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Feasibility Analysis of UAV Navigation System in Complex Terrain

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Abstract:

With the continuous advancement of science and technology, unmanned aerial vehicles (UAVs) have gained extensive application, and the societal demand for them is on the rise. However, there exists a significant gap in the research of their navigation systems when operating in complex terrains. This study conducts a comprehensive analysis of the working principles of UAVs, covering both the flight and navigation control system aspects. Additionally, it elaborates on the challenges encountered in navigation within forest, mountain, and urban complex terrains, including vegetation cover, terrain undulation, and electromagnetic interference. To address these challenges, technical strategies are proposed, such as calculation methods and planning optimization related to vegetation scenarios, innovative analysis and trajectory planning for urban scenarios, as well as the application of optical flow technology. Through a comprehensive analysis of the feasibility, this study aims to provide support for the safe and efficient operation of UAVs in complex environments and promote the continuous enhancement of their application in complex terrains, thereby opening new prospects for the development and application of UAVs.

Keywords: Drones, flight principle, navigation and control systems, complex terrain, forest terrain, urban terrain.

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1. Introduction

With the rapid development of science and technology, the application of UAVs in various fields is becoming more and more extensive, from military reconnaissance to civil logistics and distribution, from environmental monitoring to film and television shooting. Nowadays, the demand for UAVs in all aspects of society is constantly rising, which prompts us to continuously deepen the research and improve UAV-related technologies to better adapt to the needs of social development. Through the study of related literature, we find that the current research on UAV navigation systems mainly focuses on technological innovation and performance enhancement, but there are some limitations in analysing the feasibility of UAV navigation systems in complex terrain. The existing research has achieved certain results on the navigation problems in some specific terrains, but it lacks comprehensive and comparative research on a variety of complex terrains. In modern society, various operational tasks in complex terrain environments are more and more frequent. For example, in emergency rescue operations in mountainous areas, time is life, and traditional rescue methods may be constrained by factors such as inconvenient transportation and complex terrain, while UAVs can quickly traverse complex terrain and provide key information and material transportation support for rescuers. In the field of forest resources monitoring, there are a large number of areas in the vast forest that are difficult to reach by manpower, and UAVs can flexibly fly over the forest, and monitor the growth status of the forest and fire hazards in real-time through the various advanced sensors on board. In some infrastructure construction projects in remote mountainous areas, such as road construction, power line erection, etc., UAVs can carry out detailed surveys of complex terrain in advance, providing accurate data for engineering planning and construction. However, in the complex terrain environment, the navigation of UAVs faces many serious challenges. Complex terrain covers a variety of landforms such as mountains, forests, canyons, etc., which are characterized by large terrain undulations, numerous obstacles, and strong signal interference. In such environments, traditional navigation methods may be greatly restricted or even ineffective. For example, Global Positioning System (GPS) signals may become weak or completely lost in mountainous areas due to mountain blockage, which will seriously affect the positioning accuracy and flight safety of UAVs. Meanwhile, airflow changes in complex terrain are also very complicated and may have a huge impact on the flight stability of the UAV. In addition, the occlusion of trees in environments such as forests not only affects the visual navigation system but may also lead to collisions between UAVs and obstacles. This study will adopt a targeted analysis method to conduct in-depth research on the navigation difficulties in three typical complex terrains, namely forest, mountain and city, aiming to comprehensively analyse the feasibility of UAV navigation systems in complex terrains, and provide support for their safe and efficient operation in complex environments.

2. How drones work

2.1 Principle of Flight

Drones fly using aerodynamic principles in which Bernoulli's principle plays a key role. When air flows through a wing, the pressure difference between the upper and lower surfaces creates lift. The coefficient of lift is related to the shape of the wing, the angle of attack, etc. The angle of attack increases within a certain range and the lift increases, but if it is too large, stalling occurs. The power unit of the UAV provides power for flight, as the electric UAV adopts brushless DC motors, and the flight attitude and position can be controlled by adjusting different motor speeds [1]. The manoeuvrability of a fixed-wing UAV during aggressive flight is related to the ability to change linear velocity rapidly, with the equation:

$$\frac{(L - D\sin\alpha - mg\sin\phi)cos\phi + (L - D\sin\alpha - mg\sin\phi)\sin\phi tan\alpha}{m} \tag{1}$$

