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Under-Canopy UAV Global Path Planning for Tree DBH Estimation Using LiDAR

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Abstract

Diameter at breast height (DBH) is a fundamental parameter in forest inventory. While traditional manual measurements are labor-intensive, LiDAR-based techniques offer improved accuracy and automation. However, terrestrial and conventional aerial LiDAR systems struggle to efficiently capture DBH due to limited mobility or canopy occlusion. Under-canopy UAVs provide a promising alternative by directly observing tree stems beneath the canopy. This paper proposes a global path planning method tailored for under-canopy UAVs, aiming to improve both safety and DBH estimation accuracy. The approach leverages prior tree distribution to construct distance and visibility fields, generating three-directional observation waypoints around each tree. These points are then globally optimized to ensure safe flight and uniform angular coverage. Simulation and field experiments demonstrate that the planned paths enable complete trunk coverage and effective under-canopy navigation. The extracted DBH values, estimated via least-squares circle fitting, achieve a root mean square error (RMSE) of 6.69 cm. These results confirm the method's effectiveness in enabling precise and efficient autonomous forest inventory.

1. Introduction

Diameter at Breast Height (DBH) is an essential forest structural parameter. Traditional manual measurements are labor-intensive and inefficient. Although LiDAR-based methods improve efficiency and accuracy, terrestrial and backpack LiDAR systems are limited by range and labor demands (Cabo et al., 2018), while airborne and Uncrewed Aerial Vehicle (UAV)-based LiDAR struggle to capture DBH due to canopy occlusion (Feng et al., 2022).

Under-canopy UAVs offer a promising solution, as their small size and maneuverability allow them to operate beneath the canopy where DBH data is accessible (Hyyppä et al., 2020). Accurate DBH estimation further requires LiDAR scans from multiple, evenly distributed horizontal angles to ensure complete trunk reconstruction (Heo et al., 2019). However, most existing under-canopy UAV path planning approaches are limited to basic navigation tasks, such as point-to-point or back-and-forth flights, without accounting for observation quality. Prior information is often underutilized, and sufficient angular coverage around tree trunks is rarely guaranteed (Yao and Liang, 2024a). Therefore, a global path planning approach is needed—one that leverages prior knowledge and real-time data to guide the UAV along safe, efficient, and informative trajectories, enabling accurate and consistent DBH acquisition in complex forest environments.

To address these limitations, this study proposes a global path planning method tailored for under-canopy UAVs. The method leverages prior knowledge of tree distribution and real-time data to guide the UAV along safe, efficient, and informative trajectories. By constructing Euclidean Signed Distance Fields (ESDF) and Visibility Fields (VF), observation waypoints are generated and globally optimized to ensure uniform angular coverage and flight safety. Simulation experiments demonstrate that the proposed method enables complete trunk coverage, stable under-canopy navigation, and accurate DBH estimation, achieving a root mean square error (RMSE) of 6.69 cm.

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This paper makes the following contributions: it introduces a novel global path planning framework that integrates prior knowledge and real-time data to optimize UAV trajectories; constructs ESDF to ensure obstacle avoidance and VF to maximize visibility for observation waypoint generation; and achieves high accuracy in DBH estimation, as validated through simulation experiments. The proposed method demonstrates its effectiveness in enabling precise and efficient autonomous forest inventory, providing a robust solution for under-canopy UAV navigation.

The remainder of this paper is organized as follows: Section 2 reviews related work on forest inventory and UAV exploration. Section 3 describes the proposed method, including global path planning and local replanning. Section 4 presents experimental results and analysis. Section 5 discusses future work and potential improvements.

2. Related Work

2.1 Forest Inventory

Forest inventory has been revolutionized by close-range sensing technologies, including Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), and UAV-based systems (Strahler et al., 2008, Panagiotidis et al., 2022, Liang et al., 2018). TLS provides millimeter-level accuracy for detailed forest data acquisition and has become a critical tool for plot-scale forest measurement (Wang et al., 2019). TLS systems rely on rotating LiDAR with wide field of view to efficiently scan forest areas, generating precise 3D point cloud data. Tower-mounted TLS systems also provide long-term, repeatable observation data for high spatio-temporal resolution studies (Liang et al., 2016). However, TLS is limited by its static working mode, which reduces efficiency in large-scale or dynamic data collection tasks.

