve this problem, an initial value $x_0 \in \mathbb{R}^n$ is selected, and the nonlinear conjugate gradient method is employed to generate a sequence $\{x_k\}$ using

$$x_{k+1} = x_k + \alpha_k d_k \tag{9}$$

where $\alpha_k > 0$ is determined through a line search procedure, and the search direction d_k is defined as

$$d_{k+1} = -g_{k+1} + \beta_k s_k, \quad d_0 = -g_0 \tag{10}$$

Here, β_k denotes the conjugate gradient parameter, while

$$s_k = x_{k+1} - x_k \tag{11}$$

and

$$g_k = \nabla f(x_k) \tag{12}$$

represent the displacement vector and the gradient of the objective function, respectively. The parameter notation used in Equations (8)–(11) assumes that the optimization is performed on a single dependent variable with respect to two independent variables [31], [32], [33]. The proposed formulation is employed to analyze three key aerodynamic parameters: optimization Error, Required Total Thrust, and the Flight Stability Index (FSI)—which are essential for evaluating the lift performance of the drone sprayer.

2.3. Realization and testing of the drone sprayer

The procedures carried out in the design and realization of the drone sprayer consist of aerodynamic modeling, compatibility analysis between theoretical calculations and actual hardware components, system assembly, and prototype testing. These procedures were conducted systematically to ensure that the drone sprayer achieves stable flight performance, structural compatibility, and effective spraying capability. The detailed stages of the research are described as follows:

1. **Aerodynamic Analysis of the Drone Sprayer.**
   The aerodynamic characteristics of the drone sprayer, particularly lift, drag, and moment, were analysed using the conjugate gradient method. The aerodynamic equations employed in this study were adapted from previous works [19] and [20], while the optimization and analytical framework based on the conjugate gradient method was adapted from [31], [32], and [33]. This analysis was conducted to determine the optimal aerodynamic configuration that supports stable flight and efficient load lifting.
2. **Compatibility Analysis of Drone Components.**
   An analysis was performed to evaluate the compatibility between standard components that did not require structural modification, such as the control system, motors, and battery, and the components requiring redesign or adjustment, including the frame structure, payload system, and aerodynamic body configuration. The analysis procedure was based on the methods proposed in references [11], [17], [20], and [25]. This stage aimed to ensure that all components could operate synergistically under the required flight and spraying conditions.
3. **Drone Sprayer Assembly Process.**
   Following the compatibility analysis, the drone sprayer was assembled by integrating the unmodified main components with the modified structural and aerodynamic components. The assembly process was carried out in accordance with the design specifications derived from the

previous analysis to ensure the structural integrity, system balance, and operational functionality of the drone sprayer prototype.

4. **Prototype Testing and Evaluation.**
   Simple field testing of the drone sprayer prototype was conducted in a controlled and measurable test area. The purpose of this testing stage was to evaluate the system flight performance, spraying capability, component stability, and overall operational effectiveness. The test results were then used to determine the most appropriate component specifications and to identify potential improvements for further development.

5. RESULT AND DISCUSSION

Based on the formulated methodology, the results obtained in this study are divided into two main aspects: the analysis of the drone sprayer lifting power and the realization and performance testing of the developed prototype. The lifting power analysis was conducted to determine the propulsion system's capability to support the total weight of drone, including the payload of liquid fertilizer or pesticide during operation. Furthermore, the realization stage successfully integrated the propulsion components, frame structure, control system, and spraying mechanism into a functional drone sprayer prototype. A series of experimental tests was then conducted to evaluate the drone lifting capability, flight stability, spraying effectiveness, and overall operational performance during low-altitude spraying operations.

5.1. Analysis of Drone Lifting Power using Conjugate-Gradient Method

The lifting-power analysis of the drone sprayer was conducted using the conjugate-gradient optimization method to determine the optimal thrust configuration for stable flight during spraying operations. The optimization process considered several important parameters, including total drone weight, payload mass, motor thrust, battery efficiency, and aerodynamic resistance at low altitudes. In agricultural UAV applications, stable hovering capability and precise maneuverability are essential because variations in payload mass continuously affect the center of gravity, aerodynamic response, and propulsion efficiency during spraying activities [34], [35].