(where D= $D_{wing} + D_{tail}$ and other parameters), affected by propulsion, lift, and drag, etc.; agility is related to the ability to change the rotation rate quickly, e.g. $\frac{P}{I_{XX}}$, $\frac{Q}{I_{YY}}$, $\frac{R}{I_{ZZ}}$, (I is the moment of inertia), affected by the turning moment, moment of inertia, and stability. Cruise flight requires low energy for fast flight, high intrinsic stability to reduce gust sensitivity, and power optimization through lift-to-drag ratio (P = TV). Bird-inspired UAVs with wing and tail deformation affect the flight principle; in manoeuvrability, deformation changes lift and drag, e.g., wing extension affects lift slope; in agility, deformation affects pitch and roll moments; pitch stability depends on pitch coefficient slope; in terms of power demand and speed range, different morphologies perform differently at high and low speeds while optimizing the relevant parameters can adjust power demand.

2.2 Principles of Navigation and Control Systems

In the principle of navigation and control system of UAV, sensors are the key part. GPS receives signals to determine the position through the satellite constellation [2], but it will be affected by environmental factors; accelerometers and gyroscopes of inertial navigation systems get the position, velocity, and attitude information through integration operation, and there are drift and alignment errors; visual sensors rely on computer vision algorithms (e.g., feature extraction matching algorithms) to process the images to provide the environment information, and their field of view and resolution affect navigation. Navigation algorithms cover path planning (e.g., A*, Dijkstra's algorithm), attitude control (PID control algorithms as in Fig. 1[3], whose parameters are related to the UAV characteristics), and navigation fusion (weighted averaging, Kalman filtering [4,5], and other approaches). There are challenges in complex terrain navigation, indoor localization relies on devices with limitations, emerging UWB technology may improve; height estimation is difficult under irregular obstacles, MMAE-based algorithms cope with this by using multiple Kalman filters, adjusting the weights based on the principle of Occam's razor, and the filters work differently in different scenarios, and these elements are related to the UAV's navigational challenges and related techniques in complex terrains, such as forests, urban areas and mountainous terrains. Navigation challenges and related technology research [6].

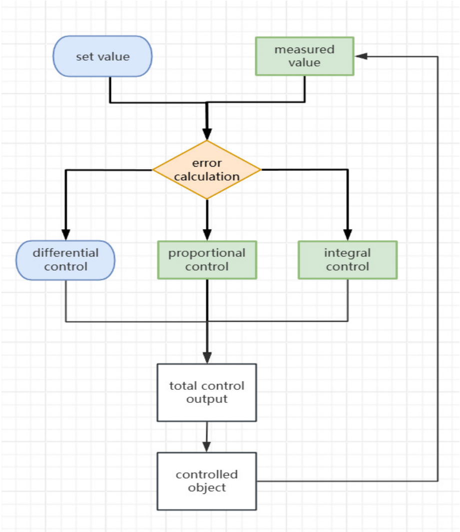

Fig.1 PID control flow chart

2.3 Flight control system

In terms of hardware components, the flight controller receives sensor data, runs navigation algorithms and control algorithms, and sends commands to actuators such as motor drives. The motor driver controls the motor speed and steering according to the instructions, and the actuator also includes the servo and other components, which are used to control the flight attitude of the UAV. In terms of software functions, the control algorithm regulates the UAV's flight attitude and speed, prepares safety protection functions, sets flight altitude and speed limits, and activates the emergency handling mechanism when an abnormal situation occurs.

3. Navigation challenges and technology optimization for UAVs in complex terrain

3.1 Forest terrain

The forest terrain has many remarkable features, and its vegetation is rich and diverse, including a variety of trees, shrubs herbaceous plants, etc., which builds up a complex ecosystem and provides habitats and food sources for a large number of animals. At the same time, the terrain is more complex, covering mountains, hills, valleys and other landforms, which have an important impact on the ecological environment and species distribution of the forest. The forest terrain is usually humid because the vegetation releases a lot of water through transpiration, but the specific characteristics of the forest terrain in different regions vary according to the differences in climate, soil, altitude and other factors.

Vegetation cover is high, with Chongqing Municipality reaching 52.5% forest cover in 2020. Despite the penetrating nature of 3D mapping scans, the number of ground point clouds acquired in more densely vegetated areas is small and cannot be quasi-presented. The ground characteristics lead to the deviation of the difference generated by DEM data from the real ground surface. In the traditional route planning stage, the altitude of the measured area is usually circled for route planning, ignoring the impact of natural environmental factors such as vegetation growth in the measured area on route planning [7].

