

RESEARCH ARTICLE OPEN ACCESS

UAV-Based Precision Seed Dropping for Automated Reforestation

Qi Rui Lee¹  | Henrik Hesse¹  | Khuanphirom Naruangsri²  | Worayut Takaew²  | Stephen Elliott²  | Dinesh Bhatia³ 

¹James Watt School of Engineering, University of Glasgow, Glasgow, UK | ²Forest Restoration Research Unit, Chiang Mai University, Chiang Mai, Thailand | ³School of Science, Engineering & Technology, RMIT University, Ho Chi Minh City, Vietnam

Correspondence: Henrik Hesse (henrik.hesse@glasgow.ac.uk)

Received: 25 August 2025 | **Revised:** 23 July 2026 | **Accepted:** 17 August 2026

Funding: APNIC Foundation, Grant/Award Number: 202403-02759

Keywords: automated seeding | precision agriculture | reforestation | seed-based restoration | UAV

ABSTRACT

Wildfires and deforestation pose significant threats to forest ecosystems, motivating scalable methods for reforestation beyond labor-intensive cultivation of native forest seedlings in nurseries. To enable large-scale direct seeding of native species, this paper presents the design, analysis, and field evaluation of a UAV-based seed-dropping system. The approach integrates a lightweight carriage mechanism for gravity-based seeding systems with an open-source multirotor UAV to enable precision seeding operations. Precise seed placement enables adherence to ecologically motivated spacing, for example, 1.8 m for framework-species plots, which broadcast seeding cannot readily achieve. Additionally, the system uses 30 mm biochar-coated seed balls, which facilitate the handling of multiple seed varieties and enhance overall germination success in framework-species approaches. The autonomy stack combines LiDAR-based terrain following with deterministic actuation and on-board seed-drop confirmation via an outlet limit switch, providing a geotagged record of each seed drop for post hoc analysis of the reforestation efforts. Field evaluations at an active reforestation site in Northern Thailand have demonstrated the feasibility of the proposed solution. An altitude sensitivity study at 5, 10, and 15 m height revealed wind-aligned drift and terrain interactions; operations at 3–5 m height were found to provide practical operating windows for precision deployments, with 95% of drops landing within 0.66 m of the target for a controlled test at 5 m height. A representative 27-waypoint autonomous mission demonstrated a 90% success rate, with 24 drops confirmed by the on-board system and matched ground observations. Unlike conventional aerial seeding systems, the proposed precision seed-dropping approach significantly reduces seed wastage, making the solution scalable for large-scale ecological restoration and biodiversity recovery initiatives.

1 | Introduction

Wildfires and deforestation pose significant threats to forest ecosystems, highlighting the need for large-scale initiatives to restore destroyed forest areas. Recent examples include catastrophic fires in North America, Australia, and tropical Asia, which have destroyed millions of hectares of vegetation and significantly reduced natural regeneration capacity (British Columbia 2025; Noble 2020). In particular, the

evergreen forests of Northern Thailand remain highly vulnerable to large-scale wildfires during the dry season (Puttapirat et al. 2024; Ong et al. 2025), disrupting forest ecosystems and significantly degrading the air quality in the region (Chen and Kocha 2023). These events underscore the importance of developing restoration methods that are both scalable and resilient under increasingly unpredictable environmental conditions.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Journal of Field Robotics* published by Wiley Periodicals LLC.

In response, major international programs, such as the United Nations Decade on Ecosystem Restoration Program and the Trillion Trees Initiative (United Nations 2021; WWF 2025), have emphasized rapid and large-scale reforestation as a critical strategy for reversing ecosystem degradation and biodiversity loss. Regional initiatives throughout Europe, North America, and Asia similarly aim to restore substantial forested areas through scientifically informed approaches (Cruz 2025). In Southeast Asia, the Forest Restoration Research Unit at Chiang Mai University (FORRU-CMU) has led restoration efforts for more than two decades using the Framework Species Method, which relies on carefully selected native tree species to accelerate forest recovery (Elliott et al. 2013).

Conventional reforestation methods rely on nursery propagation and manual planting of seedlings. While ecologically effective, these labor-intensive approaches are slow to scale and limited by the logistical challenges of transporting seedlings to remote or mountainous terrain. To overcome these limitations, there is increasing interest in the use of Unmanned Aerial Vehicles (UAVs) to automate and accelerate reforestation efforts. Several commercial initiatives have demonstrated the feasibility of this approach (Nonko 2023; Walker 2021; Asher 2023). Yet, for ecological restoration purposes, UAVs must be able to deploy individual seed balls at precise locations and operate reliably in real environmental conditions. Seed spacing is critical for the establishment of young forests. In practice, restoration guidance uses close spacing to accelerate canopy closure, e.g. species-specific trials motivate spacing of 2 by 2 m (Elliott et al. 2013; Bahru et al. 2023).

Hence, there is a clear need for systematic research and validation of UAV-based seeding as an established tool for ecological restoration. This paper presents the design and development of a UAV system for precision seed dropping in the context of reforestation applications in Northern Thailand. The work aims to address key challenges in automated reforestation systems, including seed delivery accuracy, operational reliability, and deployment efficiency, with the goal of contributing to a scalable approach for future reforestation programs.

1.1 | Problem Statement: Reforestation Efforts in Northern Thailand

Northern Thailand's upland evergreen forests remain highly vulnerable to degradation caused by wildfires, land conversion, and prolonged dry seasons. Restoration programs in this region, led by FORRU-CMU, have developed detailed, science-based approaches using the Framework Species Method (FSM) to accelerate forest recovery through the establishment of carefully selected native tree species (Elliott et al. 2013). While effective, these traditional restoration methods depend on seedling nurseries, transportation to remote sites, and labor-intensive manual planting in remote, inaccessible areas (Goldapple 2017; Stamatopoulos et al. 2024).

Direct seeding offers a promising alternative, as seeds are sown directly into the soil at the restoration sites,

eliminating the need for nursery infrastructure (Waiboonya and Elliott 2020; Naruangsri et al. 2023). However, direct seeding is often associated with lower establishment rates when compared to nursery-grown seedlings (Grossnickle and Ivetic 2017). Seeds are easily removed by wildlife in exposed landscapes (Naruangsri et al. 2023). Another issue is the result of blanket seeding, which spreads seeds randomly over the terrain, leading to uneven seed distribution and undesirable tree clusters (Stamatopoulos et al. 2024). This makes direct seeding unsustainable for large-scale projects, which naturally demand a reliable and continuous seed supply (Velasquez-Camacho et al. 2021). Moreover, viable seeds for native forest species are inherently scarce. They need to be collected by hand from wild stands and curated under species-specific storage protocols. Every lost seed, therefore, carries a high opportunity cost, making low-waste deployment essential (Elliott et al. 2013; Waiboonya and Elliott 2020).

Seed coating addresses several of these challenges by improving handling, reducing predation, and creating a uniform size suitable for mechanical delivery (Allen 2007; Fukuoka 2013). Inspired by agricultural permaculture practices, encapsulating seeds in biodegradable coating material creates a secure environment for germination and reduces predation risks (Taylor et al. 2020; Zhang et al. 2022). The seed balls used in this study, shown in Figure 1, measure approximately 30 mm in diameter and weigh about 17.5 g (Naruangsri 2023; Naruangsri et al. 2024). These parameters impose strict design requirements on any UAV-based delivery mechanism, particularly regarding payload capacity, seed-handling geometry, and jamming resistance.

Despite the promise of seed balls and direct seeding, there exists no lightweight and reliable deployment mechanism specifically designed for precision seeding of large forest-restoration seed balls. Current UAV seeding systems are either designed for small agricultural seeds or rely on complex pneumatic systems that exceed the payload limits of common multirotor UAV platforms. Hence, the limitations of current seeding technologies can be summarized as:

- lack the ability to release individual seeds on demand,
- rely on blanket seeding methods and dispersal patterns,
- use pneumatic systems that are too heavy and mechanically complex for lightweight multirotor UAVs, and
- are prone to jamming when handling irregular or larger seed formats.

At the scale of emerging billion-tree initiatives, these constraints amplify that seed supply, reforestation logistics, and seedling survival are critical. This is infeasible without mechanisms that minimize seed wastage and provide auditable deployment. Despite growing commercial deployments, peer-reviewed quantitative evaluations of UAV-based direct seeding for native forests remain scarce, particularly for (i) seed preparation and coating/pelleting, (ii) UAV-based dispersal mechanisms for large pellets, and (iii) the effects of release height, wind, and terrain on placement accuracy (Stamatopoulos et al. 2024; Mohan et al. 2021).

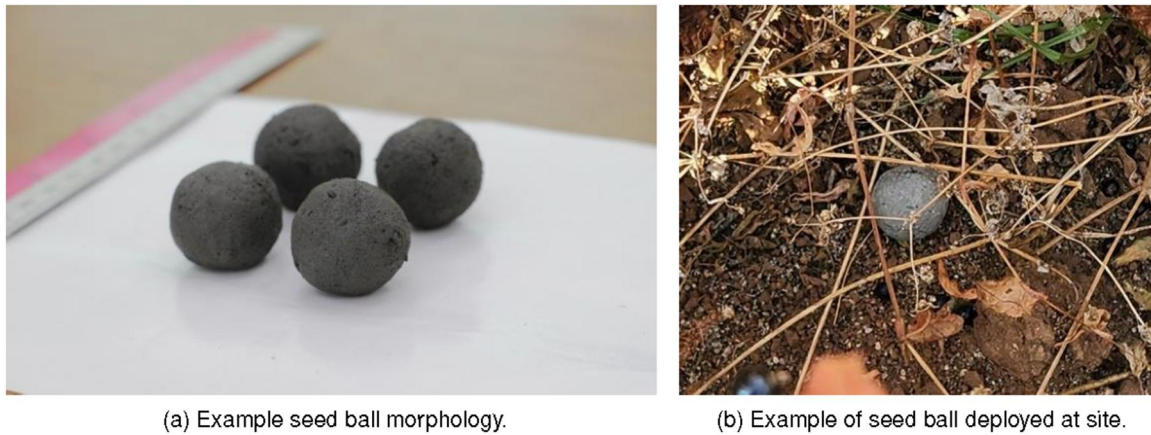


FIGURE 1 | Overview of biochar-based seed balls used in this study to incorporate *Sarcosperma arboreum* seeds. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

1.2 | Related Work: UAV-Based Aerial Seeding

UAV-based seeding has gained increasing attention as a promising tool for ecological restoration. Recent commercial and research initiatives have demonstrated that UAVs can support efficient direct seeding across large and inaccessible landscapes, enabling rapid intervention after disturbances such as wildfire or land degradation (Elliott et al. 2020). Several studies have proposed the use of UAVs in automated reforestation, leveraging the capabilities of UAVs across multiple stages of the reforestation life cycle, including pre-deployment mapping, ecological site analysis, automated seed dispersal, and post-deployment monitoring (Mohan et al. 2021; Castro et al. 2024; Kim et al. 2019).

The effectiveness of UAV-based reforestation is driven by the performance of the seed dispersal mechanisms. Most existing designs originate from agricultural applications, which typically handle small seeds such as rapeseed, rice, or wheat (Kim et al. 2019; Huang et al. 2020). However, native tree seeds in tropical forests normally vary greatly in size (Naruangsri et al. 2024). Given these requirements, UAV-compatible seed dispersal systems must be lightweight, robust, and versatile to accommodate diverse seed morphologies while providing precise timing and spatial distribution of seed release. These factors drive the classification of existing seed-dropping systems, as described next (Mohan et al. 2021).

Gravity-Drop Seeding Systems are widely employed in large-scale agricultural operations for distributing seeds, fertilizers, or animal feed from hoppers. These systems can be categorized into either constant mass flow or precision drop devices (Lysych et al. 2021). Constant mass flow devices use stationary openings controlled by flaps or shutter mechanisms similar to camera apertures, which can be adjusted to regulate the sowing rate (Karademir 2025). More advanced constant mass flow mechanisms employ fluted rollers or rotating drums driven at constant speeds to achieve more consistent seed release rates (Kus 2021). However, these methods are not suitable for targeted seeding operations in reforestation projects. Instead, *precision drop systems* aim to

enhance seed placement accuracy through mechanical mechanisms, such as rotating discs, or vacuum-based approaches (Zhong et al. 2024). Vacuum-based systems use suction to securely hold and precisely release seeds from perforated discs. This offers high precision and uniform spacing common in ground-based agricultural machinery. However, adapting vacuum suction systems to UAVs is challenging due to the weight and complexity of the required vacuum systems. Regardless of the underlying mechanical design, gravity-based systems are vulnerable to environmental factors, including wind conditions, UAV propeller downwash, and altitude, which can significantly affect seed dispersion accuracy (Zhu et al. 2025).

Other common seeding mechanisms used in agriculture consider *Centrifugal Seeding Systems*, which incorporate fast-spinning discs to radially accelerate and evenly distribute seeds over targeted areas (Song et al. 2018). Similar to constant mass flow devices, centrifugal seeding systems cannot control the release of individual seeds for precision applications, leading to seed wastage and making this approach less suitable for UAV-based reforestation applications. Centrifugal systems are often integrated with *Airflow Seeding Systems* where airflow generated by fans directs seeds through nozzles (Huang et al. 2020; Yuan et al. 2024). The speed and direction of the airflow can be adjusted to control the distribution pattern and density of the seed dispersal (Zhu et al. 2025). Despite the improved performance, airflow systems increase the mechanical complexity and weight of the seeding system, and they also lack the required precision. Finally, *Pneumatic Seeding Systems* use compressed air to propel seeds into the soil (Zhang et al. 2023; Govender et al. 2022). The system provides optimal placement precision and soil penetration, which can help germination and protect seeds from predation (Lysych et al. 2021; Liu et al. 2023). While the dispersal precision makes this seeding system ideal for reforestation projects, the complexity and weight of the pneumatic mechanisms lead to high payload requirements and much larger UAV systems. These systems also tend to block. To overcome this, seeds are typically encapsulated in standardized seed balls, which also accommodate varying seed sizes and protect seeds during impact.

Across these categories, several consistent limitations emerge when the mechanisms are evaluated for forest restoration rather than agriculture:

- They are optimized for small, lightweight seeds, not larger seed balls.
- They rarely support single-seed, on-demand dispensing integrated with UAV systems.
- Mechanisms offering precision tend to be too heavy for typical multirotor UAVs.
- Blanket seeding systems lack spatial accuracy required for ecological planting approaches.
- Most systems have not been validated in uneven terrain or with seed balls of the mass and geometry relevant to forest restoration.

Therefore, no existing UAV seeding system satisfies the combined requirements of precision, reliability, compatibility, low mechanical complexity, and adaptability needed for large-scale applications of tropical forest restoration. Few UAV systems explicitly enforce ecologically motivated interplant spacing, underscoring the need for single-seed, spacing-enabled actuation (Bahru et al. 2023).