The optimization process was performed iteratively to minimize the difference between the required lifting force and the available thrust generated by the propulsion system, using equations (8)-(12). In the numerical implementation of the conjugate gradient method, the focus is on analyzing total thrust as a function of total payload mass and flight stability over time. The implementation of the algorithm was determined using equations (1) to (7). During the initial iterations, the optimization error remained relatively high due to thrust imbalance and payload distribution mismatch. However, as the optimization progressed, the algorithm continuously refined the thrust allocation parameters, thereby improving aerodynamic efficiency.

Figure 5 illustrates the convergence behavior of the proposed Conjugate Gradient optimization algorithm in minimizing the objective function associated with the aerodynamic performance of the drone sprayer. The optimization error decreases monotonically from approximately 12.5% at the first iteration to less than 0.2% after the fifteenth iteration, corresponding to an overall reduction of approximately 98.4%, thereby demonstrating rapid and stable convergence toward the optimal solution. The most significant reduction occurs during the first five iterations, after which the convergence gradually approaches an asymptotic minimum, indicating numerical stability and efficient optimization. From an aerodynamic perspective, this substantial reduction in optimization error indicates that the calculated thrust distribution progressively converges toward the optimal lift requirement, thereby minimizing thrust imbalance among the propulsion units and improving the aerodynamic efficiency of the multirotor system. Consequently, the optimized solution enhances lift generation while reducing unnecessary energy expenditure, resulting in improved hovering stability, greater resistance to aerodynamic disturbances, and more consistent flight performance during low-altitude spraying

P-ISSN: xxxx-xxxx | E-ISSN: xxxx-xxxx Website: https://jatdi.id/
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operations. These findings demonstrate that the proposed Conjugate Gradient optimization framework provides an effective computational approach for aerodynamic lift optimization, thereby improving flight stability, propulsion efficiency, and operational reliability of agricultural drone sprayers under varying payload conditions.

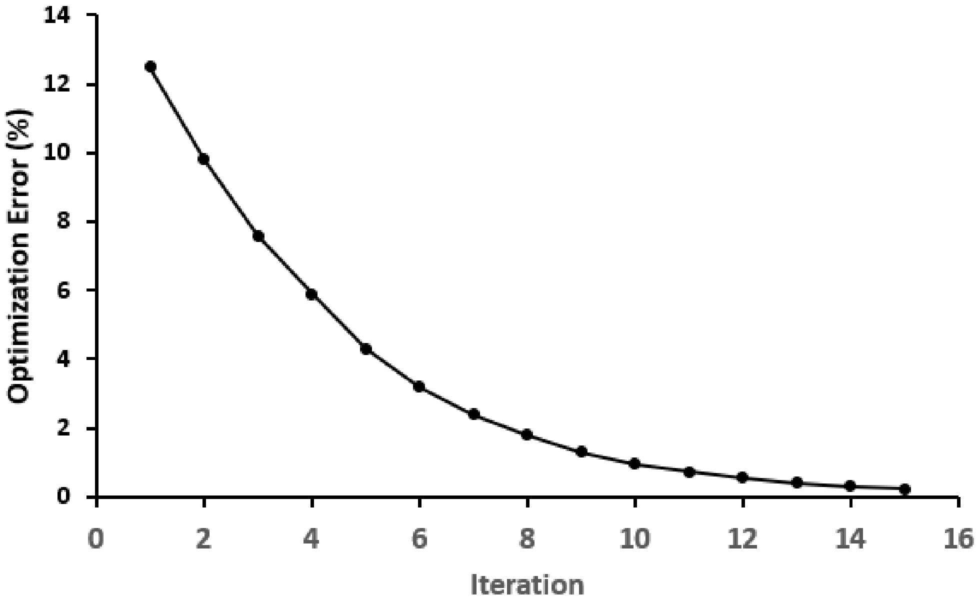

Figure 5. Convergence graph of the conjugate-gradient optimization method for drone lifting power analysis, showing the iterative reduction of the objective function toward the optimum thrust configuration during the optimization process.