3.1.1 "Fuzzy" calculation of vegetation cover

In research on the application of UAVs in areas such as geographic information collection, accurate assessment of vegetation coverage is critical for subsequent route planning. UAVs equipped with 3D laser scanners have become a key tool in this field due to their unique ability to penetrate vegetation. In the research process, we first extracted single-band images from remote sensing images of the study area and calculated the associated vegetation indices through a series of band operations. Then, based on all the obtained vegetation indices, we carefully constructed classification samples and training datasets to train the random forest classifier and screened out the classification models corresponding to the vegetation indices with classification accuracies of more than 95% with rigorous criteria. Among them, the ultra-red index (EXG), the modified green-red vegetation index (MGRVI), the normalized green-red difference index (NGRDI), and the red-green ratio index (RGRI) were able to efficiently identify dense vegetation capable of shading the ground as vegetation objects during the classification process, and at the same time, the non-vegetation, low vegetation, and sparse vegetation in the landslides were relatively ambiguously categorized as non-vegetation objects. Finally, we calculated the vegetation cover of each vegetation index classification result after screening and took its average value to derive the vegetation cover of the study area, to meet the key requirements of route planning optimization. [7]

3.1.2 Route Planning Vector Environmental Impact Analysis

In the academic research field of route planning, the number of location nodes in the route planning vector environment significantly affects the planning effect and is closely related to the speed and convergence rate of the route planning method. Our analysis shows that in different categories of route planning vector environments constructed, the smaller the number of location nodes, the faster the speed and convergence rate of route planning. By comparing the route planning results obtained by applying this paper's method in different environments, the following conclusion can be drawn: when facing a dense vegetation area and the route planning task is time-critical, it is recommended to use a route planning vector environment with a smaller number of location nodes to improve the efficiency of task completion. On the contrary, when the main objective of the route planning task is to obtain more ground data to construct high-precision surface data, the route planning vector environment with a larger number of position nodes should be selected for the related work [7].

3.1.3 Optimization of Route Planning Algorithms

The core measure of this study is to carry out innovative optimization based on the classical ant colony algorithm. By introducing the "fuzzy" results of vegetation coverage, the pheromone initialization, state transfer rules, and pheromone computation and updating strategies in the classical ACO algorithm are optimized. After the optimization, the unmanned airborne LiDAR adaptive route planning method for densely vegetated areas performs very well in a series of validation experiments. Compared with the classical ACO algorithm before optimization, the method achieves faster iteration speed, significantly reduces the time cost required for completing route planning and demonstrates excellent optimization capability. In addition, the method can fully consider the vegetation coverage of the flight area, autonomously searching for areas with low vegetation coverage for route planning, and combining with the scanning angle effectively improves the acquisition probability of ground points, providing a solid basic guarantee for accurately acquiring terrain information [7].

3.1.4 Problem Coping and Accuracy Optimization of UAV Point Cloud Construction in Forested Terrain

In the forest terrain, the DJI Phantom 3 Professional was used for data acquisition, and the flight parameters were set according to the characteristics of the forest terrain. The semi-automatic flight mode was used, taking into account the flight altitude, speed, and camera settings, to ensure that the images overlapped, to obtain sufficient data to cope with the complexity of the forest. For data processing, the camera was pre-calibrated using Agisoft LENS software, and the images were processed using Agisoft PhotoScan Professional 1.2.6 software, with the parameters carefully set to ensure accuracy during the processing steps. Multiple Ground Control Points (GCPs) were set up and multiple configurations were designed to incorporate them into the beam method of leveling to optimize the scaling of the point cloud based on the forest environment. For accuracy assessment and analysis, multiple accuracy indicators (e.g., root-mean-square coordinate error, root-mean-square horizontal error, etc.) are used for statistical and spatial analysis. The comprehensive accuracy assessment results analyze the influencing factors, such as the influence of plot features on horizontal accuracy, the different performance of vertical accuracy in different slope plots, and the complexity of the influence of GCP configuration on accuracy, and then propose optimization suggestions for UAV application in forest terrain, including adjusting the flight and acquisition mode according to terrain features, and reasonably setting the number of GCPs, etc., to improve the accuracy of the point cloud [8].