1.3 | Objectives, Contributions, and Scope

Based on these identified challenges, the objective of this work is to design, implement, and field-validate a UAV-based precision seed-dropping system specifically tailored to forest-restoration seed balls and the environmental conditions of Northern Thailand. The key contributions of this paper are:

1. A novel design of a gravity-fed seeding mechanism capable of releasing individual seed balls on command while remaining lightweight and compatible with multiple seed species.
2. A structured design methodology, including a quantitative comparison of existing mechanisms and a detailed analysis of the proposed design.

3. Integration of the mechanism with an open-hardware multirotor UAV platform for automated seeding missions, incorporating autonomous waypoint navigation, terrain-following in hilly terrain, and a real-time seed-drop confirmation system for post-deployment assessment.
4. Comprehensive experimental field evaluation, including laboratory testing, controlled indoor trials, outdoor field experiments, and full deployment at an active restoration site.
5. A discussion and evaluation of system limitations, environmental sensitivities, and pathways for scaling the concept to large-scale reforestation missions.

This work represents the first demonstration of a UAV-based precision seeding system, which combines a lightweight gravity-fed carriage system with multi-species seed deployment and terrain-following. The system is field-validated and the accuracy is demonstrated using seed balls for real-world restoration settings.

The remainder of the paper is organized as follows. Section 2 details the concept, hardware design, and software implementation of the UAV-based seed dropping platform. Section 3 presents the experimental evaluation of the system, including indoor validation results and initial field tests. Section 4 discusses the field implementation in Northern Thailand. Section 5 discusses the insights gained from field tests and concludes the paper with suggestions for large-scale implementation.

2 | Concept, Design, and Implementation of Seed-Dropping System

This section presents the overall system architecture, the design rationale of the precision seed-dropping mechanism, and its integration with a multirotor platform and the flight-control software stack.

2.1 | System Overview

The UAV-based seed-dropping system integrates a custom mechanical dispenser with a quadrotor platform to enable



(a) Conceptual design with seed mechanism in gray.



(b) Field testing of the actual system.

FIGURE 2 | System overview of the proposed UAV-based seed-dropping mechanism. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

precision aerial seeding for reforestation applications. As shown in Figure 2, the system is composed of two major subsystems: (1) the quadcopter UAV platform, and (2) the proposed seed delivery mechanism.

The X500 quadcopter UAV used in this work provides a versatile research platform commonly considered for aerial robotics projects (Holybro 2025). The X500 is an open-hardware research platform with modular payload mounting and a Pixhawk-class flight controller, suitable for controlled experiments in autonomy and payload control. We adopt the Pixhawk/Ardupilot environment (Pixhawk 2024) as the open-source flight stack to implement the fully autonomous seeding operation, as introduced in Section 2.4. A downward-facing LiDAR enables terrain-following altitude control, which is essential for maintaining consistent drop height over uneven reforestation landscapes.

Considering the specifications of the seed balls (30 mm, 17.5 g) in Section 1.1 and the technical specifications of the UAV system in Table 1, the initial design constraints of the baseline UAV system are defined. The UAV is powered by four KV920 brushless motors, which can deliver a maximum combined thrust of approximately 5 kg using 10-inch propellers. Considering the allowable payload specified by the manufacturer and the measured battery mass, a maximum mass of approximately 1000 g is available for the seed-dropping mechanism while maintaining adequate thrust-to-weight margins for safe and stable flight (Ong et al. 2019). The flight endurance was assessed through experimental flight tests using a 5000 mAh LiPo battery under no-payload conditions, resulting in an average flight time of approximately

TABLE 1 | Technical specifications of Holybro X500 V2 UAV and initial flight test results.

Parameter	Value
Wheelbase ^a	500 mm
Frame Mass ^a	610 g
Allowable Payload Mass (incl. battery) ^a	1500 g
Battery Mass (5000 mAh LiPo) ^b	542 g
Flight Time (under no-payload) ^b	18 min

^aObtained from the Holybro X500 V2 manufacturer specifications (Holybro 2025).

^bMeasured experimentally.

TABLE 2 | System design specifications of UAV-based seed-dropping mechanism.

Aspect	Objective	Criteria
UAV function	Autonomous route following	UAV with autonomous waypoint following.
Reliability	Consistent seed dropping	Seed-dropping mechanism to achieve at least a 90% success rate in seed deployment per mission.
Capacity	Maximize seed capacity	Tank to hold a minimum of 30 seed balls.
Performance	Seed dispensing speed	Dispense at least 1 seed ball per second.
Precision	Seed metering rate	Controlled seed dispensing, one seed ball per command.
Mass	Adhere to payload limits of the UAV	Total mass of mechanism should not exceed 1,000 g.

18 min. This provides the starting point for defining the design requirements of the seed dropping mechanism in the next section. A detailed analysis of the system, including a thrust analysis, will be discussed in Section 3.

2.2 | Design of Seed-Dropping Mechanism

2.2.1 | Design Requirements and Constraints

Effective reforestation using UAVs depends strongly on the precision and reliability of the seed-dropping process. These considerations define the design requirements summarized in Table 2. As discussed in Section 1.2, most existing UAV-based seeding systems rely on blanket seeding methods (Stamatopoulos et al. 2024), which distribute seeds broadly along the flight path and often result in uneven spatial patterns and low establishment rates. A precision mechanism is therefore required to deliver individual seed balls at specified locations, thereby reducing seed wastage and improving ecological outcomes.

Pneumatic and suction-based precision mechanisms offer accuracy but are generally too heavy for lightweight multirotors and are frequently prone to jamming, especially when handling large or irregular seed formats (Lysych et al. 2021). However, the UAV constraints listed in Table 1 impose strict limits on payload mass, component dimensions, and power consumption, all of which directly influence the achievable hopper capacity and overall flight endurance.

2.2.2 | Concept Generation and Quantitative Selection

We applied the total design methodology by Pugh (1991) to generate design concepts and compare them consistently against the design requirements in Table 2. Based on a review of designs in Section 1.2, three gravity-based concepts were generated: (i) a rotating drum with a single cavity (Figure 3), (ii) an iris-type aperture (Figure 4), and (iii) a translating carriage (Figure 5). The considered design concepts were evaluated using 3D modeling and simulation, as shown in Figures 3–5, to assess mechanical feasibility and compatibility with the UAV platform. We limited the design scope to gravity-based, mechanical mechanisms for precision drop, as pneumatic systems were deemed too heavy and unreliable given the design requirements (Lysych et al. 2021).

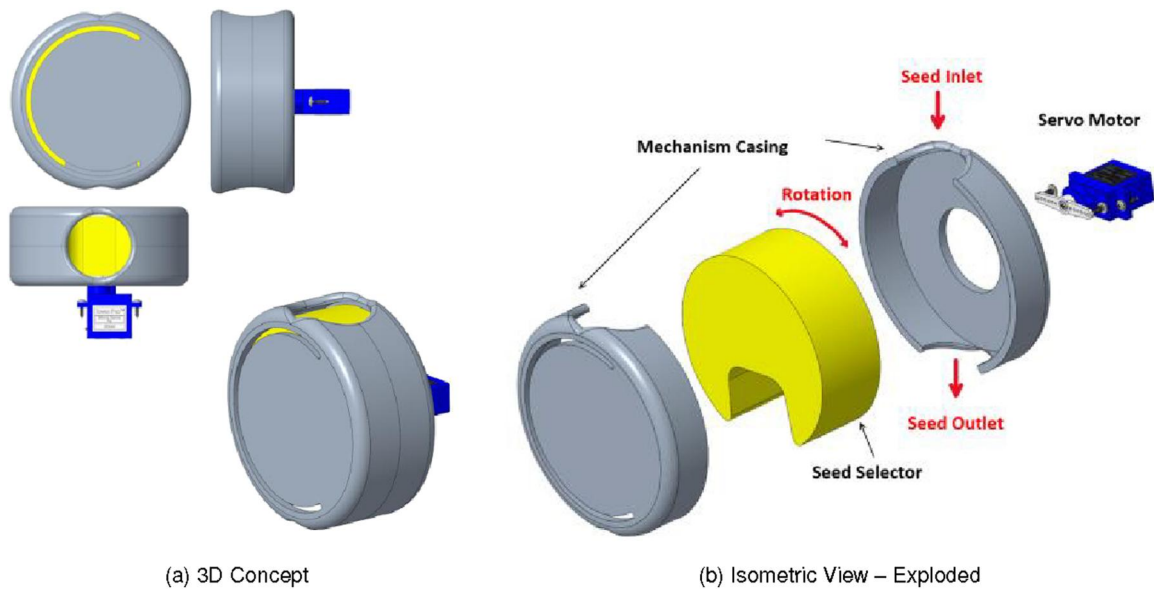


FIGURE 3 | Generated conceptual designs for the seed-dropping mechanism. Concept 1: Rotating Drum. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

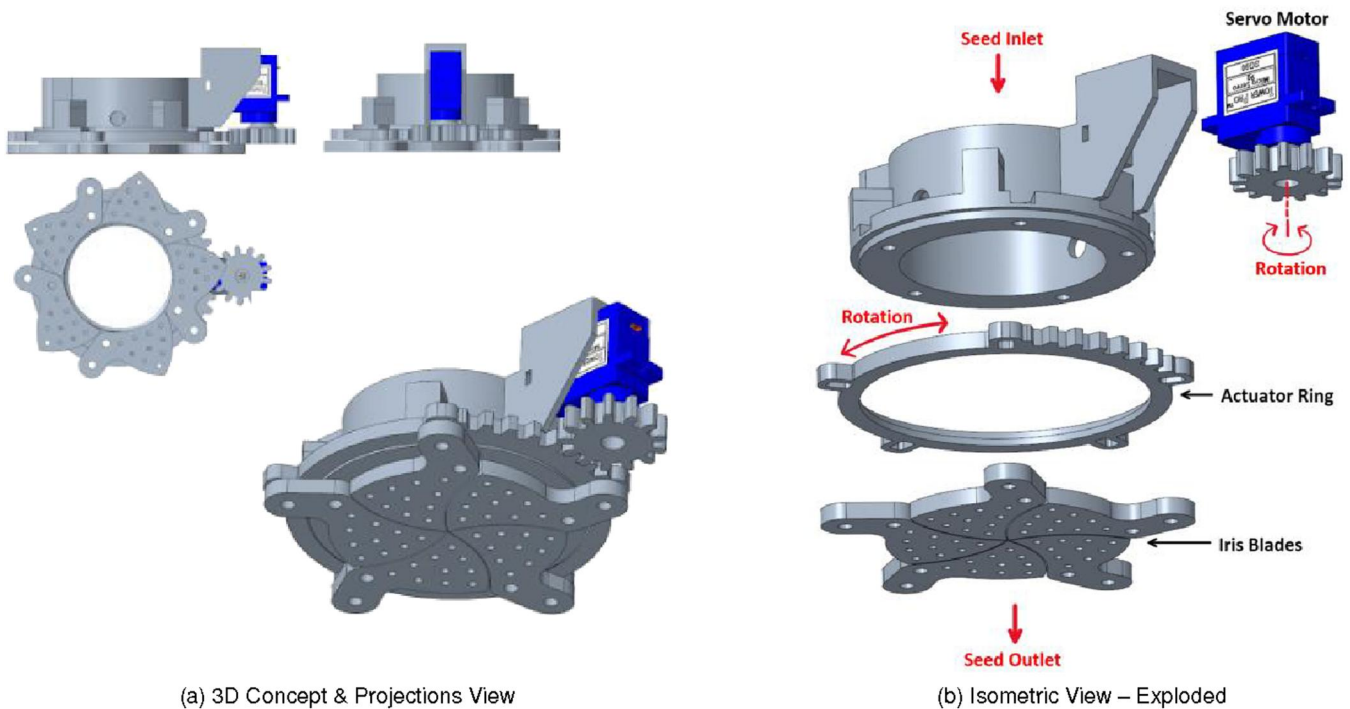


FIGURE 4 | Generated conceptual designs for the seed-dropping mechanism. Concept 2: Aperture. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

Similar to the design by Zhong et al. (2024), the *Rotating Drum Concept* presented in Figure 3 is a cylindrical seed selector that consists of a drum with a single hole. A servo motor is integrated to rotate the drum, allowing individual seed balls to be released through the outlet. The *Aperture Concept* in Figure 4 feeds seed balls into an iris mechanism (Karademir 2025). A servo motor rotates the actuator ring, which opens the iris blades, allowing seed balls to pass through the aperture. Finally, the proposed *Carriage Mechanism Concept* in Figure 5 is a novel concept that has not been explored previously for precision

seeding operations. The mechanism consists of a translating carriage that moves laterally upon servo actuation. When a seed ball inside the slot aligns with the seed outlet, the seed ball is dropped through the outlet.

Following the total design methodology (Pugh 1991), a Pugh matrix was generated as a structured tool to compare the generated concepts against the design criteria defined in Table 2. Weightings were assigned based on their relevance to the UAV-based seed deployment requirements. The

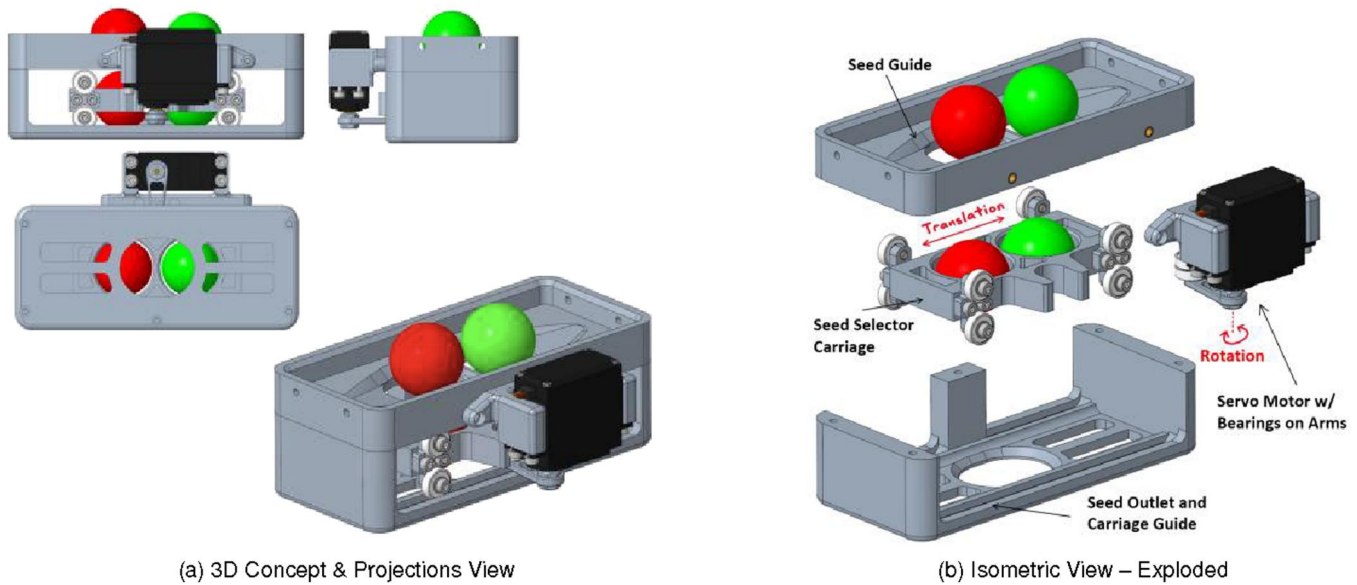


FIGURE 5 | Generated conceptual designs for the seed-dropping mechanism. Concept 3: Carriage Mechanism. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

TABLE 3 | Pugh matrix for seed-dropping mechanism concept selection.