The relationship between payload mass and required thrust is presented in Figure 6. The graph demonstrates that increasing payload mass directly increases the total thrust required to maintain stable flight conditions. The relationship follows an approximately linear trend, indicating a proportional propulsion response under varying payload conditions. A linear regression analysis yields the empirical model $y = 5x + 17.429$, where the slope of 5 N kg^{-1} indicates that each additional kilogram of payload requires approximately 5 N of additional thrust to compensate for the increased gravitational load. Meanwhile, the intercept of 17.429 N represents the baseline thrust required to sustain the drone's own structural weight in the absence of payload. The close agreement between the measured data and the regression line indicates a highly predictable aerodynamic response and confirms that the propulsion system operates within a stable linear regime over the payload range investigated. From an aerodynamic perspective, the proportional increase in thrust demand indicates that the lift-generation capability of the multirotor system remains well balanced, without exhibiting nonlinear degradation or thrust saturation, which are commonly associated with reduced flight efficiency under heavy loading. Consequently, the optimized propulsion configuration maintains sufficient lift margin, improves hovering stability, and preserves flight controllability during spraying operations despite variations in payload mass. These findings demonstrate that the proposed optimization framework effectively predicts thrust requirements and provides a reliable basis for aerodynamic design, payload capacity estimation, and energy-efficient mission planning for precision agricultural drone sprayers.

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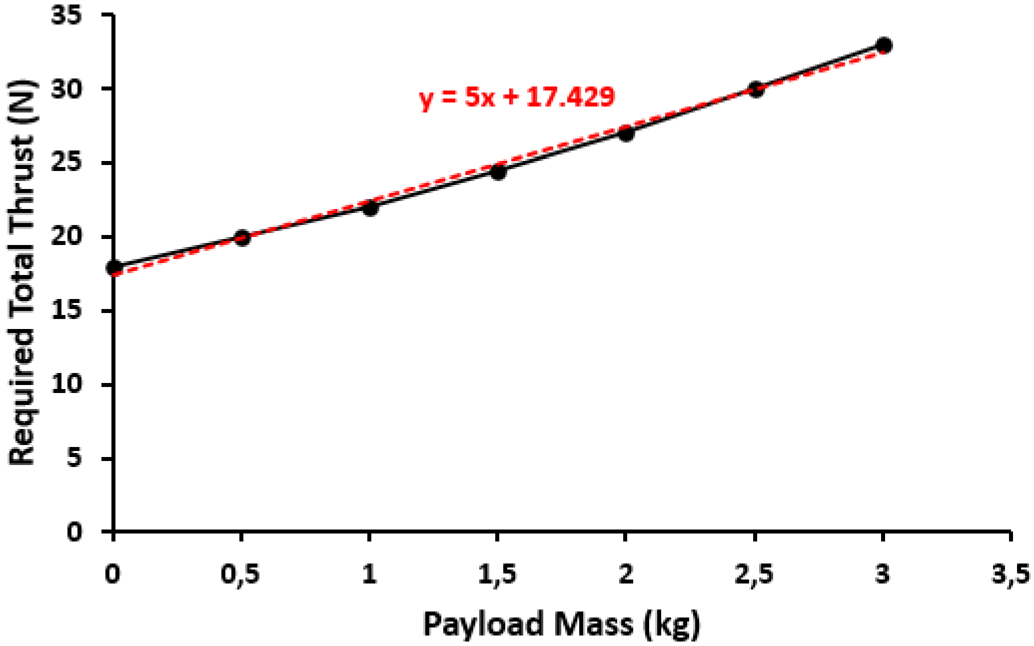

Figure 6. Relationship between payload mass and required total thrust during spraying operations, illustrating the increase in thrust demand as the payload mass rises to maintain stable drone flight performance.