To address these limitations, Mobile Laser Scanning (MLS) systems have gained increasing attention. Ground-based MLS offers more flexible configurations through wearable backpack systems, handheld devices, and consumer-grade sensors (Liang et al., 2014, Shcherbacheva et al., 2024). These mobile systems excel in areas inaccessible to static devices, providing flexibility and convenience for forest data collection. The development of efficient MLS platforms has enabled comprehensive forest mapping in challenging terrain conditions.

UAVs have brought new breakthroughs to forest data collection by overcoming the limitations of ground-based platforms (Hyyppä et al., 2020). Recent UAV applications in plot-scale and individual tree inventory include parameter estimation, volume calculation, and biomass assessment. The integration of airborne LiDAR with TLS has become a research hotspot, enabling comprehensive forest structure analysis from canopy to ground level (Shao et al., 2021, Gollob et al., 2020).

Notably, research on understory UAVs has gradually emerged as a promising solution for forest inventory. Some studies have achieved seamless data collection both above and below the forest canopy, enabling comprehensive tree parameter derivation (Mokros et al., 2021). However, most current understory UAV applications rely on manual flight operations, lacking autonomous flight capabilities. Recent research has begun exploring autonomous understory UAVs for forest inventory (Bobrowski et al., 2023), highlighting the potential for efficient data acquisition in areas inaccessible or hazardous to field investigators.

2.2 Autonomous Exploration

Autonomous UAV exploration in forest environments has developed rapidly, focusing on improving flight efficiency and safety in complex environments (Gollob et al., 2021). Through optimization of environmental perception and path planning, numerous studies have achieved efficient autonomous exploration. Real-time semantic SLAM technology has been used to suppress odometry drift errors and ensure planning stability (Bazezew et al., 2018). Multi-UAV collaborative exploration systems based on real-time perception have been successfully applied to forest search and rescue missions (Wang et al., 2019).

Autonomous exploration methods for quadrotor UAVs are categorized into three main types: frontier-based, sampling-based, and hybrid approaches. Frontier-based methods first locate boundaries between known and unknown regions (frontiers) and then solve for global paths to visit these frontiers (Paris et al., 2017). Initially applied in 2D environments, these methods have been extended to 3D through algorithms based on stochastic differential equations that simulate gas diffusion (Jurjevic et al., 2020). To ensure flight efficiency, methods have been proposed to select frontiers that minimize speed changes, reducing frequent attitude adjustments and improving energy efficiency (Wang et al., 2021).

Sampling-based methods randomly sample viewpoints in open spaces to find trajectories with maximum information gain. The Next Best View Point (NBVP) strategy comprehensively considers cumulative trajectory information and uses Rapidly-exploring Random Tree (RRT) algorithms to determine optimal target points and paths (Eric et al., 2020). Improvements include RRT-like reconnection techniques that maintain and optimize tree structures throughout exploration, gradually enhancing path quality (Yao and Liang, 2024b). These techniques refine paths through tree structure reconnection and optimize path selection during exploration (Liu et al., 2022).

Recent advances focus on improving exploration efficiency and information gain. Sampling-based strategies generate inspection routes covering frontiers, optimizing exploration order and reducing repeated areas (Tian et al., 2020). Historical maps of previous samples enable evaluation of exploration potential and optimization of orientation angles (Bartolomei et al., 2023). Combining NBVP and frontier algorithms with cached points accelerates information gain calculation, enhancing exploration efficiency (Yamauchi, 1997).

Hybrid methods address large-scale exploration by combining sampling and frontier technologies with global information consideration. The FUEL framework supports rapid UAV exploration through hierarchical planning that identifies frontier regions and uses improved Traveling Salesman Problem solutions for visit order determination (Shen et al., 2012). The Fast Autonomous Exploration Planner (FAEP) employs heading constraints to reduce redundant operations in small-scale scenarios (Cieslewski et al., 2017). However, these methods often exhibit greedy decision-making and are primarily validated in small-scale areas, leading to inefficient back-and-forth movements in large-scale forest environments.