Criterion	Weight	Concept 1: Drum	Concept 2: Aperture	Concept 3: Carriage
Reliability	1	+	+	+
Seed dispensing speed	2	++	++	0
Controlled dispensing	2	—	—	++
Different types of seeds	3	0	0	++
Light weight	1	+	+	—
Low complexity	1	+	0	—
Weighted total		+3	+2	+9

ratings in Table 3 are based on the expected operation of each concept, with +, 0, and - indicating favorable, neutral, and unfavorable performance, respectively. The conventional rotating drum (Concept 1) and aperture mechanism (Concept 2) both feature simpler designs than Concept 3, resulting in favorable ratings for weight and complexity. While both designs can release seeds at high rates due to their simple release mechanism, resulting in positive ratings for seed dispensing speed, they lack the ability to release individual seeds in a controlled manner. Hence, Concept 3 is superior in terms of controlled dispensing and the ability to release different types of seeds. However, the carriage must move to the release position and return to the loading position for each drop, resulting in a lower dispensing speed than the other concepts. Overall, Table 3 shows that Concept 3 (Carriage Mechanism) achieved the highest score, outperforming the other concepts in seed dispensing accuracy and versatility.

2.2.3 | Detailed Design of Carriage Mechanism for Precision Seed Dropping

Using Concept 3 as a starting point, a detailed design of the Carriage Mechanism was developed, considering the structural

and operational constraints of the UAV platform. The design boundaries included payload mass and mounting dimensions. We also ensured that the center of gravity remains at the center of the UAV to maintain stability (Ong et al. 2019). To reduce the influence of rotor downwash on the release trajectory, the outlet is placed away from the propeller wash and aligned with the vehicle heading to keep disturbance minimal (Hou et al. 2024).

Figure 6 (right) shows the final design of the seed dropping mechanism fully integrated with the UAV frame. The seed hopper (item 2) is securely mounted onto the UAV with the mounting bracket (item 1). Each hopper (item 2) can carry 20 seed balls, which are fed into the seed selector carriage (items 3-6). The carriage is actuated by a servo motor (item 4), which translates the carriage horizontally to align a seed cavity with the outlet and releases a single seed per command. The cavity dimensions were chosen to admit exactly one 30 mm seed ball with minimal clearance. The rear throat offset prevents a second seed ball from entering during translation. The outlet (item 7) integrates a limit switch sensor (item 8), which is used to detect the presence of seeds falling through the outlet. The limit switch provides real-time confirmation of each successful drop, enabling feedback to the ground station or operator (see software implementation in Section 2.4).

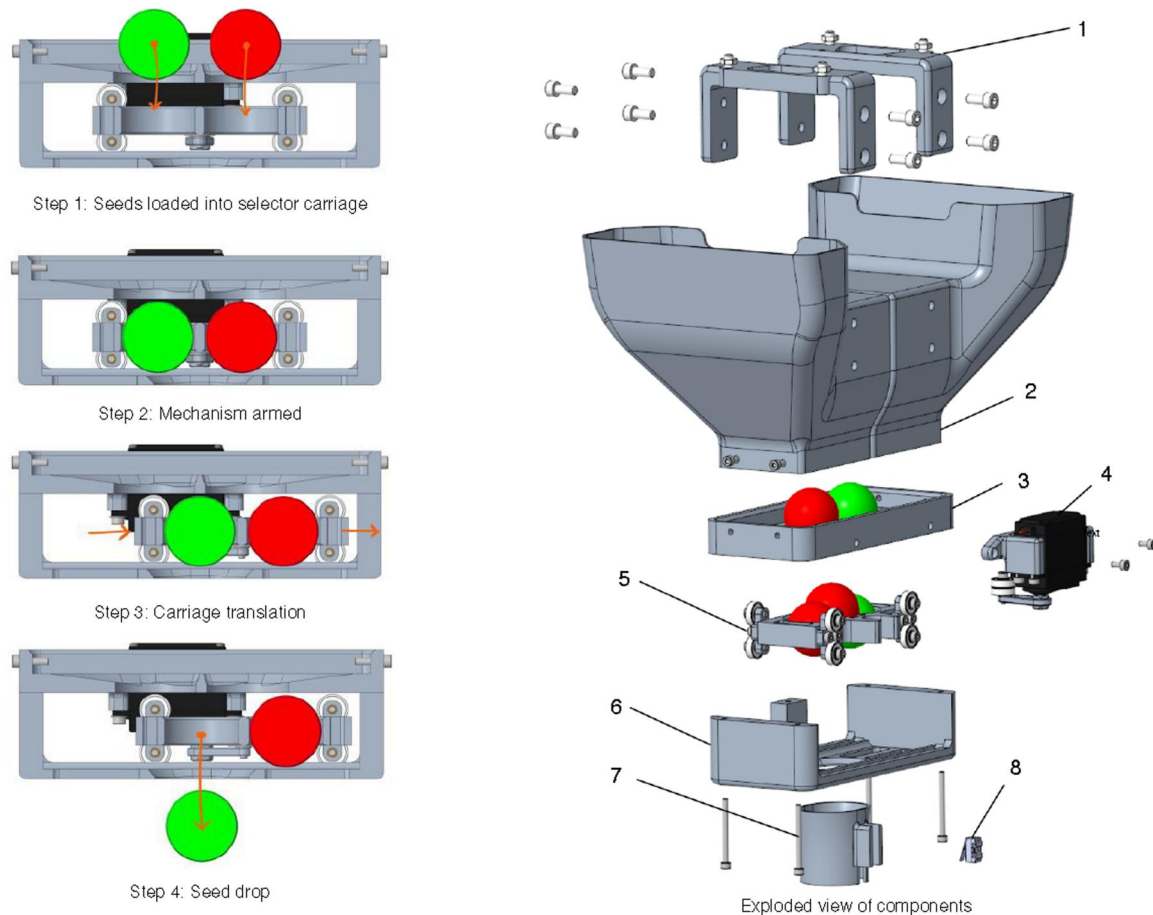


FIGURE 6 | Detailed design of the seed-dropping mechanism with operational sequence (left) and with the exploded view of the components: (right): 1- Seed hopper mounting bracket, 2- Seed hoppers, 3- Seed guide, 4- Servo motor with arm and mount, 5- Seed selector carriage, 6- Seed outlet and carriage guide, 7- Outlet sensing attachment, 8- Micro limit switch. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

The seed dropping mechanism follows a four-step actuation cycle, as illustrated in Figure 6 (left):

- **Step 1: Seeds Loaded into Selector Carriage**—Seeds are initially loaded from the hopper into the selector carriage. The hopper funnels a continuous supply of seeds into the carriage for subsequent dispensing.
- **Step 2: Mechanism Armed**—The seeds are now in position within the selector carriage, ready to be dispensed.
- **Step 3: Selector Carriage Translation**—Upon receiving a command for seed dispense, the servo motor activates and causes the selector carriage to translate. The seed moves from its initial position to align with the outlet hole.
- **Step 4: Seed Drop**—The seed falls through the outlet hole once the selector carriage completes its translation. This step concludes the seed dispensing cycle. The selector carriage is then reset to the center position, loading the next seed.

This design enables discrete and repeatable seed deployment with high precision. The mechanism supports up to 40 seed balls per mission via two independent hoppers, allowing for the simultaneous release of up to two tree species. The geometry was iteratively developed using simulation and fused deposition modeling 3D printing to reduce the overall weight while

maintaining structural integrity. The 3D design considers the limitations of the additive manufacturing process, for example, limiting the slope of the hopper walls. Since the mechanism relies on gravity feeding, the reliability of the seed release also depends on the continuous movement of seed balls from the hopper into the carriage. The hopper walls and throat geometry were designed to guide the seed balls toward the carriage. However, contact between adjacent seed balls may result in bridging above the hopper throat, which is an inherent limitation of gravity-based systems (Lysych et al. 2021). Hence, while the carriage system provides controlled release of loaded seed balls, the current design does not entirely remove the risk of jamming. This will be discussed further in Section 4.3.

The total mass of the final design shown in Figure 6 (right) is 660 g (excluding seed balls). This comprises 240 g for the dual-hopper assembly and 420 g for the metering mechanism (carriage, guides, servo mount, outlet, and limit-switch attachment). The effect of the additional payload on system performance and flight time will be evaluated in more detail in Section 3.3.

2.2.4 | Kinematic Analysis of the Carriage Mechanism

The proposed carriage mechanism has been designed to enforce the deterministic release of individual seed balls, as shown in

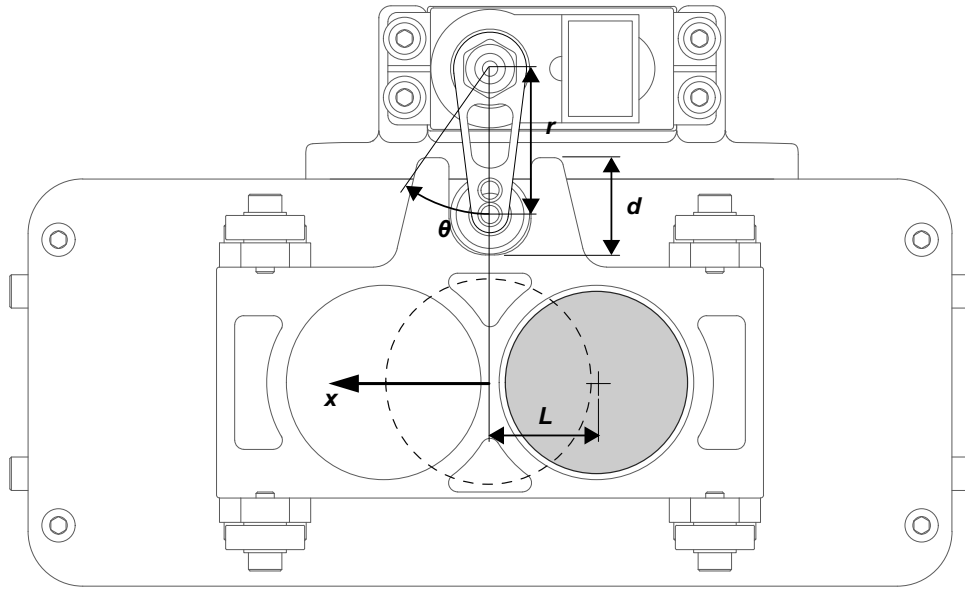


FIGURE 7 | Geometry of the carriage mechanism (bottom view) showing a seed ball (gray shading) loaded in the neutral state. The dashed circle illustrates the outlet. The kinematic parameters are defined in Table 4.

TABLE 4 | Kinematic parameters for the carriage mechanism shown in Figure 7.

Servo arm length, r	24 mm
Servo ledge height, d	17 mm
Outlet diameter	34 mm
Required translation, L	17 mm
Max. required servo rotation, θ_L	45.1 deg

Figure 7. The carriage shuttle is geometrically constrained using rollers to allow for a single translational degree of freedom, denoted by x , which corresponds to the lateral position of the selector carriage relative to the hopper throat and seed outlet.

Unlike common seeding systems found in agriculture (see Section 1.2), the proposed system operates as an actuated sliding gate in which the loading and release states are spatially separated. Three discrete carriage positions are mechanically defined:

$$x \in \{x_L, x_N, x_R\},$$

where x_N denotes the neutral (loading) position beneath the hopper throat, and x_L and x_R denote the left and right release positions aligned with the outlet. Figure 7 illustrates the neutral (loading) state ($x = x_N = 0$), in which the seed balls are loaded from the throat hopper. For clarity, only the right seed ball is shown in gray shading; in normal operation, both bays would be loaded simultaneously with seed balls. The seed outlet is not explicitly shown in Figure 7, but it is indicated by the dashed circle for reference. The outlet diameter (34 mm) was chosen to be slightly larger than the nominal seed ball diameter (≈ 30 mm) to accommodate variations in seed ball size.

The carriage translation is actuated by a rotary servo motor via a rigid servo arm of length r , as defined in Figure 7. The rotational motion of the servo, denoted by θ , is converted into lateral carriage displacement through the geometric relationship,

$$x = r \sin \theta,$$

which defines the required servo rotation to achieve the translation L between the loading and release positions. The mechanism is symmetric about the neutral position, such that $\theta_N = 0$ corresponds to $x = x_N$. The release states are achieved through equal clockwise and counterclockwise rotations to generate translations toward x_R and x_L , respectively.

To ensure a compact design and given the negligible torque requirements, the 180-deg MG996R servo with a servo arm length of $r = 24$ mm was used. The required translation was fixed at $L = 17$ mm to prevent blockage of the outlet while maintaining a compact overall geometry. Table 4 summarizes the kinematic parameters of the proposed carriage mechanism. Finally, to prevent slippage between the servo arm and the carriage shuttle, the servo ledge height $d = r \cos \theta$ was also considered in the mechanism design.

The discrete structure of the carriage mechanism is implemented through three predefined servo command states corresponding to the carriage positions x_L , x_N , and x_R . In the current implementation, these positions are realized using three Pulse Width Modulation (PWM) commands of 1100, 1500, and 1900 to translate the carriage to the left-drop, neutral-reload, and right-drop positions, respectively. For each state change, the servo mechanism requires ≈ 0.3 s. This discrete PWM-based state machine provides reliable timing and synchronization with waypoint execution during autonomous missions (see Section 2.4.2).

2.3 | UAV Integration

The final design of the seed dropper has been integrated with the HolyBro X500 V2 quadrotor platform, as shown in Figure 2. As introduced above, the multirotor UAV features a modular carbon-fiber frame and an open-source architecture that facilitates the seamless integration of custom payloads. At the core of the system architecture is the Pixhawk 6C flight controller, which is running the ArduPilot firmware (details of the flight control software are presented in Section 2.4).