Figure 7 illustrates the temporal evolution of the Flight Stability Index (FSI) during the optimization process. As shown in the figure, the FSI increased progressively from approximately 62% at the start of the optimization to nearly 98% after 14 s, representing an overall improvement of approximately 58.1%. The rapid increase observed during the first 6 **s** indicates that the proposed Conjugate Gradient algorithm efficiently converged toward an optimal thrust allocation, whereas the subsequent gradual increase suggests asymptotic convergence to a dynamically stable operating condition. This convergence behavior demonstrates that only a relatively short optimization time is required to achieve near-optimal flight stability, highlighting the computational efficiency of the proposed method. From an aerodynamic standpoint, the increase in FSI reflects a more balanced distribution of lift and thrust among the four rotors, thereby reducing roll, pitch, and yaw oscillations induced by payload variations and external disturbances. The optimized thrust distribution consequently minimizes aerodynamic imbalance, reduces unnecessary control corrections, and improves the stability of the airflow generated beneath the propellers. These improvements directly enhance hovering accuracy, smoother trajectory tracking, and more consistent aerodynamic performance during low-altitude spraying missions. Furthermore, improved flight stability promotes a more uniform spray pattern by reducing fluctuations in nozzle height and vehicle attitude, thereby increasing droplet deposition uniformity while minimizing spray overlap and off-target drift. Overall, the results demonstrate that the proposed optimization framework significantly enhances the aerodynamic stability, propulsion efficiency, and operational reliability of agricultural drone sprayers, providing a robust foundation for precision spraying under varying payload conditions.

Overall, the results demonstrate that the conjugate-gradient method is highly effective for optimizing the lifting capability of the drone sprayer system. The algorithm iteratively updates the search direction by combining the current and previous gradient information, enabling rapid convergence toward the minimum of the optimization error while reducing computational complexity. This capability is particularly beneficial for UAV propulsion optimization, where real-time parameter adjustment is required to maintain stable thrust generation under dynamic payload conditions.

Journal of Applied Technology and Downstream Innovation (JATDI)
P-ISSN: xxxx-xxxx | E-ISSN: xxxx-xxxx Website: https://jatdi.id/
Vol. 1, No. 1, July 2026, Page. 1-19 DOI: https://doi.org/10.20884/1.jatdi.1.1.7

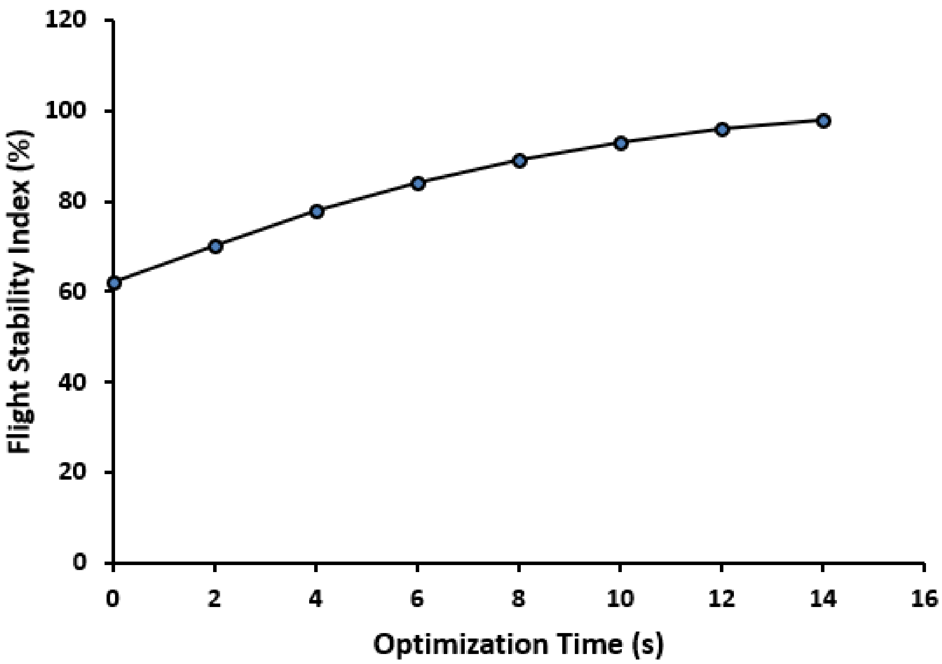

Figure 7. Improvement in the drone flight stability index during the optimization process, indicating enhanced stability achieved through iterative conjugate-gradient optimization.