2.3 Path Planning

Path planning and trajectory generation are essential for efficient autonomous exploration. UAV trajectory generation methods are generally classified into hard-constraint and soft-constraint approaches (Bircher et al., 2016). Hard-constraint methods strictly adhere to pre-set constraints such as flight safety, speed, and obstacle avoidance, often relying on mathematical optimization techniques like quadratic programming to generate precise trajectories (LaValle, 1998). These methods are suitable for high safety requirements but may involve computational overhead.

Soft-constraint methods, on the other hand, offer flexibility by allowing compromises on certain constraints. They balance multiple objectives such as path smoothness, safety, and energy consumption, achieving higher computational efficiency and flight speeds (Chen et al., 2015). Recent advances include B-spline parameterization for trajectory representation, enabling local replanning and dynamic adaptability (Ding et al., 2018). However, soft-constraint methods may lead to local optimal solutions and cannot strictly satisfy all constraints, posing challenges for real-time applications in dynamic environments.

The challenge remains in balancing efficiency, safety, and response speed for real-time applications, especially in complex forest environments.

3. Methods

The pipeline of the proposed method is illustrated in Figure 1. In this work, we propose a method for under-canopy UAV path planning in forest environments, leveraging both prior knowledge and real-time data to ensure safe and efficient navigation. The method begins with the acquisition of point cloud data from above the canopy. From this data, the distribution of tree trunks is estimated, which is then used to generate a prior map that incorporates the above-canopy point cloud information. This prior map serves as the basis for path planning and collision avoidance. Based on the estimated tree trunk distribution, a ESDF and a VF are computed. Initial waypoints are then generated on the ESDF, which serves as the foundation for global path planning. A global path is planned using the A* algorithm, considering both the ESDF and VF to ensure the UAV can safely navigate through the environment while avoiding obstacles and maximizing visibility. The generated path is further refined by smoothing it with B-spline interpolation to ensure smooth transitions and reduce abrupt changes in direction.

During flight under the canopy, the UAV's position on the prior map is updated in real-time using LiDAR odometry, which leverages under-canopy LiDAR data to accurately track the UAV's movements. Collision checking is continuously performed in real-time to monitor potential obstacles in the UAV's path. When an obstacle is detected, the local planner is activated to adjust the UAV's trajectory and generate a new path, ensuring that the UAV can adapt dynamically to changing environmental conditions.

3.1 Prior Map Generation

First, individual tree segmentation is performed on the point cloud data acquired from above the canopy, and the segmented point cloud is used to estimate the distribution of tree trunks. Since tree trunks are typically located at the center of tree crowns, the crown centers can be estimated by identifying the positions of local maximum elevation values in the point cloud. Due to the lack of point cloud data beneath the canopy, this paper assumes that the trunk radius is constant. Based on the estimated trunk distribution, a prior grid map containing tree center positions and radius information is generated.

3.2 VF and ESDF Generation

In this study, tree trunks are defined as obstacles, and the interior of the tree trunks is considered as the obstacle's interior. The Euclidean Signed Distance Field (ESDF) is computed by assigning each grid cell in the map a signed distance to the nearest tree trunk. The signed distance is positive if the grid cell is outside the tree trunk and negative if it is inside the tree trunk. The ESDF calculation is expressed as:

$$d_{\text{cell}} = \text{sign}(\text{cell}) \cdot \min_{i \in \text{TreeTrunks}} \sqrt{(x_{\text{cell}} - x_i)^2 + (y_{\text{cell}} - y_i)^2} \quad (1)$$

The sign of the distance is defined as follows: it is set to -1 for grid cells inside the obstacle (tree trunk interior) and +1 for grid cells outside the obstacle (tree trunk exterior). This distinction allows the ESDF to effectively represent safe regions, collision zones, and boundary areas. The ESDF provides a continuous representation of obstacle proximity, which is essential for collision avoidance and safe navigation.

The Visibility Field (VF) is constructed by assigning to each grid cell a visibility value, defined as the number of tree trunks visible from that cell. For each tree trunk, a visibility region is computed based on the effective measurement range of the LiDAR sensor, denoted as r_{vis}. A ray-casting method is used to identify the set of grid cells $\mathcal{V}_i$ that are visible from the i-th trunk. The final VF is then obtained by accumulating the visibility contributions from all trunks:

$$\text{VF}(\mathbf{c}) = \sum_{i \in \text{TreeTrunks}} \mathbb{I}(\mathbf{c} \in \mathcal{V}_i) \quad (2)$$

where $\mathbb{I}(\cdot)$ is the indicator function that returns 1 if the condition is satisfied and 0 otherwise.