The Pixhawk flight controller allows the UAV to interface with various components to enable coordinated flight and payload control. Figure 8 details the system architecture with the interfaces between the different UAV components. The flight stack is integrated with standard components to support basic UAV operation: u-blox GPS module with integrated compass for global positioning and heading, a telemetry radio for real-time bidirectional communication with the Ground Control Station (GCS), and a Radio Control (RC) receiver for manual control of the UAV and override during safety-critical operations. The electrical power is managed by a central power module and distributed via a power distribution board, which regulates the nominal voltage of 14.8 V from the 4S 5000-mAh LiPo battery to the motors and the flight control board. An additional Battery Eliminator Circuit is used to step down the

voltage to supply regulated power to the peripheral components, including the seed-dispensing servo motor and the limit switch at the outlet. Signal routing is handled through two separate Pulse Width Modulation (PWM) breakout boards, allowing for the parallel connection of the four motors and the actuators. The complete system architecture, wiring layout, and specifications of the UAV components can be seen in Figure 8.

2.4 | Software Architecture

The UAV system is managed using the ArduPilot firmware, which runs onboard the Pixhawk 6C flight controller (Pixhawk 2024). ArduPilot is an open-source, comprehensive autopilot software environment for developing fully autonomous vehicles, providing advanced flight control capabilities, custom mission scripting, and flexible integration of sensors, actuators, and external logic. We use the Mission Planner software in conjunction with ArduPilot to implement the GCS interface (MissionPlanner 2024). The Mission Planner environment provides UAV operators with tools for UAV setup, mission configuration, real-time telemetry monitoring, and data logging. These functions are implemented in this work to enable waypoint planning, low-level actuator control, and in-flight feedback monitoring required for autonomous seed deployment.

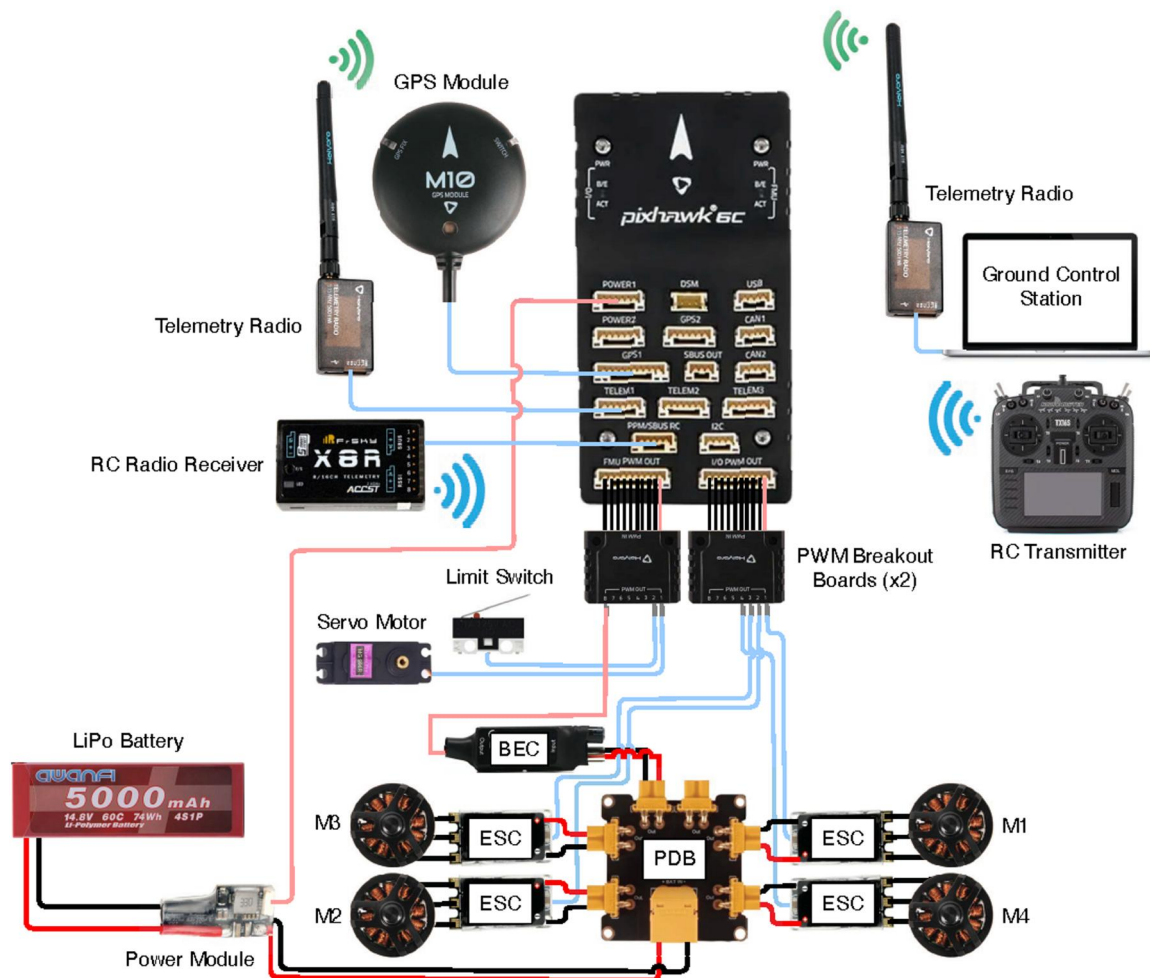


FIGURE 8 | Overview of UAV component integration. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

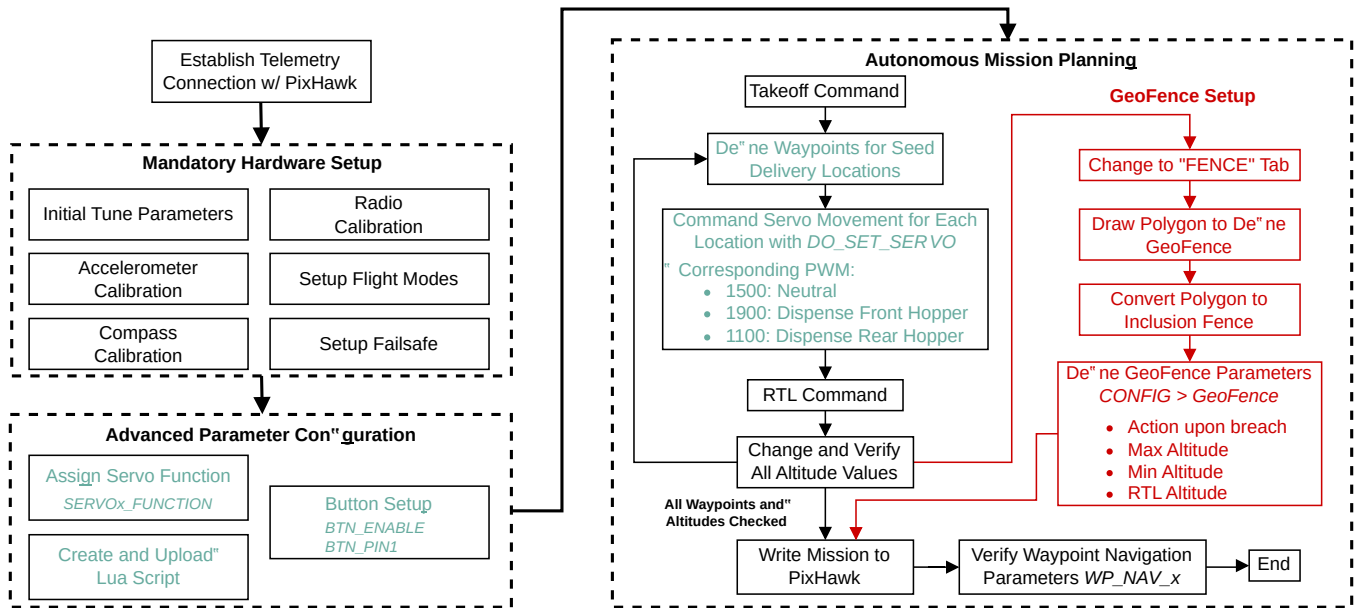


FIGURE 9 | Flowchart of software implementation using Mission Planner ground control environment. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

2.4.1 | Basic UAV System Configuration

Figure 9 presents a summary of the required steps to configure the UAV system for automated seed dispensing. The initial configuration of the UAV system follows the mandatory setup through Mission Planner. The gains of the PID-based flight controller are initialized based on system specifications, including propeller size, motor performance, and airframe size. The gains are subsequently adjusted following preliminary flight tests to account for the additional payload mass (Cheng et al. 2019). To enable autonomous flight mission profiles, we configured different flight modes using the RC transmitter to toggle between Auto and Manual modes. The UAV considers different failsafe scenarios in case the RC connection is lost or the batteries are low, triggering the automatic RETURN_TO_LAUNCH action to ensure that the UAV will return safely to the take-off position. As an additional safety feature, we implemented geofencing to restrict flight boundaries. Finally, to enable consistent seeding altitude over complex terrain, a downward-facing LiDAR (LightWare LW20C) was integrated into the flight control system for real-time, terrain-following during autonomous missions. This feature is useful for operations in mountainous regions, such as our test site in Northern Thailand, where reliance on global terrain maps (e.g. SRTM data) is insufficient due to low resolution and errors in local elevation maps. In Auto mode, the LightWare LW20C provides direct altitude-above-ground measurements of up to 100 m to dynamically adjust flight altitude along the mission path, ensuring uniform seeding height even along hillsides.

2.4.2 | Implementation of Automated Seed Dropping

As detailed in Section 2.2, the seed-dispensing carriage is actuated by a servo motor. To command the servo, it is connected to the FMU PWM OUT port of the Pixhawk flight controller via a PWM breakout board (see Figure 8). The servo is configured in Mission Planner to respond to discrete PWM

signals corresponding to three predefined carriage positions. A PWM signal of 1500 holds the carriage in its neutral center position beneath the seed hopper, allowing it to load seeds (Steps 1–2 in Figure 6). PWM commands of 1100 and 1900 translate the carriage left or right, respectively, to release individual seeds from the rear or front hoppers (Steps 3–4). This enables the integration of the seed dispensing operation within the autonomous mission profile of the UAV.

A limit switch is mounted at the outlet of the seed-dispensing mechanism to provide confirmation of successful seed release at the pre-programmed drop locations. The switch is connected to the second PWM breakout board operating at 5 V and is configured as a digital General-Purpose Input/Output (GPIO) pin. This setup enables the Pixhawk flight controller to read the switch state directly as a digital input. To support in-flight monitoring, the switch was further configured in Mission Planner as a virtual button, allowing its state to be accessed via onboard Lua scripting. This configuration enables the system to register each seed drop event and transmit confirmation messages to the GCS in real time. The total number of drops is stored as an onboard variable and displayed on the GCS during flight. Full details of the Lua script implementation are presented in Appendix A.

2.5 | Implementation of Mission Profile for Automated Seeding Operation

Mission profiles for the automated seeding operation are developed through Mission Planner by sequentially assigning MAVLink-compatible commands such as TAKEOFF, WAYPOINT, and RETURN_TO_LAUNCH. The seed release is commanded via DO_SET_SERVO to deliver PWM signals to the servo motor controlling the seed-dispensing carriage. As shown in Figure 10, the mission iterates through each waypoint k commanding the servo to dispense a seed from the

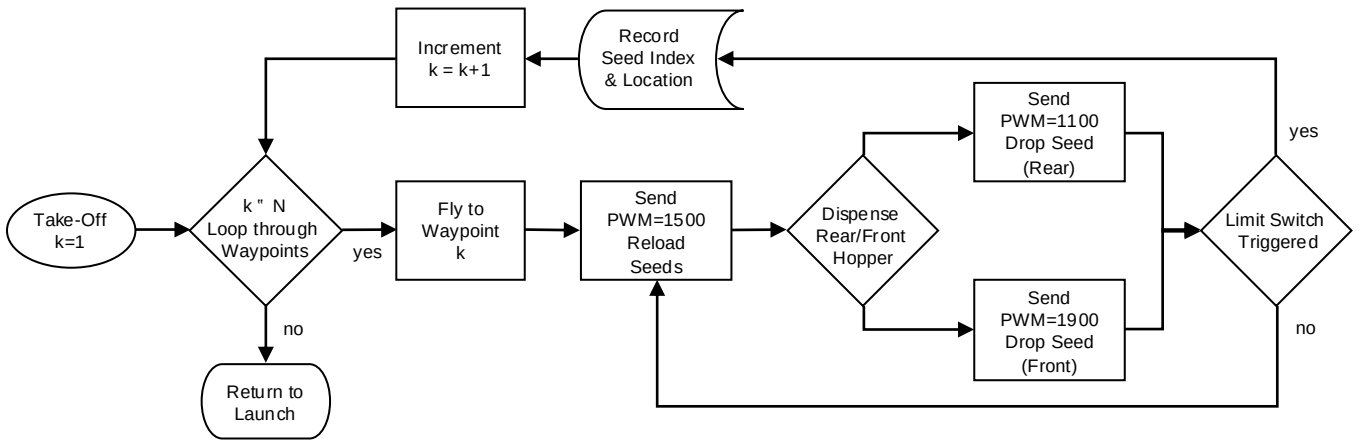


FIGURE 10 | Flowchart of mission profile for automated seed dispensing at N locations.



FIGURE 11 | Flight testing locations with planned autonomous mission waypoints (green) and geofences (blue): (1) netted futsal court; (2) outdoor field. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

appropriate hopper using a defined sequence of PWM signals: 1500 to return the carriage to its neutral loading position to reload seeds, followed by 1100 or 1900 to dispense a seed from the rear or front hopper, respectively. The sequence can be adapted to missions where different seed types are loaded in the front and rear hoppers, enabling selective release of seeds. The limit switch confirms each successful drop, which is logged and transmitted to the GCS. The mission concludes with an automatic return-to-launch sequence when all N waypoints have been completed. The implementation of the seed-dropping mechanism, mission profile, and UAV flight control has been evaluated in detail in Section 3.

To enable independent verification and auditing of each commanded release, the payload mechanism uses the outlet limit switch and on-board Lua script to log confirmed events when a seed is successfully released through the outlet (Appendix A). For every waypoint, the autopilot records (i) the commanded servo PWM (1100/1500/1900), (ii) the limit-switch state/timestamp, (iii) the intended hopper (front/rear), (iv) the GNSS position and heading, and (v) the

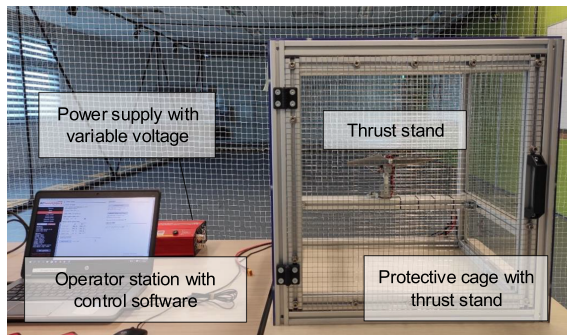
LiDAR altitude. These events are logged, and the cumulative drop counter informs the operator in real-time during flight (see Figure 14). This end-to-end implementation of the automated release makes the operation sequence repeatable and auditable, and it allows cross-checking with independent ground observations after flight (see Section 4.2).