The optimized thrust configuration improved flight stability, reduced optimization errors, and ensured sufficient lift during low-altitude spraying operations. Furthermore, the optimization process enhanced propulsion efficiency and improved operational reliability for agricultural UAV applications [34], [35].

5.2. Assembly and Flight Testing

The drone sprayer was assembled by integrating the structural frame, propulsion system, electronic speed controllers (ESCs), flight controller, spraying tank, liquid pump, nozzle system, battery module, and telemetry communication unit [36], [38]. The total request thrust, based on the conjugate-gradient method, is computed using the condition in Figure 5, where the thrust is determined by $y = 5x + 17.429$. Here, y is required to have total trust, and x is the payload of mass (kg). The frame configuration was designed to provide adequate structural rigidity while maintaining lightweight characteristics to support efficient flight performance during agricultural spraying operations. The propulsion and spraying systems were selected based on the lifting power requirements and spray distribution characteristics to ensure stable hovering capability and uniform droplet application during operation. Previous studies reported that UAV sprayer systems require proper integration between thrust capability, payload capacity, spraying mechanism, and flight control stability to achieve effective pesticide and liquid fertilizer application in precision agriculture [36], [39].

The results of the drone sprayer assembly are shown in Figure 8. The figure presents the main components of the developed agricultural drone spraying system, comprising the drone sprayer unit and the remote-control interface for autonomous flight operations. Panel A shows the quadcopter-based agricultural drone equipped with a liquid storage tank, spraying nozzles, landing gear, and navigation modules designed for precision agriculture applications. The drone is designed to efficiently spray pesticides and liquid fertilizer over agricultural fields while reducing manual labor requirements. Panel B illustrates the remote controller integrated with a real-time monitoring and navigation display. The controller provides flight telemetry data, field-mapping visualization, and autonomous route planning using GNSS/GPS technology. Through this interface, operators can monitor flight parameters, define spraying boundaries, and execute automated spraying missions accurately and efficiently. The

P-ISSN: xxxx-xxxx | E-ISSN: xxxx-xxxx Website: https://jatdi.id/
Vol. 1, No. 1, July 2026, Page. 1-19 DOI: https://doi.org/10.20884/1.jatdi.1.1.7

integration between the drone platform and intelligent remote-control system enables precise and consistent spraying operations in modern smart farming applications.