3.2 Urban Terrain

Many characteristics of cities have an impact on UAV navigation. In terms of building layout, the density of high-rise buildings can block GNSS signals and cause positioning deviation, create complex airflow and increase the difficulty of flight control, and glass curtain walls can interfere with visual sensors; in terms of the regularity of the building arrangement, a regular arrangement is conducive to the stabilization of GNSS signals and the identification of landmarks by visual navigation, whereas an irregular arrangement increases the difficulty of navigation. At the same time, there are a lot of shadow fading and multipath effects in the transmission of electromagnetic wave signals among tall buildings, especially there may be Global Navigation Satellite System (GNSS) rejection and a lot of magnetic aberrations, which puts forward higher navigation and localization requirements for the equipment [9]. In the traffic conditions, the density and complexity of the road network affect the flight path planning and obstacle avoidance decision, and the road construction needs to update the map information to adjust the path; the traffic signals and signs can assist in calibrating the position direction but may also interfere with the visual sensors. In the electromagnetic environment, wireless communication signal strength and interference may affect UAV communication and sensor accuracy, and electromagnetic fields generated by power facilities may affect the accuracy of sensors such as magnetic compasses and communication systems, so the navigation system needs to take measures such as anti-jamming, calibration compensation and communication enhancement. Under meteorological conditions, wind direction and speed affect flight energy consumption and speed, and wind shear threatens flight safety, so navigation systems need to be adjusted; accordingly, precipitation affects visual sensors, and haze weakens GNSS signals and visual sensors, so navigation needs to rely on other technologies and adjust flight parameters.

3.2.1 Three-dimensional urban environment analysis based on raster method

The purpose of 3D environment modelling is to simulate the real scene, to reproduce the physical space to the abstract space, and to establish an environment model that can be and is easy to process by the computer, in essence, it is the constraints that the algorithm needs to deal with the obstacles and so on in the physical environment are mapped one by one and the path search can be intuitively displayed in the virtual scene, to facilitate the intuitive display of the path planning scenario and the planning results. The main method for modelling 3D environments is to use the same method as that used for the physical environment. The mainstream method of 3D environment modelling is the raster method [9,11]. Raster method according to the proportion and segmentation requirements, the simulation environment will be divided into several identical grids, and then the environment parameters for each grid, according to the actual or hypothetical environment, set each grid's obstacles. Establish a three-dimensional right-angle coordinate system with the origin, model the three-dimensional urban environment as a large rectangle, the threat area as a cylinder and the mission objectives as a three-dimensional coordinate, as shown in Fig.2. Apply the raster method to divide the planning space into regularly arranged, same-sized discrete cells, and simplify the urban buildings as a single rectangle or a combination of several rectangles to establish a rasterized three-dimensional urban combat-based space model, so that the location of obstacles and feasible areas can be more intuitively displayed, and the position information of each location is significantly marked by rows and columns to truly portray the complexity of the urban environment [10].

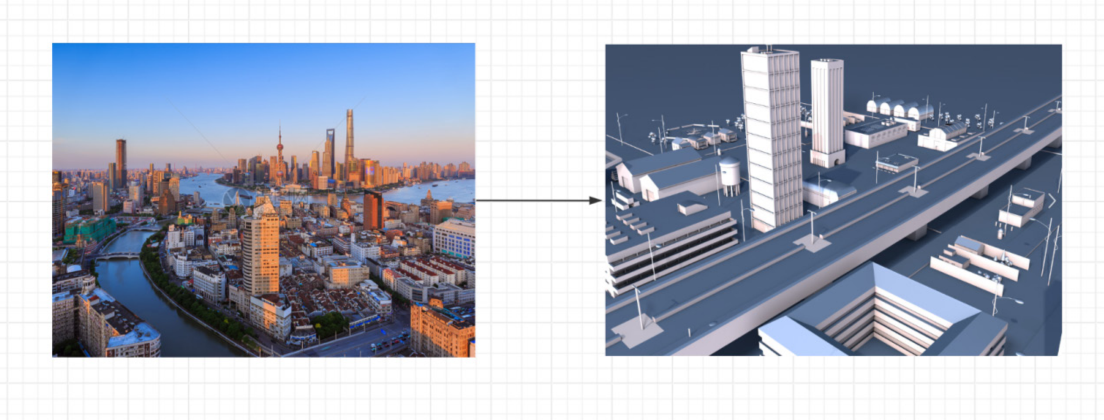

Fig.2 The mission objectives as a three-dimensional coordinate

3.2.2 Reinforcement Learning-Based UAV Cluster Trajectory Planning

Reinforcement learning maximizes the cumulative rewards through the mechanism of “exploration-exploitation”, in which on the one hand, the agent continuously explores the environment and obtains observations, and on the other hand, it utilizes the existing experience and information to continuously update the learning strategy. The principle of Reinforcement Learning is shown in Fig 3. In Reinforcement Learning, the decision maker or Agent is generally defined, and things outside the Agent are defined as the Environment, and the system is integrated with the environment, and the interaction process between the Agent and the environment consists of state, action, reward and reward. The interaction process between the intelligent body and the environment consists of three elements: state, action and reward. The interaction process between the intelligent body and the environment consists of three elements: state, action, and reward.