3 | Field Evaluation

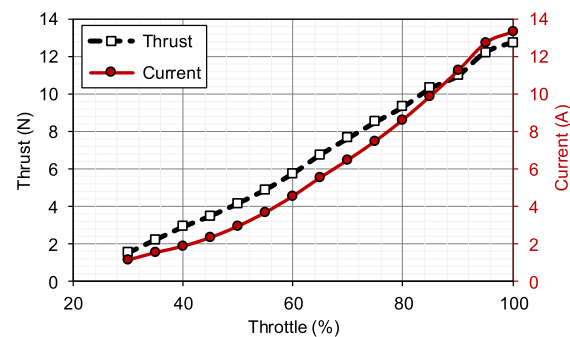
Preliminary flight experiments were conducted to evaluate the performance of the proposed UAV-based seed dispersal concept. The objectives were to assess (i) UAV flight performance, (ii) system implementation (autonomy and payload actuation), and (iii) drop accuracy. As shown in Figure 11, tests were performed at two locations in Singapore. The netted futsal court (Location 1) provided a controlled environment for initial safety checks and hover tests, while the outdoor field test (Location 2) enabled evaluation under real-world conditions. Both environments were geofenced for safe operations, as shown in Figure 11.

TABLE 5 | Mass statement of prototype and flight test configurations.

		Empty configuration	Seed drop configuration
Empty mass	UAV Vehicle	1,121 g	1121 g
Fixed payload	Seed-Dropping Mechanism	660 g	660 g
	LiPo battery (5000 mAh)	542 g	542 g
Variable payload	Seed-Balls	0 g	$17.5 \times 8 = 140$ g
	Total mass	2,324 g	2,464 g



(a) RCbenchmark Series 1585 Test Stand.



(b) Thrust stand results.

FIGURE 12 | Propulsion characterization for the 2216 KV920 motor with a 10-inch propeller. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

3.1 | UAV Flight Characteristics

Two configurations of the UAV were evaluated in the initial flight testing: an empty seed tank and another loaded with eight seed balls (four in each hopper). The corresponding mass breakdowns are presented in Table 5. Testing both configurations allowed us to compare the battery consumption, thrust-to-weight ratios, and hover performance against the platform specifications in Table 1.

3.1.1 | Flight Endurance and Thrust Performance

To determine the UAV flight endurance, we conducted hover endurance tests by flying the UAV manually in *Loiter* and *PosHold* modes using the loaded and unloaded configurations. In both configurations, the UAV demonstrated stable flight lasting 13 min 46 s for the unloaded configuration and 11 min 51 s for the loaded configuration. Here, we considered that LiPo batteries should not be discharged below 20% capacity to maintain safe battery health (Ong et al. 2019). While flight times may vary slightly in real-world scenarios due to wind and maneuvering, the flight times are sufficient for short seeding missions in this proof-of-concept implementation. For more realistic missions, the seed dropping concept can be translated to larger UAVs for extended flight times.

To ensure that the UAV can safely operate in a fully loaded configuration, we further considered the thrust-to-weight (T/W) ratio of the UAV system, calculated as

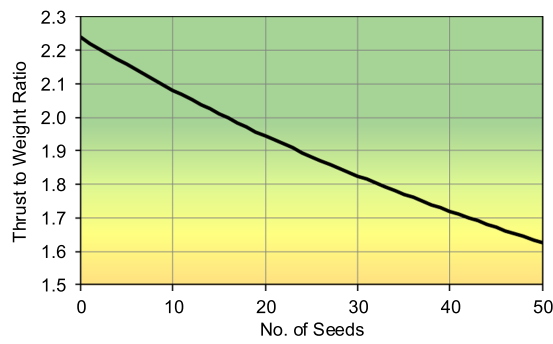
$$T/W \text{ Ratio} = \frac{\text{Max Combined Thrust}}{\text{UAV Takeoff Weight}}.$$

We used the RCbenchmark Series 1585 Test Stand, as shown in Figure 12, to measure the produced thrust and power requirements at different throttle settings (Chew et al. 2021). Each rotor provides up to 12.8 N of thrust, yielding a maximum combined thrust of 51 N for the quadcopter. With a takeoff weight of 22.8 N (empty) and 24.2 N (loaded with 8 seed balls), the corresponding T/W ratios are 2.24 and 2.11. T/W ratios above 1.9 typically provide sufficient performance to maintain stable flight even under mild wind conditions (Biczyski et al. 2020).

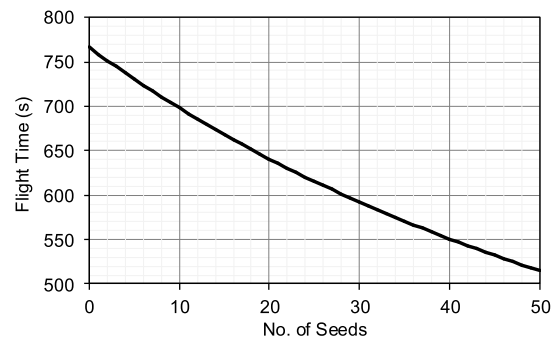
Using the experimental thrust test results above, we conducted a broader performance assessment presented in Figure 13. The analysis shows how the T/W Ratio degrades with increasing number of loaded seed balls. The colored shading indicates acceptable T/W Ratio for sufficient flight performance (Putra et al. 2020). While it is still possible to fly outdoors at full hopper capacity (40 seeds), the low T/W Ratio = 1.73 means that the flight performance would be very sluggish and potentially infeasible in high-wind conditions. Hence, a loading of max. 30 seeds is suggested for the final field implementation to maintain sufficient maneuverability in realistic outdoor conditions. The endurance model in Figure 13b projects ≈ 10 min flight time for 30 seeds (under constant load), with actual endurance slightly longer as the payload decreases during the mission.

3.1.2 | Autonomous Mission Performance

To evaluate the performance of the autonomous waypoint tracking and seed-dropping tasks, a representative mission using 4 seed balls was implemented and tested in an outdoor



(a) Thrust-to-weight ratio T/W Ratio.



(b) Estimated flight time.

FIGURE 13 | Estimated thrust-to-weight ratio and flight time versus number of seed balls. Colored shading in (a) indicates feasible flight envelopes: T/W Ratio < 1.6 indoor flight, $1.6 \leq T/W$ Ratio ≤ 1.9 outdoor flight in light wind conditions, and T/W Ratio > 1.9 outdoor flight in heavy wind conditions. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

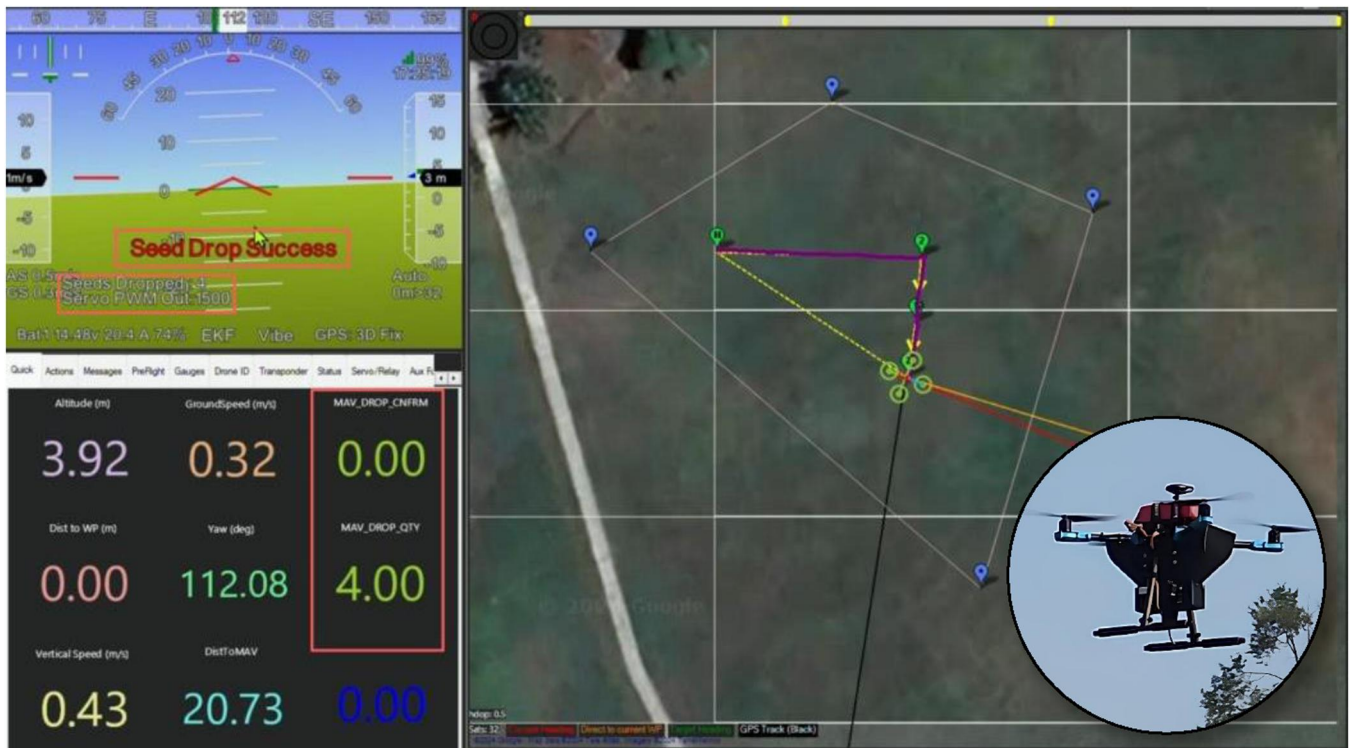


FIGURE 14 | Autonomous mission overview. Green: waypoints; blue: geofence; purple: trajectory. Dashboard messages (orange box) confirm seed drops to operator. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

environment (see Location 2 in Figure 11). The mission includes a sequence of waypoints representing typical restoration targets and commands for seed dispensing, as described in Section 2.4.2. Figure 14 shows the mission dashboard during the autonomous operation. The UAV was commanded to climb to 4 m relative to the ground, navigate through a series of waypoints while maintaining a constant altitude above ground, dispense seeds at the defined locations, and return to the launch site. During the test flight, the UAV closely followed the planned trajectory (shown in yellow). The downward-facing LiDAR sensor was integrated to enable real-time terrain following.

The Lua script was also implemented to track the seed release, as described in Section 2.4.2. Figure 14 shows the real-time dashboard alerts that are displayed to the operator each time a

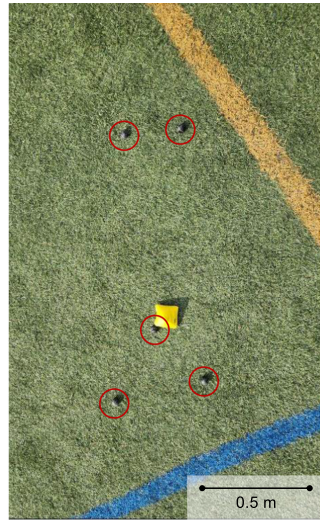
seed is successfully dispensed, and a user-defined parameter (MAV_DROP_QTY) is incremented to show the total number of seeds released. This provides better oversight for the operator and enables cross-validation with ground-truth observation data. The implemented seed counter stores the geolocation of the actual seed drops. In the future, this record can be used for ecological assessment and auditing of large-scale UAV-based reforestation missions.

3.2 | Drop Accuracy and Placement Metrics

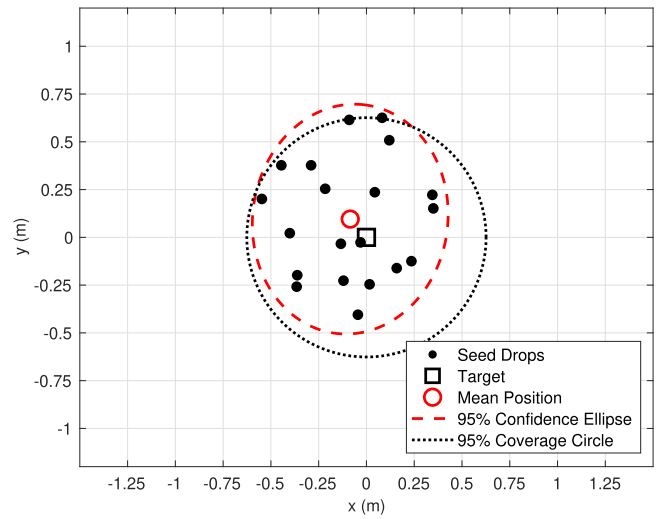
The accuracy of the seed dropping mechanism was assessed through flight tests conducted at the two locations indicated in Figure 11. Tests at the futsal court (Location 1) were limited to a



(a) UAV dispersing seeds.



(b) Seed dispersion pattern.



(c) Extracted coordinates of seeds after 20 drops.

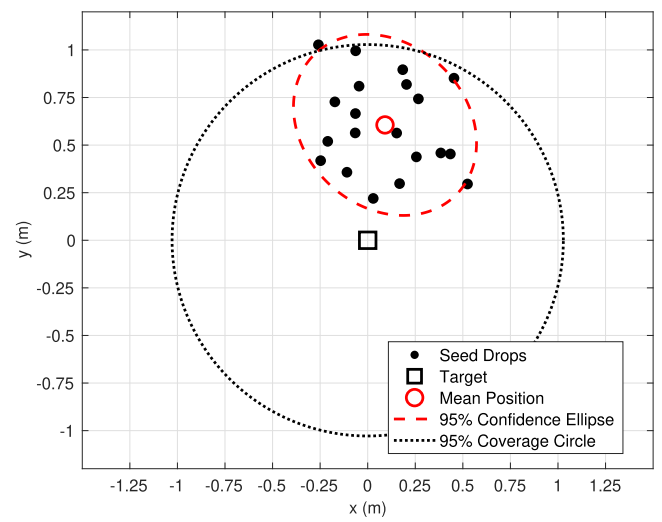
FIGURE 15 | Seed dispersion patterns observed during flight tests at futsal court (Location 1) from a drop altitude of 1.5 m. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]



(a) UAV dispersing seeds.



(b) Seed dispersion pattern.



(c) Extracted coordinates of seeds after 20 drops.

FIGURE 16 | Seed dispersion patterns observed during flight tests at Location 2 from a drop altitude of 4 m. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

maximum altitude of 1.5 m. For the outdoor tests, we fixed the altitude at 4 m to provide sufficient clearance above weeds and bushes while reducing potential damage to seed balls from higher drop heights. In Section 4, we also evaluate different altitudes at the final evaluation site.

Figure 15 illustrates the futsal court test results, showing the seed drop pattern around the intended target locations under no-wind conditions. The dispersion patterns were analyzed for 20 seeds using the mean offset, a 95% confidence ellipse (assuming a bivariate normal distribution), and a 95% coverage circle (based on radial distances from the target). The mean position was within 0.13 m of the target position. However, the smooth surface caused the seed balls to bounce and roll after the initial impact, which resulted in a larger radial standard deviation of 0.29 m. Nonetheless, the 95% coverage circle shows

reliable results, with most seeds landing within a radius of 0.63 m of the intended target.