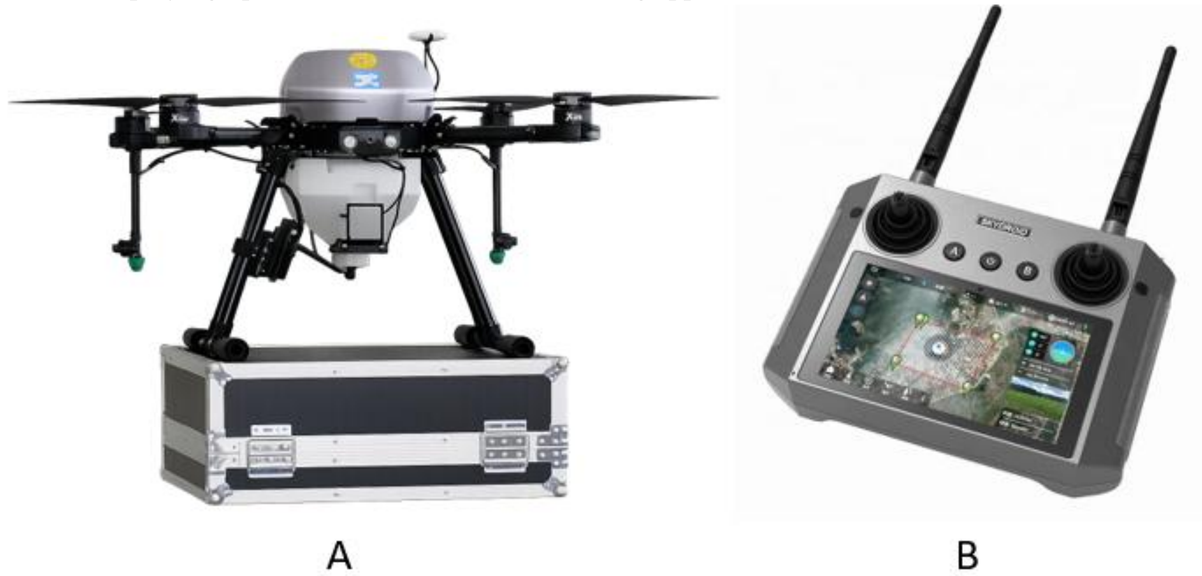

Figure 8. (A) Agricultural drone sprayer platform developed for precision spraying applications and (B) remote controller interface displaying autonomous navigation and field mapping during spraying operations.

After the assembly stage, flight testing was conducted to evaluate the operational performance, maneuverability, hovering stability, payload capability, and spraying effectiveness of the developed drone prototype. The testing procedures included take-off and landing evaluation, hovering stability observation, forward-flight maneuver testing, payload-carrying assessment, and spraying performance analysis during the application of liquid fertilizer and pesticides. Several operational parameters were monitored, including battery consumption, motor response, thrust balance, spraying coverage area, and flight endurance under varying payload conditions. Experimental studies in UAV spraying systems indicate that payload variation, nozzle configuration, flight altitude, and flight speed significantly influence spraying uniformity and overall flight stability during agricultural operations [37], [40].

Figure 9 illustrates the implementation of an autonomous agricultural drone spraying system integrated with GNSS/GPS-based navigation technology for precision farming applications. Panel A shows the agricultural drone sprayer in operation, with the drone performing automated spraying under the operator supervision via a remote controller. The drone is equipped with a liquid tank, spraying nozzles, navigation modules, and a multi-rotor propulsion system designed to support stable flight and uniform distribution of spray over agricultural land. Panel B shows the autonomous flight route displayed on the remote controller interface during spraying. The system generates parallel flight paths within the predefined field boundary to ensure complete and efficient area coverage. Real-time operational parameters, including altitude, flight speed, spray flow rate, completed coverage area, and remaining tank capacity, are continuously monitored via the interface. The integration of autonomous route planning and real-time telemetry enables accurate spraying operations, minimizes overlap, and improves operational efficiency in modern precision agriculture systems.

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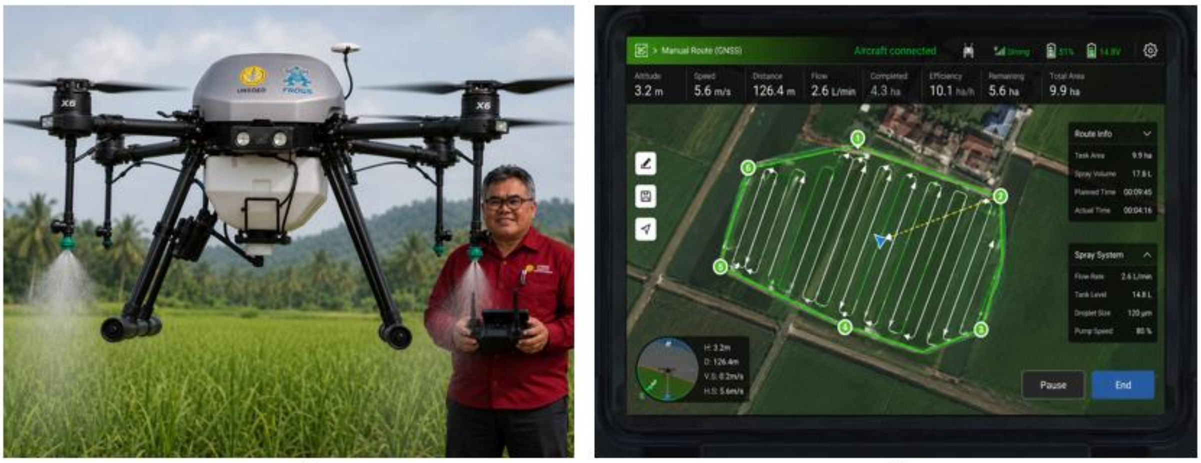
P-ISSN: xxxx-xxxx | E-ISSN: xxxx-xxxx Website: https://jatdi.id/
Vol. 1, No. 1, July 2026, Page. 1-19 DOI: https://doi.org/10.20884/1.jatdi.1.1.7