3.3 Global Path Planning

The initial global waypoints are generated based on the Euclidean Signed Distance Field (ESDF), which encodes the distance from each location to the nearest tree trunk and serves as a basis for safe waypoint placement. For each tree, n initial waypoints are uniformly distributed in n angular directions around the tree trunk, each located at a fixed distance d from the trunk center. To enhance obstacle clearance, each waypoint is then adjusted to the nearest local maximum of the ESDF within a circular neighborhood centered at its original position. This adjustment ensures that the waypoints are positioned in regions with higher clearance from nearby trunks, while maintaining a relatively uniform angular distribution across different trees. As a result, the UAV can navigate more safely through the forest and achieve more consistent point cloud density around the tree trunks.

To determine an efficient global flight path through these waypoints, the waypoint visiting sequence is formulated as a Traveling Salesman Problem (TSP), with pairwise distances computed using A* search on the ESDF map. For each pair of waypoints, the A* algorithm calculates the shortest collision-free path, taking into account the signed distance values from the ESDF to avoid tree trunks and prioritize safer regions. These path lengths are used to construct a distance matrix, which represents the true traversable cost between waypoints.

The TSP is then modeled as a Mixed-Integer Linear Programming (MILP) problem, where binary decision variables represent whether a path segment is included in the final tour. The formulation includes standard degree constraints to ensure entry and exit at each node, and subtour elimination constraints based on the Miller–Tucker–Zemlin (MTZ) formulation. The MILP is solved using CBC (Coin-or Branch and Cut), an open-source MILP solver known for its efficiency in handling combinatorial optimization problems.

Once the optimal visiting sequence is obtained, the final global trajectory is constructed by concatenating the corresponding A* paths between consecutive waypoints. This hybrid planning approach ensures that the UAV follows a globally efficient route while maintaining local safety, enabling robust and accurate navigation through complex forest environments.

To generate a smooth and adaptive velocity profile along the planned trajectory, an initial speed is assigned to each waypoint based on its visibility value, which reflects the local density of obstacles. Higher visibility indicates a more open environment, while lower visibility suggests a cluttered area. These values are normalized to the range [0, 1] and linearly interpolated to compute the base speed. This base speed is then modulated according to the curvature of the trajectory, which captures the sharpness of turns. A piecewise function is employed: in low-curvature regions, the speed remains unchanged; in high-curvature regions, the speed is reduced to ensure safe maneuvering; and in intermediate regions, a quadratic function provides a smooth transition between the two. To further refine the velocity distribution, a convolution-based smoothing operation is applied to suppress abrupt speed changes. Finally, the trajectory and its associated speed profile are jointly smoothed through waypoint downsampling and spline interpolation, resulting in a continuous and stable flight path that enhances both navigation safety and motion efficiency.

3.4 Local Relanning

During autonomous flight along the globally planned route, the UAV may encounter situations where the local path becomes obstructed due to dynamic environmental changes, mapping errors, or limitations in sensor visibility. To enable robust obstacle