Figure 16 presents the results from the outdoor test (Location 2), conducted under light wind conditions at 4 m altitude. During the autonomous mission defined in Figure 14, four seed drops were commanded, with two from the rear hopper at the first waypoint and two from the front hopper at the second waypoint. The experiment was repeated five times to get 20 representative seed drops. As illustrated in Figure 16, a lateral bias in drop accuracy was observed, resulting in a mean offset of 0.61 m from the intended target location. This larger offset is likely due to the effect of wind or a slight misalignment of the GNSS locations. However, the grassy surface helped the seed balls to land smoothly, with minimal rolling observed. This leads to a reduced radial standard deviation of 0.24 m and a 95%

confidence ellipse, as plotted in Figure 16. Overall, most seeds landed within 1.03 m of the intended target, as illustrated by the 95% coverage circle.

3.3 | Discussion of Preliminary Field Evaluation

The field experiments presented in this section provide a preliminary validation of the UAV-based seed dispersal concept under realistic conditions. A total of 40 seed drops were analyzed across two test sites. The controlled environment of the futsal court (Location 1) allowed us to safely evaluate the system reliability and dispersion geometry under calm conditions, while the open field tests (Location 2) introduced realistic disturbances in terms of wind conditions, terrain topography, and navigation accuracy. The smoother ground condition at the futsal court caused a larger variance in the seed dispersion compared to grassy conditions at Location 2. This finding is particularly relevant when considering deployment over smooth (dry soil) or rougher (grass or weeds) surfaces. In addition, we observed a minor offset from the target locations for the outdoor tests, which was likely due to light wind conditions and potential GNSS inaccuracies. Nonetheless, all seed drops remained within 1 m of the intended target location, as captured by the 95% coverage circle. These results show that the developed seed-dropping system can be used successfully for reforestation missions. However, the results also highlight the importance of considering the surface characteristics and environmental conditions when planning aerial seeding operations using gravity-drop systems.

4 | Field Implementation for Automated Seeding in Northern Thailand

To evaluate the feasibility of autonomous aerial seeding, a structured field trial was conducted at a FORRU-CMU

reforestation site near Ban Pong Yaeng Nok in Chiang Mai Province, Thailand (Figure 17). The bamboo-deciduous plot covers approximately 16,000 m² at an altitude of 800 m. Following a fire during the 2024 dry season, approx. 3500 trees were planted in July 2024 as part of FORRU-CMU's ongoing restoration efforts (Laohasom 2024). Figure 17a shows details of the original reforestation efforts.

4.1 | Altitude Sensitivity Under Operational Terrain

Before demonstrating the full mission, we examined the effect of drop height at the Ban Pong Yaeng Nok site under representative field conditions. The test area is currently used for farming and features small trenches (see Figure 18e). A light wind of 2–4 m/s was blowing predominantly from the south at the time of testing, which has been qualitatively annotated in Figure 18 along the local x-axis. Because these conditions differ from the controlled Singapore tests in Section 3, we treat the results as a *site-specific sensitivity analysis* to evaluate the influence of wind and terrain on placement accuracy. For these tests, we conducted 12 seed drops at a single target (shown in red) at different heights of 5, 10, and 15 m. Figure 18a–c show the scatter plots with the centroid for each case, a 95% confidence ellipse (assuming a bivariate normal distribution), and a 95% coverage circle (based on radial distances from the target). Figure 18d summarizes the distribution of radial errors by height, with the placement statistics detailed in Table 6.

The results show that with increasing height, the dispersion generally increased, but the underlying mechanisms differ. At 10 m height, the pattern was dominated by downwind advection, resulting in the largest mean offset of 1.22 m with a 95% coverage circle of 1.71 m. On the other hand, the variance is comparatively small for 10 m, as most seeds

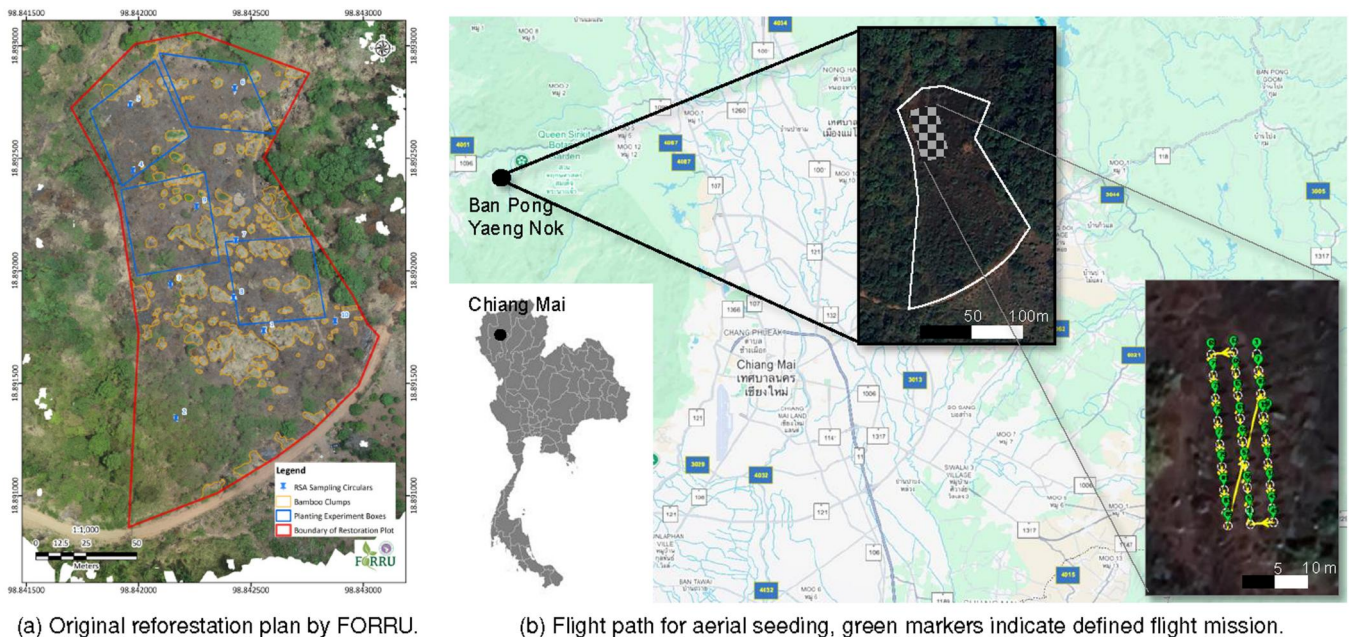


FIGURE 17 | Location of field site for reforestation near Ban Pong Yaeng Nok in Thailand. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

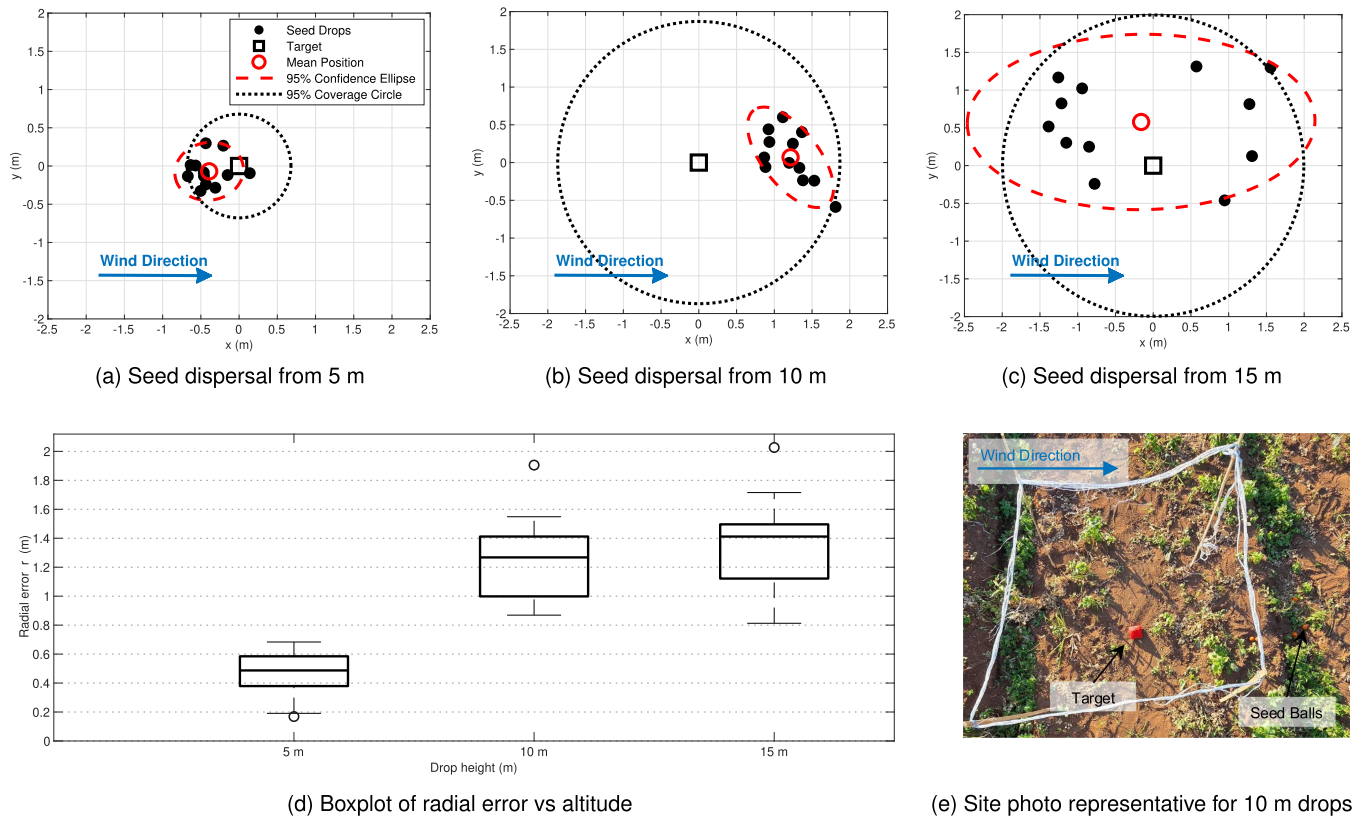


FIGURE 18 | Altitude field tests at Ban Pong Yaeng Nok site: (a–c) seed dispersal patterns from 5, 10, and 15 m with centroid, 95% confidence ellipse, and 95% coverage circle; (d) radial-error boxplot; (e) site photo representative for 10 m drops. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

TABLE 6 | Placement accuracy by altitude for the field tests in Figure 18.

Height	Mean vector $[\bar{x}, \bar{y}]$ (m)	Mean radial offset (m)	95% coverage radius (m)
5 m	$[-0.39, -0.07]$	0.40	0.66
10 m	$[1.22, 0.07]$	1.22	1.71
15 m	$[-0.16, 0.58]$	0.60	1.86

rolled into the small trench, which is shown in Figure 18e. At 15 m height, downwind advection remained evident, but in this case, we observed seeds bouncing and rolling into either of the two trenches visible. This led to a smaller mean offset (0.60 m), but the 95% confidence ellipse became markedly elongated, and the 95% coverage circle increased to 1.86 m radius. By contrast, a height of 5 m produced compact dispersal patterns (mean offset 0.40 m, coverage radius 0.66 m), showing that wind effects and terrain interaction are negligible in this case.

Overall, the altitude sweep shows that, for this site and wind conditions, higher drop altitudes amplify wind-aligned drift and the effect of terrain due to bouncing and rolling. Conversely, drop heights of 3–5 m minimize drift and terrain effects while retaining sufficient operational margin for safe flight and reliable actuation. We therefore selected 4 m for the subsequent autonomous grid mission, where the full workflow (planning, actuation, and seed drop confirmation) is demonstrated in Section 4.2.

4.2 | Autonomous Seeding Mission

A 600 m² rectangular area (checkered region in Figure 17b) was used for the autonomous mission. A regular grid pattern with waypoints 3 m apart was generated using Mission Planner, leading to 27 waypoints to cover the designated test area. The spacing matches the position of the young trees already planted at the plot. To maintain sufficient thrust margins, the seed load was kept below 30 seed balls (Section 3.1.1). The UAV flight mission is illustrated in Figure 17b, with the green markers indicating the planned waypoints. As described in Section 2.4.2, the UAV was programmed to follow the trajectory in AUTO mode and release one seed at each waypoint. Terrain following was achieved by maintaining a relative altitude of 4 m using the onboard LiDAR sensor for altitude control. A geofence was defined to restrict operations within the test plot.

Existing tree locations (planted in July 2024) served as ground references for seed dropping accuracy. Figure 19 illustrates the field condition during the dry season in February 2025, when

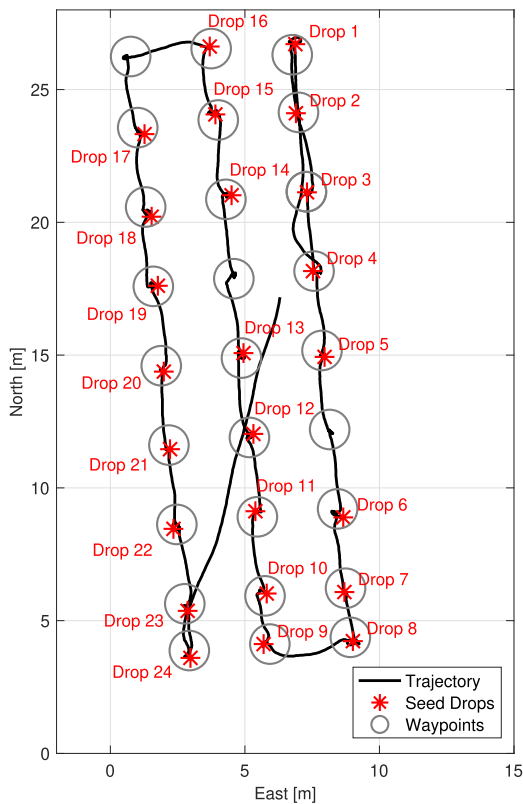


(a) View of field site after completed UAV mission.