St, the intelligent body performs action At and interacts with the environment, gets reward Rt and gets updated to the next state St+1[10].

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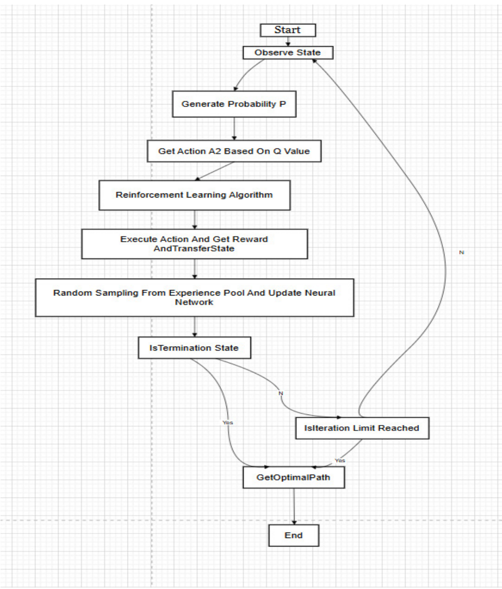

Fig.3 Flow chart of reinforcement learning agent

3.2.3 From Multi-Resolution Search to Semantic Segmentation and Simulation Verification

From multi-resolution search to semantic segmentation and simulation validation To address these challenges, a variety of processing methods are employed. Multi-resolution probabilistic search methods were applied, including a hierarchical exploration strategy, starting from high altitude and gradually reducing the altitude to re-explore to converge to a safe landing point; a probabilistic model was constructed, using a beta distribution to describe the probability of cell landing adaptation and its uncertainty, and updating the beliefs based on Bayes' theorem, and a Generalized Bernoulli Distribution model was used to deal with the problem of correlation of measurements at different altitudes. For information processing based on semantic segmentation, the BiSeNet [12] network is selected and trained with urban flight images at different altitudes, assigning a priori weights to the different categories, and determining the landing adaptability by weighted average pixel probability scores. Using simulation environment testing and validation, the AirSim [13] simulator is constructed with two purposes testing the multi-resolution method and generating offline data, and the validity of the model and method is initially verified by analyzing and testing in the simulation environment [14].

3.3 Mountainous terrain

Mountainous regions have unique topographical features and surface patterns. Some mountains are parallel like the Andes, while others overlap like the Hengduan Mountains. The complex terrain is caused by plate movement. Mountain slopes are steep, generally over 30 degrees and up to 60 degrees in some places. This affects human activities and transportation. For UAV navigation, steep slopes require UAVs to adjust flight attitude and power output. Climbing steep slopes increases energy consumption and may reduce range. The undulating terrain blocks signals, especially in valleys where GPS signals may be weak or lost, affecting UAV positioning and navigation. Mountain valleys are deep and V-shaped due to water erosion. Valleys form unique microclimates and ecosystems. When UAVs cross gullies, the airflow becomes unstable, affecting flight stability. The cliffs may reflect and interfere with wireless signals, increasing navigation difficulty. In mountainous terrain, radio wave propagation has difficulties. Signal strength depends on altitude, and multipath scattering makes it hard to predict signal changes. Traditional wave propagation models (e.g., Hata - COST321 model,[15] etc.) focus on near-ground signal propagation and cannot describe mountainous terrain well, having limited application value.

3.3.1 Optical flow

When the human eye observes a moving object, the object scene on the retina of the human eye forms a series of continuous changes in the image, a series of continuous changes in the information constantly "flow-through" the retina, as if a light "flow", so it is called the optical flow (Optical) Optical Flow.) The camera and the human eye are similar, the object scene is reflected in the image plane, and the movement of the series of images produced between the grey scale changes [16].

3.3.2 Optical Flow and Terrain Estimation

Optical Flow expresses the changes in the image and can be used to determine the motion of a target since it contains information about the target's motion. At the same time, the optical flow changes differently for objects of different distances, so the optical flow can also be used to determine the distance of the object. As shown in Fig. 4, an external target moves to the right with velocity v relative to the camera sensor, forming an image motion with velocity v(flow) on the image sensor. v(flow) is proportional to the velocity v and inversely proportional to the distance h.