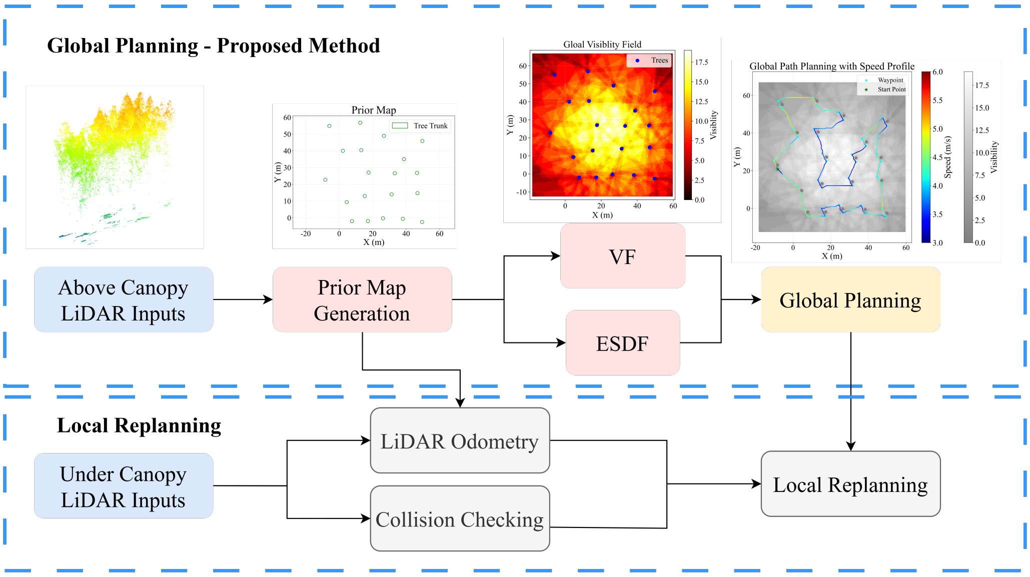

Figure 1. The pipeline of the proposed method.

avoidance and dynamic trajectory adjustment, this work integrates Fast-Planner as the local replanning module, which generates safe, feasible, and dynamically consistent trajectories in real time.

Fast-Planner begins by generating an initial path as guidance and formulates a trajectory optimization problem under dynamic feasibility constraints using B-spline parameterization. The objective function considers multiple factors, including trajectory smoothness, dynamic feasibility (e.g., velocity and acceleration limits), and obstacle clearance. By minimizing this objective, the optimizer produces a high-quality, continuous trajectory that satisfies kinematic constraints while maintaining a safe distance from obstacles.

The local replanning module operates continuously within a sliding time window, allowing new safe trajectories to be generated promptly when the goal position changes or when updated environmental information becomes available. Benefiting from Fast-Planner's efficient structure and optimization strategy, the module can operate at a high frequency, ensuring agile obstacle avoidance and stable flight in complex and dynamic environments.

4. Experiments and Results

4.1 Experimental Setup

The MARSIM simulator (Kong et al., 2023) was utilized to evaluate the proposed method in a simulated forest environment. MARSIM is a lightweight, point-realistic simulator specifically designed for LiDAR-based UAVs. Unlike traditional simulators that rely on dense mesh maps, MARSIM constructs depth images directly from point cloud maps and interpolates them to generate realistic LiDAR point measurements. This approach enables the simulation of real-world environments with high fidelity while maintaining low computational requirements, making it suitable for lightweight computing platforms.

MARSIM supports various LiDAR configurations, including different resolutions and scanning patterns, as well as dynamic obstacles and multi-UAV systems. In this study, MARSIM was used to simulate a forest environment for under-canopy UAV navigation.The simulation environment used in this study is illustrated in Figure 2. The UAV was equipped with a Livox Mid-360 LiDAR, which features a 360° horizontal and 59° vertical field of view, enabling comprehensive under-canopy scanning. Waypoints and speed commands were sent to the UAV within MARSIM to execute the planned global paths. The point cloud and IMU topics generated by the simulator were subscribed to by Fast-LIO2 (Xu et al., 2022) for real-time LiDAR-inertial odometry and mapping. This setup allowed for the evaluation of the proposed method in a controlled yet realistic environment, ensuring the reliability and applicability of the results.The generated dense under-canopy point clouds were used for subsequent DBH estimation and structural analysis.

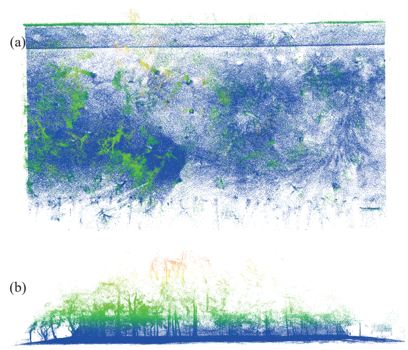

Figure 2. Simulation environment in MARSIM. The point cloud represents the forest environment, showing tree trunks and canopies. (a) Top view, (b) Front view. Colors indicate point height.

4.2 Results

The computed Visibility Field (VF) is presented in Figure 3, where each grid cell value represents the number of visible tree trunks from that location. The central area of the study region, along with areas of lower tree density and open regions at the top and bottom, exhibit the highest visibility values. These regions provide maximum visibility of tree trunks, which is advantageous for UAV navigation and data collection.