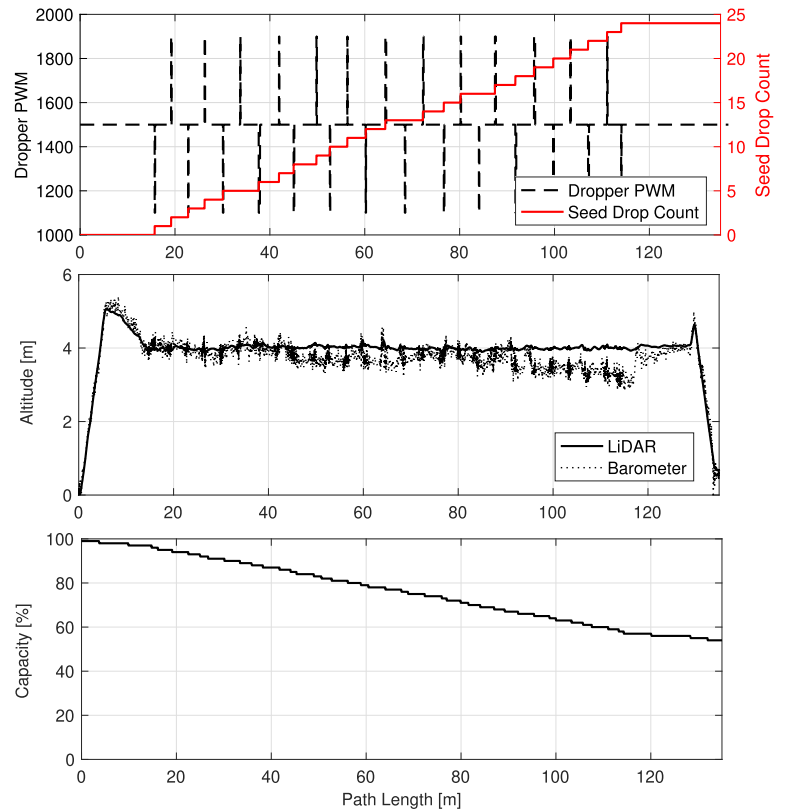


(b) Example seed locations (red) with respect to target locations (blue).

FIGURE 19 | Confirmation of seed locations after the automated seeding mission at the Ban Pong Yaeng Nok field site. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]



(a) UAV trajectory with targets and actual seed drops.



(b) Details of UAV parameters during the UAV mission.

FIGURE 20 | Details of the automated seed-dropping mission at the Ban Pong Yaeng Nok site. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

the field trials were conducted. The clear terrain during the dry season (free from weeds) allows for visual inspections of the seed drops (see Figure 19). All seeds landed within 0.5 m of the intended locations, demonstrating the successful deployment of the seed-dropping mechanism.

Figure 20 presents the detailed analysis of the seeding mission, with Figure 20a showing the actual UAV trajectory overlaid with the waypoints (gray circles) defined in Mission Planner. The mission lasted 390 s and the UAV covered a total flight path of 135 m. The red markers show the position of successful seed drops. Of the 27 seeds planned for the deployment mission, 24 were confirmed by the limit-switch as successful drops. The implemented onboard script (see Section 2.4.2) records the GNSS location of each successful deployment. The position information will be used in future work by FORRU-CMU to monitor germination rates and for ecological assessment. The three failed releases were traced to seed bridging at higher fill levels, which is also visible as missing confirmation events in the audit log.

Figure 20b plots the UAV parameters against the cumulative path length of the mission. The top plot shows the PWM signals sent to the seed-dropping servo, alternating between 1100 and 1900 (black curve) to indicate the commanded seed release from the front and rear hoppers, respectively. The red curve shows the sequence of recorded seed releases, which has been obtained from the logged limit switch actuation, indicating successful seed drops. It is clear that the hopper failed to release 3 seeds due to sporadic jamming of the hopper. However, the mechanism is able to release the jam for the next seed release. The experimental tests show that the proposed mechanism can achieve a 90% success rate. The center subplot in Figure 20b compares the UAV altitude derived from the downward-facing LiDAR versus the barometric sensor. Although the test site is relatively flat, minor variations are apparent. The LiDAR-based terrain-following system was able to maintain an accurate 4 m target altitude, which demonstrates the effective tracking of the varying terrain topography. In contrast, barometric altitude measurements naturally show significant deviations as the barometric sensor cannot sense the actual terrain unevenness. The results highlight the need for a LiDAR-based system when considering the operation of UAV-based seeding systems in hilly terrain. Finally, the bottom subplot in Figure 20b tracks the battery capacity (as a percentage of the battery voltage). The mission consumed 46% of the total battery capacity over the 6.5 min mission. Given that only 80% of nominal battery capacity is usable (to preserve battery health), this result aligns closely with the predicted endurance for 30-seed missions presented in Figure 13.

4.3 | Discussion of Field Results

The combined results for the tests in Sections 3–4 provide a coherent picture of the mechanism behavior and the sensitivity of the system to environmental factors. The controlled tests in Section 3, with smooth surfaces and grass, demonstrated the impact of surface topology on seed motion and dispersion accuracy. Similar trends were observed at the operational site in Section 4, where seed drops from a height of 15 m showed

significant variations due to the bouncing of the seeds. Slopes and trenches can also cause the seeds to roll and agglomerate, as shown for the 10 m case.

The effect of wind was also demonstrated at the operational site, causing a significant bias of 1.2 m relative to the target location for the 10 m case. In reforestation applications, this error would cause uneven tree distributions, increased competition among seedlings, and inefficient use of seeds. Hence, in practical applications, the operational altitude should be selected based on the local wind conditions and the required clearance from the terrain and existing vegetation. Since the wind drift effects increase with flight altitude, the drone operator should select the lowest possible altitude that provides safe clearance from obstacles. Under conditions similar to the present field tests, an operating window of 3–5 m provides the best balance of ground clearance and seeding accuracy. However, it is critical to implement a LiDAR-based, terrain-following controller to ensure that a stable flight altitude above the uneven terrain is maintained. Since the present flight tests were conducted under wind speeds of approximately 2–4 m/s, further tests are required to establish the operational limits under different wind conditions.

From a systems standpoint, the field implementation demonstrates the feasibility of the proposed seed-dropping system in realistic reforestation scenarios. For the small grid in Section 4.2, manual seeding could be faster in absolute terms (on the order of ≈ 5 s per seed) than our initial autonomous sequence (≈ 14 s per seed). In the current implementation, the seeding mission is executed sequentially as described in Section 2.4.2, where the sequence of servo actions (using `DO_SET_SERVO`) is executed after reaching the associated waypoint. This stop-and-actuate structure was chosen in the field tests to decouple the evaluation of waypoint tracking from the evaluation of dispensing accuracy and drop confirmation. However, the drop sequence time can be reduced substantially by synchronizing UAV movement with servo actuation (i.e., triggering the drop while tracking the waypoint) and by exploiting the known mechanism latency (Section 2.2.3). A practical way to implement this parallel actuation within the same flight stack is to extend the onboard Lua scripting approach already used for outlet limit-switch confirmation (Appendix A). The same scripting framework can be used to trigger the servo sequence based on the onboard state during waypoint tracking. With these changes, a practical target of ≈ 2 s per seed is achievable. This also preserves verifiable seed-drop execution via the outlet limit switch, enabling auditable missions and post hoc ecological tracking. For traditional seeding operations by hand, these capabilities would not be sustainable for large-scale reforestation operations. In short, automated precision placement lets ecologists meet spacing requirements for effective reforestation (Bahru et al. 2023).

The UAV-based solution can scale to larger operations in the future following the proposed design methodology in Section 2. The primary design factor limiting reliability is intermittent bridging at higher hopper fill levels of more than 5–7 seed balls. As found in granular-flow studies, spherical particles can exhibit bridging and intermittent blockage in gravity hoppers depending on throat geometry and friction

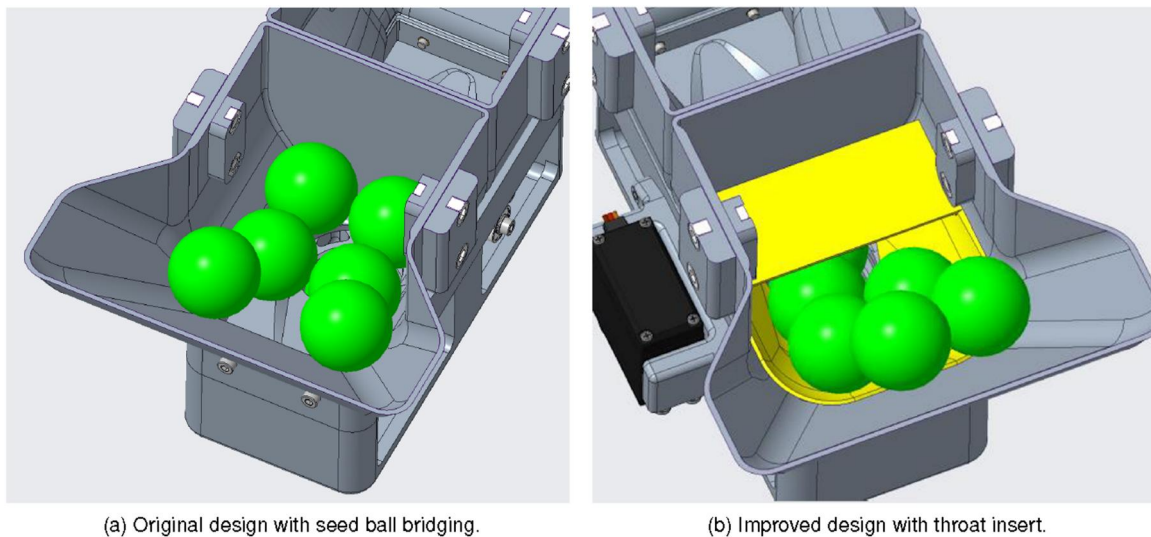


FIGURE 21 | Analysis of possible causes for seed hopper jam. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rob.70344)]

conditions (Lysych et al. 2021). To mitigate this, a revised throat insert is proposed in future work to smooth the transition into the metering region and reduce local constriction (see Figure 21). This modification is expected to increase the reliability further for effective reforestation efforts and larger-scale deployment in the future.

5 | Conclusion and Future Work

Traditional reforestation methods typically rely on growing seedlings in nurseries, which is often slow, labor-intensive, and difficult to implement at large scale in remote areas. To address these constraints, this paper has presented the development of an automated UAV-based seed-dropping system equipped with a novel carriage-based seed dispensing mechanism designed to release individual seeds. Unlike heavier pneumatic seeding systems commonly used for precision aerial seeding, the proposed carriage-based, gravity-drop system is mechanically driven, allowing it to be easily integrated with various multi-rotor UAV platforms. The seeds have been coated with a bio-char mixture to produce consistent 30 mm balls for various native seed species. The seed dispersal mechanism has been implemented with an open-source UAV navigation system to enable automated seeding missions. The integrated downward-facing LiDAR improves the robustness of the flight control system, even in complex and hilly terrain, where UAV-based seeding can be a critical enabler for reforestation missions. To evaluate the success of aerial seeding, a limit switch was integrated to provide real-time confirmation of each release. The on-board script tracks the geolocation of all successful seed drops, including information on PWM command, limit-switch state change/timestamp, GNSS position/heading, and LiDAR-based altitude. This enables independent verification and the post hoc observation of seedlings as part of future large-scale reforestation campaigns.

The initial laboratory and flight tests confirmed the effectiveness of the proposed seeding mechanism and UAV integration. The field evaluations highlighted the impact of UAV altitude,

terrain, and wind conditions on seed deployment accuracy. An altitude sweep at 5, 10, and 15 m revealed wind-aligned drift and terrain interactions at higher release heights, with 95% of seeds landing within 1.86 m of the target location for 15 m case, while at 5 m the 95% coverage radius was 0.66 m. These results motivate a practical operating window of 3–5 m altitude for precision seeding, using LiDAR-based terrain following to maintain a constant altitude. Critically, single-seed actuation allows missions to meet prescribed interplant spacing, typically 2 by 2 m for framework-species approaches, which broadcast seeding cannot guarantee.

The final field evaluation demonstrated the successful deployment at an active reforestation site managed by the Forest Restoration Research Unit at Chiang Mai University in Northern Thailand. The field tests verified the system efficacy, achieving 90% successful seed deployments at 27 planned target locations covering an area of 600 m². Overall, these field results highlight the system's potential for scalable, low-cost, and precise reforestation in inaccessible or degraded areas. By introducing the concept of multi-species hoppers, the system can help enhance ecological diversity, support rapid restoration of degraded sites, and improve overall biodiversity efforts.

Although the current configuration is limited to 30 seed balls and a flight time of 10 min, the modular design allows for the integration of the system with larger UAVs and seed hoppers capable of extensive coverage and operational endurance. The mass of the metering mechanism itself is 420 g (without the hopper) and is largely independent of mission seed capacity. Hence, extending this concept to large-scale operations is primarily driven by (i) the variable seed mass and (ii) the hopper mass required to store a larger number of seed balls. For example, integrating a lightweight 20 L plastic box as a hopper can store ~900 seed balls of 30 mm diameter, considering random packing. The total required payload for such a large-scale system would be ~18 kg. At 2 m spacing for the established framework-species approaches, 900 seeds correspond to a 60×60 m plot per flight, and three UAVs operating in parallel would

therefore cover approximately 1 ha per flight. Considering the availability of agricultural UAVs with payload capabilities of >20kg, the proposed concept can be scaled to landscape-level reforestation programs in the future. Such large-scale automated approaches would also need to consider concepts for replenishing or swapping the UAV batteries (Kute et al. 2024) and multi-UAV path planning to optimize energy consumption. Future work can consider energy-aware methods for coverage planning (Stefanopoulou et al. 2024) to divide the restoration area among multiple UAVs based on battery constraints and energy consumption.

Finally, as this study primarily focused on the technological development of the aerial seeding system, further long-term ecological studies will be necessary to comprehensively evaluate the overall success of UAV-based reforestation using seed balls, including seedling establishment rates, survival, and broader ecological impact.