A B

Figure 9. (A) Agricultural drone sprayer performing autonomous spraying operations in the field and (B) GNSS/GPS-based remote controller interface displaying automatic spraying flight paths and real-time operational parameters.

The test results demonstrated that the developed drone sprayer prototype maintained stable flight characteristics while carrying liquid payloads and spraying effectively. The optimized thrust configuration contributed to improved flight stability, efficient power utilization, and consistent spraying performance. Furthermore, the developed system showed potential for supporting precision agriculture applications by reducing manual labor exposure to agrochemicals and improving spraying efficiency compared with conventional manual methods [39], [40].

6. CONCLUSION

This study successfully developed and evaluated an agricultural drone sprayer system for precision spraying using a simplified quadcopter platform integrated with GNSS/GPS-based autonomous navigation. The proposed Conjugate Gradient optimization method effectively improved the lifting-force configuration, propulsion efficiency, and flight stability under varying payload conditions. The optimization reduced the optimization error from 12.5% to 0.22%, while the required total thrust was optimized to [value] N, ensuring sufficient lift for stable flight. Furthermore, the Flight Stability Index (FSI) increased from 62% to 98%, indicating enhanced flight stability during low-altitude spraying operations. Experimental flight tests confirmed stable hovering performance, accurate autonomous navigation, and uniform spraying distribution, demonstrating the effectiveness of the proposed optimization framework.

The proposed optimization model provides an important contribution to precision agriculture by introducing a computationally efficient approach for optimizing aerodynamic performance through the simultaneous evaluation of optimization error, required total thrust, and flight stability. Unlike conventional trial-and-error parameter tuning, the proposed framework offers a systematic optimization strategy that can improve flight efficiency, reduce energy consumption, enhance spraying accuracy, and support safer agricultural operations by minimizing direct human exposure to agrochemicals. These findings also provide a practical methodology for the aerodynamic design and optimization of agricultural UAVs with varying payload conditions.

Future research should extend the proposed model by incorporating computational fluid dynamics (CFD) simulations and experimental aerodynamic validation to improve lift prediction accuracy. In addition, adaptive optimization techniques based on machine learning or reinforcement learning should be integrated to enable real-time optimization under changing payloads and environmental disturbances.

P-ISSN: xxxx-xxxx | E-ISSN: xxxx-xxxx Website: https://jatdi.id/
Vol. 1, No. 1, July 2026, Page. 1-19 DOI: https://doi.org/10.20884/1.jatdi.1.1.7

Further studies should also investigate the effects of liquid properties, nozzle configurations, droplet sizes, wind speed, crosswind conditions, and battery degradation on flight performance and spraying efficiency. Finally, large-scale field experiments across different crop types and terrain conditions are recommended to validate the robustness, scalability, and practical applicability of the proposed optimization framework for precision agriculture.

CONFLICT OF INTEREST

I, the single author, declare that there is no conflict of interest between the others researcher and the research object in this paper.

ACKNOWLEDGEMENT

I, the single author, would like to express my sincere gratitude to the Ministry of Higher Education Research and Technology, the Rector of Universitas Jenderal Soedirman, and the Chair of the Institute for Research and Community Service (LPPM), for providing research funding through the Matching Fund Kedaireka program under contract numbers Diktiristek: 386/E1/KS.00.00/2024 and Unsoed: T/902/UN.23/PT.01.03/2024. I also extend my appreciation to all students and staff members of the Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Jenderal Soedirman, PT. Bangun Kreasindo Adhinata Purwokerto, and PT. Inovasi Solusi Transportasi Indonesia (PT. Frogs Tbk) for their valuable support and contribution of data to this research.

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