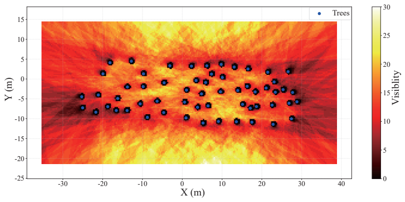

Figure 3. Global Visibility Field (VF) map. The color bar indicates the number of visible tree trunks from each grid cell.

To illustrate the effectiveness of the global planning algorithm, Figure 4 shows the planned global path and its corresponding speed distribution. The path successfully covers all tree trunks, and the speed distribution remains uniform throughout, highlighting the safety and efficiency of the proposed method.

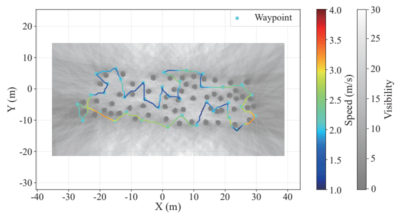

Figure 4. Global path planned by the global planning algorithm. The color bar indicates the UAV speed along the path.

Point cloud data acquired during the under-canopy flight is visualized in Figure 5. Subfigure (a) provides a top view, while subfigure (b) offers a front view. The color-coded points represent height, clearly revealing the complex structure beneath the canopy and the spatial distribution of tree trunks. These data enable the extraction of tree trunk diameters for further analysis.

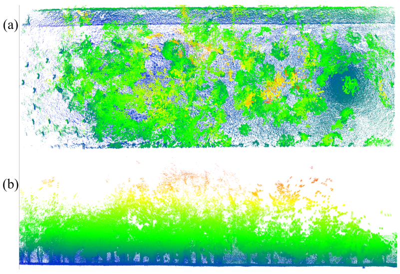

Figure 5. Point cloud acquired during the under-canopy flight: (a) top view, (b) front view. Colors represent the height of the points.

The relationship between DBH estimates derived from the point cloud and ground truth measurements is depicted in Figure 6. Using the least-squares circle fitting method, the extracted diameters demonstrate a bias of 0.18 cm and a root mean square error (RMSE) of 6.69 cm. These results confirm the high accuracy and consistency of the proposed method in extracting tree trunk diameters from point cloud data.

5. Future Work

The future work will focus on three main aspects to further enhance the proposed method. First, improving the individual tree segmentation process is critical, as the accuracy of the prior map heavily depends on precise tree segmentation results. The

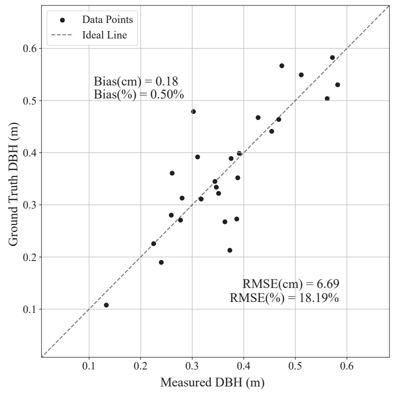

Figure 6. Scatter plot of Diameter at Breast Height (DBH) estimates from point clouds against ground truth measurements.

quality of the prior map directly affects the effectiveness of subsequent path planning and navigation. Future research will explore more efficient and accurate tree segmentation algorithms to enhance the reliability and precision of the prior map, ultimately improving the overall performance of the system.

Second, the generation of initial waypoints will be refined by introducing adaptive adjustments to the distance and angle relative to tree trunks. The current approach uses fixed parameters for waypoint generation, which may not be suitable for all tree species and environmental conditions. Future efforts will focus on developing adaptive strategies that dynamically adjust waypoint generation parameters based on tree characteristics and environmental factors. This will improve the flexibility and adaptability of the path planning process, ensuring optimal performance across diverse scenarios.

Lastly, the speed planning mechanism will be enhanced by incorporating adaptive strategies for determining speed ranges. Currently, the maximum and minimum speed limits are manually set based on empirical knowledge, and the algorithm operates within these predefined boundaries. Future research will aim to develop algorithms capable of autonomously determining speed ranges based on environmental complexity and task requirements. This will enable the system to optimize flight efficiency and safety dynamically, further enhancing its applicability in complex and dynamic forest environments.

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