Acknowledgments

This work was supported by a grant from the APNIC Foundation via the ISIF Asia Fund (Grant No: 202403-02759): FIREfly 2.0: Enhancing Forest Fire Monitoring and Biodiversity Conservation with a UAV-Based IoT System. The authors received further support from the Forestry Restoration Research Unit at Chiang Mai University. The authors would also like to thank Steven Chua from the Singapore Institute of Technology for the technical support in the UAV development.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Allen, J. 2007. *Smart Permaculture Design*. New Holland Publishers.
- Asher, C. 2023. "Cutting-Edge Drones Give Reforestation a Helping Hand." Mongabay.Org Corporation. <https://news.mongabay.com/2023/07/new-tree-tech-cutting-edge-drones-give-reforestation-a-helping-hand/>.
- Bahru, T., N. Eshete, and Z. Woldemariam. 2023. "Effect of Spacing on Survival and Growth Performance of Eucalyptus Grandis Hill ex Maiden at Holeta Research Site, Central Ethiopia." *International Journal of Forestry Research* 2023: 1–12. <https://doi.org/10.1155/2023/9957776>.
- Biczyski, M., R. Sehab, J. F. Whidborne, G. Krebs, and P. Luk. 2020. "Multirotor Sizing Methodology With Flight Time Estimation." *Journal of Advanced Transportation* 2020: 1–14. <https://www.hindawi.com/journals/jat/2020/9689604/>.
- British Columbia. 2025. "British Columbia Wildfire Season Summary." (April) Government of British Columbia. <https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-history/wildfire-season-summary#previous-wildfire-season-summaries>.
- Castro, J., D. Alcaraz-Segura, J. L. Baltzer, L. Amorós, F. Morales-Rueda, and S. Tabik. 2024. "Automated Precise Seeding With Drones and Artificial Intelligence: A Workflow." *Restoration Ecology* 32, no. 5: e14164. <https://doi.org/10.1111/rec.14164>.
- Chen, H., and O. Kocha. 2023. "Smoke From Forest Fires Blankets Northern Thailand in Thick Pollution." (April) CNN. <https://www.cnn.com/2023/04/05/asia/chiang-mai-air-pollution-thailand-intl-hnk/index.html>.
- Cheng, D., A. C. Charles, S. Srigrarom, and H. Hesse. 2019. "Morphing Concept for Multirotor UAVs Enabling Stability Augmentation and Multiple-Parcel Delivery." *AIAA Scitech 2019 Forum*: AIAA 2019-1063. <https://doi.org/10.2514/6.2019-1063>.
- Chew, F., S. Gan, and H. Hesse. 2021. "Rapid Design Process of Shrouded Rotors for Efficient UAV Propulsion." *AIAA Scitech 2021 Forum*: AIAA 2021-0212. <https://doi.org/10.2514/6.2021-0212>.
- Cruz, R. 2025. "Reforestation by Air: How Seed-Planting Drones Are Restoring Forests." (April) Advexure LLC. <https://advexure.com/blogs/news/reforestation-by-air-how-seed-planting-drones-are-restoring-forests>.
- Elliott, S., D. Blakesley, and K. Hardwick. 2013. *Restoring Tropical Forests*. Kew Publishing.
- Elliott, S., G. Gale, and M. Robertson. 2020. *Automated Forest Restoration: Could Robots Revive Rain Forests?* Forest Restoration Research Unit, Chiang Mai University.
- Fukuoka, M. 2013. *Sowing Seeds in the Desert: Natural Farming, Global Restoration, and Ultimate Food Security*. Chelsea Green Publishing.
- Goldapple, L. 2017. "Drop Seeds, Not Bombs. Aerial Reforestation in Thailand." Atlas of the Future. <https://atlasofthefuture.org/project/aerial-reforestation-in-thailand/>.
- Govender, T., G. Bright, and I. R. Botha. 2022. "Evaluating the Seed Sowing Performance of a UAV Supported Pneumatic Planting System." In *Proceedings of IEEE International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 1–6. IEEE.
- Grossnickle, S. C., and V. Ivetić. 2017. "Direct Seeding in Reforestation—A Field Performance Review." *Reforesta* no. 4: 94–142. <https://doi.org/10.21750/REFOR.4.07.46>.
- Holybro. 2025. "Holybro X500 V2 Development Kit." (June). <https://holybro.com/collections/x500-kits/products/x500-v2-kits>.
- Hou, L., X. Han, Y. Lan, et al. 2024. "Design and Testing of a Sowing Drone Based on Rice Precision Strip Seeding." *INMATEH Agricultural Engineering* 73, no. 2: 351–363. <https://doi.org/10.35633/inmateh-73-29>.
- Huang, X., S. Zhang, C. Luo, W. Li, and Y. Liao. 2020. "Design and Experimentation of an Aerial Seeding System for Rapeseed Based on an Air-Assisted Centralized Metering Device and a Multi-Rotor Crop Protection UAV." *Applied Sciences* 10, no. 24: 8854. <https://doi.org/10.3390/app10248854>.
- Karademir, S. 2025. "Design and Implementation of a Novel Seeding Drone." *Sigma Journal of Engineering and Natural Sciences* 43, no. 1: 189–198. <https://doi.org/10.14744/sigma.2025.00014>.
- Kim, J., S. Kim, C. Ju, and H. I. Son. 2019. "Unmanned Aerial Vehicles in Agriculture: A Review of Perspective of Platform, Control, and Applications." *IEEE Access* 7: 105100–105115. <https://doi.org/10.1109/ACCESS.2019.2932119>.
- Kus, E. 2021. "Seed Damage Test for Roller-Type Device Designed at Different Flute Helical Angles." *Uluslararası Tarım ve Yaban Hayatı Bilimleri Dergisi* 7, no. 3: 495–502. <https://doi.org/10.24180/ijaws.938870>.
- Kute, I., J. Dagli, E. Khot, et al. 2024. "An Autonomous System for Docking and Battery Swapping in UAVs." In 34th Congress of the International Council of the Aeronautical Sciences. International Council of the Aeronautical Sciences (ICAS).
- Laohasom, P. 2024. *Restoring Bamboo-Deciduous Forest at Pong Yaeng Nork After Fire*. Technical Report. Chiang Mai University.
- Liu, H., Z. Chen, Z. Wang, and J. Li. 2023. "An Effective Precision Afforestation System for UAV." *Sustainability* 15, no. 3: 2212. <https://doi.org/10.3390/su15032212>.
- Lysych, M., L. Bukhtoyarov, and D. Druchinin. 2021. "Design and Research Sowing Devices for Aerial Sowing of Forest Seeds With Uavs." *Inventions* 6, no. 4: 83. <https://doi.org/10.3390/inventions6040083>.

- MissionPlanner. 2024. "Mission Planner Home." ArduPilot. <https://ardupilot.org/planner/>.
- Mohan, M., G. Richardson, G. Gopan, et al. 2021. "UAV-Supported Forest Regeneration: Current Trends, Challenges and Implications." *Remote Sensing* 13, no. 13: 2596. <https://doi.org/10.3390/rs13132596>.
- Naruangsri, K. 2023. *Developing Techniques for Direct Seeding for Forest Restoration in Northern Thailand*. (December) PhD Thesis, Chiang Mai University.
- Naruangsri, K., W. Pathom-aree, S. Elliott, and P. Tiansawat. 2024. "Selecting Suitable Tree Species for Direct Seeding to Restore Forest Ecosystems in Northern Thailand." *Forests* 15, no. 4: 674. <https://doi.org/10.3390/f15040674>.
- Naruangsri, K., P. Tiansawat, and S. Elliott. 2023. "Differential Seed Removal, Germination and Seedling Growth as Determinants of Species Suitability for Forest Restoration by Direct Seeding—A Case Study From Northern Thailand." *Forest Ecosystems* 10: 100133. <https://doi.org/10.1016/j.fecs.2023.100133>.
- Noble, F. 2020. "Government Set to Revise Total Number of Hectares Destroyed During Bushfire Season to 17 Million." Nine Digital Network. <https://www.9news.com.au/national/australian-bushfires-17-million-hectares-burnt-more-than-previously-thought/b8249781-5c86-4167-b191-b9f628bdd164>.
- Nonko, E. 2023. "Seed-Planting Drones Are Reforesting Canada With Lightning Speed." Arbutus. <https://reasonstobecheerful.world/drone-tree-planting-reforesting-after-wildfires>.
- Ong, S. H., H. L. Ang, and E. Lian, et al. 2025. "FIREfly Project: Forest Fire Monitoring and Prediction Using Machine Learning." In *International Conference on Artificial Intelligence and Machine Learning Research*, 3. SPIE.
- Ong, W., S. Srigrarom, and H. Hesse. 2019. "Design Methodology for Heavy-Lift Unmanned Aerial Vehicles with Coaxial Rotors." In AIAA Scitech 2019 Forum, AIAA 2019-2095. AIAA 2019-2095. American Institute of Aeronautics and Astronautics (AIAA). <https://doi.org/10.2514/6.2019-2095>.
- Pixhawk. 2024. "Pixhawk Open Hardware Project." Dronecode Foundation. <https://github.com/pixhawk>.
- Pugh, S. 1991. *Total Design*. Addison-Wesley Pub. Co.
- Putra, H. M., M. R. Fikri, D. P. Riananda, G. Nugraha, M. L. Baidhowi, and R. A. Syah. 2020. "Propulsion Selection Method Using Motor Thrust Table for Optimum Flight in Multirotor Aircraft." *AIP Conference Proceedings* 2226, no. 1: 060008. <https://doi.org/10.1063/5.0004809>.
- Puttapirat, P., K. Woradit, H. Hesse, and D. Bhatia. 2024. "FireFly Project: UAV Development for Distributed Sensing of Forest Fires." In *IEEE International Conference on Unmanned Aircraft Systems (ICUAS)*, 594–601. IEEE.
- Song, C., Z. Zhou, X. Luo, et al. 2018. "Design and Test of Centrifugal Disc Type Sowing Device for Unmanned Helicopter." *International Journal of Agricultural and Biological Engineering* 11, no. 2: 55–61. <https://doi.org/10.25165/j.ijabe.20181102.3757>.
- Stamatopoulos, I., T. C. Le, and F. Daver. 2024. "UAV-Assisted Seeding and Monitoring of Reforestation Sites: A Review." *Australian Forestry* 87, no. 2: 90–98. <https://doi.org/10.1080/00049158.2024.2343516>.
- Stefanopoulou, A., E. K. Raptis, S. D. Apostolidis, et al. 2024. "Improving Time and Energy Efficiency in Multi-UAV Coverage Operations by Optimizing the UAVs' Initial Positions." *International Journal of Intelligent Robotics and Applications* 8, no. 3: 629–647. <https://doi.org/10.1007/s41315-024-00333-2>.
- Taylor, J. B., K. L. Cass, D. N. Armond, M. D. Madsen, D. E. Pearson, and S. B. Clair, St. 2020. "Deterring Rodent Seed-Predation Using Seed-Coating Technologies." *Restoration Ecology* 28, no. 4: 927–936. <https://doi.org/10.1111/rec.13158>.
- United Nations. 2021. "United Nations Decade on Ecosystem Restoration (2021–2030)." United Nations Environment Programme (UNEP). <https://www.decadeonrestoration.org/>.
- Velasquez-Camacho, L., A. Cardil, M. Mohan, M. Etxegarai, G. Anzaldi, and S. de Miguel. 2021. "Remotely Sensed Tree Characterization in Urban Areas: A Review." *Remote Sensing* 13, no. 23: 4889. <https://doi.org/10.3390/rs13234889>.
- Waiboonya, P., and S. Elliott. 2020. "Sowing Time and Direct Seeding Success of Native Tree Species for Restoring Tropical Forest Ecosystems in Northern Thailand." *New Forests* 51, no. 1: 81–99. <https://doi.org/10.1007/s11056-019-09720-1>.
- Walker, A. 2021. "60 Years of Innovation: Exploring Tree Planting Drones to Make Australia Green Again!" BirdLife International. <https://www.birdlife.org.au/blogs/60-years-of-innovation-exploring-tree-planting-drones-to-make-australia-green-again>.
- WWF. 2025. "The Trillion Tree Initiative." WWF-Australia. <https://trilliontrees.org/>.
- Yuan, P., Y. Yang, Y. Wei, W. Zhang, and Y. Ji. 2024. "Design and Experimentation of Rice Seedling Throwing Apparatus Mounted on Unmanned Aerial Vehicle." *Agriculture* 14, no. 6: 847. <https://doi.org/10.3390/agriculture14060847>.
- Zhang, K., Z. Khan, Q. Yu, et al. 2022. "Biochar Coating Is a Sustainable and Economical Approach to Promote Seed Coating Technology, Seed Germination, Plant Performance, and Soil Health." *Plants* 11, no. 21: 2864. <https://doi.org/10.3390/plants11212864>.
- Zhang, X., Y. Yang, Q. Wang, H. Li, Z. Zhang, and J. Liu. 2023. "Design and Experiment of Pneumatic Seed Clearing Mechanism for Pin-Hole Tube Wheat Plot Precision Sowing Device." *International Journal of Agricultural and Biological Engineering* 16, no. 4: 85–95. <https://doi.org/10.25165/j.ijabe.20231604.8006>.
- Zhong, W., X. Zhao, F. Liu, et al. 2024. "Design and Experiment of Precision Seed Metering Device for Flow Adsorption of Quinoa Seeds." *Agriculture* 14, no. 3: 434. <https://doi.org/10.3390/agriculture14030434>.
- Zhu, Y., X. Huang, C. Yin, Q. Zhu, Y. Shi, and W. Li. 2025. "Key Parameters Determination Based on Seed Movement Process Simulation for Rice Strip Aerial Seeding Via UAV." *Computers and Electronics in Agriculture* 237: 110596. <https://doi.org/10.1016/j.compag.2025.110596>.

Appendix A

Lua Script for Limit Switch Operation

A Lua script has been implemented onboard the Pixhawk flight controller to continuously monitor the limit switch state for confirmation of successful seed drops, as described in Section 2.4-2. Figure A1 presents the logic of the limit switch operation.

The Lua script below has been uploaded to the Pixhawk flight controller. The script increments a drop counter each time a seed drop is detected.

```
local button_number=1--The button number representing the limit switch

local button_active_state=true--The 'pressed' state of the limit switch

local last_button_state

local total_drops=-1--Initialize the counter for total seed drops

function update() -- this is the loop which periodically runs
```

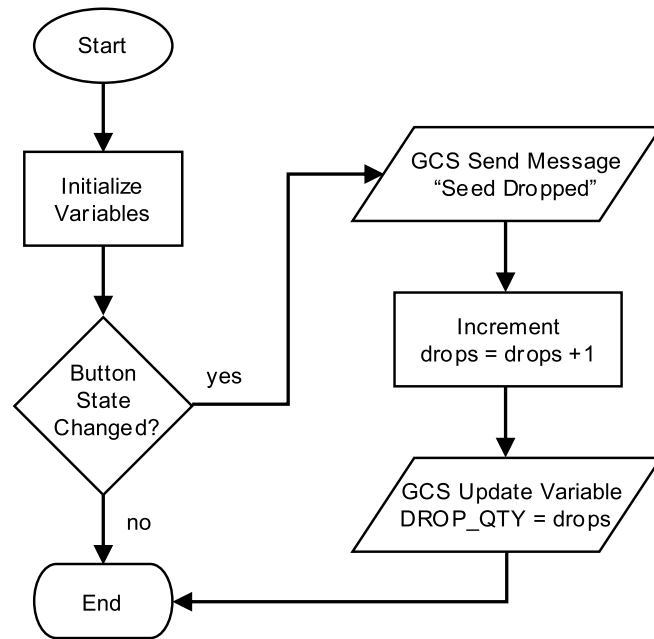



FIGURE A1 | Flowchart of Lua script used for providing seed drop feedback.

```

local button_new_state=button:get_button_state
(button_number) == button_active_state

- checks for button press

if button_new_state=last_button_state then

last_button_state=button_new_state

if button_new_state then

gcs:send_text(0, "Seed Drop Success") - Send message
to GCS

gcs:send_named_float('DROP_CNFRM', 0)

total_drops=total_drops + 1

gcs:send_named_float('DROP_QTY', total_drops)

else

gcs:send_named_float('DROP_CNFRM', 1)

end

end

return update, 0.1 - updates the loop at 10Hz

end

return update() - end of loop
  
```