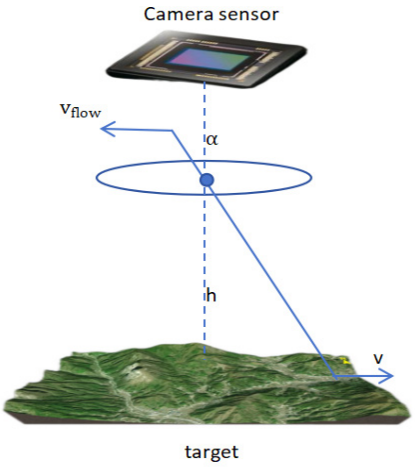

Fig.4 The relationship between optical flow velocity and distance.

Thus, once the relevant parameters of the image sensor have been determined, the speed or distance can be determined from the optical flow. If the (UAV) camera flight speed is known, the topography can be determined from the image optical flow field [16].

3.3.3 Fast optical flow estimation under topology matching

According to Eq., the UAV flying speed relative to the ground can be known, and the key to getting the UAV height h relative to the ground lies in the optical flow estimation. The commonly used algorithms for optical flow estimation include gradient-based methods, energy-based methods, phase-based methods, neural dynamics methods, and matching-based methods. The main purpose of the first four methods in this category is to obtain the motion of the target within the image range, and the matching-based methods can be used in a dense matching or sparse matching way according to the needs. UAV terrain following, which can obtain the height of the vehicle through a small number of targets on the image, without the need to obtain a large number of target optical flow fields, and more importantly, it can quickly obtain the optical flow information to realize the rapid estimation of the UAV height for terrain following. Based on the matching method, this study designs a fast optical flow estimation method under the topology matching constraint. The specific realization steps are: the first photo feature extracts a small number of points to form a polygon; using the topological constraints of the polygon, the polygon vertex position of the second photo can be quickly located. As shown in Fig.6; calculating the proportionality change of each side, without the need to calculate the coordinates of the image coordinate system, to carry out the optical flow estimation; from the optical flow estimation to estimate the current relative ground aerial altitude [16].

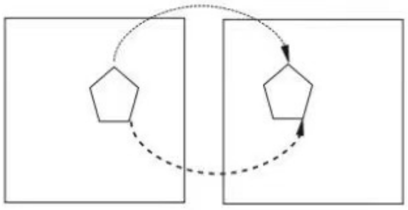

Fig.5 Fast optical flow design based on topological constraints

4. Summary

This paper delves into the working mechanism of drones, encompassing flight principles, navigation, and control systems. It thoroughly examines the navigation challenges and technological optimizations in complex terrains such as forests, urban areas, and mountains. In the context of forests, it elaborates on the calculation of vegetation cover. The accurate determination of vegetation cover is essential as it directly affects the drone's ability to plan its route. By conducting a detailed analysis of the impact of route planning, drones can avoid obstacles and find the most efficient paths. Additionally, optimizing the construction of point clouds helps in creating a more accurate map of the forest terrain. This is crucial as accurate vegetation cover assessment helps drones navigate safely and efficiently through the forested landscape. When it comes to urban terrains, the raster method is employed for analysis, combined with reinforcement learning for the trajectory planning of UAV clusters and semantic segmentation. The urban environment is characterized by a high density of buildings, people, and other obstacles. By using these techniques, drones can better understand their surroundings and make informed decisions about their movement. This enables drones to better adapt to the complex urban environment with its numerous obstacles and dynamic factors. In mountainous regions, optical flow plays a vital role in terrain estimation. A fast estimation method under topology matching is introduced. The mountainous terrain is often rough and uneven, making it difficult for drones to navigate. Optical flow helps in determining the speed and direction of the drone's movement relative to the terrain. However, there are remaining challenges. In forests, accurately accounting for vegetation cover remains a hurdle. In urban areas, the coordination of UAVs needs to be enhanced to avoid collisions and ensure efficient operation. In mountains, improving the estimation of optical flow is of great significance in improving the accuracy of terrain estimation. Future research could concentrate on develop-

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ing better models for forests, enhancing coordination in urban environments, and refining optical flow methods. By integrating multiple technologies, such as advanced sensors, artificial intelligence algorithms, and communication systems, the navigation of drones in complex terrains can be significantly improved. This will not only enhance the performance and safety of drones but also open up new applications in various fields, such as environmental monitoring, disaster response, and urban planning.

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