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Multi-task UAV Operation Technology and Practical Analysis for Hilly Tea Garden Management

Chengbin Fang
Automotive and Low-Altitude Aircraft College
Zibo Polytechnic University
Zibo, Shandong, China

Abstract: Hilly tea gardens in China feature undulating terrain and fragmented plots, which restrict the access of large-scale ground agricultural machinery. Traditional manual operation patterns suffer from high labor intensity and low production efficiency. With high flexibility and strong terrain adaptability, UAVs can simultaneously carry out multiple management tasks including pesticide spraying for pest control, remote-sensing monitoring of tea growth, and tea-garden disaster investigation. Combined with terrain, vegetation and local micro-climate characteristics of hilly tea gardens, this paper sorts out the technical system of multi-task UAV management operations, and illustrates technical essentials of three typical tasks: plant-protection spraying, remote-sensing monitoring and disaster inspection. Practical problems existing in current operations are summarized, including insufficient matching of operation parameters, low level of multi-task cooperation, operation quality interference caused by mountain wind fields, and lack of special operation specifications for tea gardens. Improvement countermeasures are proposed from the aspects of equipment adaptation optimization, multi-task operation procedure construction, operation standard system establishment and human-machine collaborative operation mode. Relevant analysis can provide practical references for integrated multi-scenario management operations of UAVs in hilly tea gardens.

Keywords: UAV; hilly tea garden; multi-task operation; tea garden management; remote-sensing monitoring; plant-protection spraying

1. INTRODUCTION

Tea is a vital characteristic cash crop in southern China, and most high-quality tea gardens are located in hilly and mountainous regions. Restricted by hillside terrain and fragmented plots, wheeled or tracked agricultural machinery can hardly enter tea gardens for large-scale operations. Work such as pest prevention and control, growth survey, frost and drought hazard investigation has long been highly dependent on manual labor. In recent years, aging rural labor force and rising labor costs bring considerable pressure to traditional tea-garden management modes.

The popularization of agricultural UAVs provides a feasible path for the modernization of mountain tea gardens. Different from flat farmland, hilly tea gardens are characterized by variable terrain elevation, low tea-tree canopy and complex local micro-climate. Operation schemes for field crops cannot be directly copied for tea-garden scenarios. At present, most UAV applications in tea gardens focus on single pesticide spraying. Spraying, monitoring and disaster inspection are carried out separately, and the practice level of integrated multi-task management remains low.

Domestic scholars have conducted numerous experimental studies on UAV spraying effect and UAV remote-sensing identification of tea growth. Nevertheless, systematic practical analysis on integrated multi-task UAV operations for hilly tea-garden scenarios is relatively scarce. Based on actual production conditions of hilly tea gardens, this paper sorts out the technical framework of multi-task UAV management operations, analyzes prominent problems in practical application, puts forward optimization suggestions, and adds actual pilot case analysis, so as to promote UAVs transforming from single spraying tools into comprehensive tea-garden management platforms.

2. Technical System of Multi-task UAV Management Operations for Hilly Tea Gardens

Multi-task UAV management for hilly tea gardens means that the same UAV platform can successively complete pesticide spraying, growth-information collection, disaster-site inspection and other production tasks in one single flight mission through quick replacement of mission payloads. Repeated take-off and landing can be reduced so as to improve overall operation efficiency. The complete technical system consists of four components: operation platform, mission payload, operation planning and data processing.

2.1 Selection of Operation Platform

Hilly tea gardens on slopes are filled with obstacles. Trees, utility poles and slope-protection structures are scattered throughout the operation area, which imposes certain requirements on UAV platforms in terms of wind resistance, low-altitude flight stability and convenient transportation capability. Multi-rotor UAVs are the mainstream in tea-garden applications. Plant-protection missions demand sufficient payload capacity to carry pesticide tanks and atomizing spraying components. Remote-sensing monitoring and disaster-inspection tasks have relatively low payload requirements and place more emphasis on low-speed flight stability.

To realize multi-task switching, platforms shall support quick disassembly and assembly of payloads, balancing payload capacity and endurance performance. Heavy-load plant-protection UAVs generally have shorter endurance and are suitable for concentrated spraying operations; lightweight inspection UAVs have longer endurance and are suitable for large-scale remote-sensing surveys. In actual multi-task operations, a formation mode of "main plant-protection UAV + auxiliary inspection UAV" can also be adopted, with one UAV responsible for spraying and the other synchronously collecting image data to further improve operation efficiency.

2.2 Multi-type Mission Payloads

Payloads are the core to realize different management tasks. Spraying missions adopt pesticide tanks and centrifugal atomizing nozzles to spray pesticides and foliar fertilizers. Growth-monitoring missions are equipped with visible-light and multispectral cameras to collect surface images of tea gardens. For disaster inspection, high-definition visible-light cameras are equipped, and thermal-infrared payloads can be adopted in some scenarios to identify frost damage and drought stress of tea trees.

Different payloads can be quickly replaced to realize multiple types of work by one UAV. However, payload replacement also has practical constraints: after plant-protection operations, pesticide tanks and pipelines retain residual liquid. If optical cameras are installed immediately, pesticide droplets may contaminate the lens and render images unusable. Therefore, in multi-task operations, equipment protection is required, or the operation sequence should be planned to prioritize image collection before spraying operations.

2.3 Route Planning Technology for Mountainous Areas

Plots of hilly tea gardens are irregular with slope variations. Traditional two-dimensional route planning may lead to frequent fluctuation of flight altitude, resulting in missing-spray and distortion of collected images. For mountain tea gardens, terrain-following route planning is required. Flight height is dynamically adjusted according to terrain elevation data, maintaining a relatively stable distance between UAV and tea-tree canopy, while avoiding ground obstacles such as trees and utility poles to guarantee operation safety and quality.

Terrain-following altitude data mainly comes from digital elevation models and airborne LiDAR. The accuracy of elevation data directly determines operation effectiveness. If terrain data errors are large, the UAV may fly too close to the canopy and cause collision risks, or fly too high and cause spray drift. For small scattered tea gardens, it is difficult to obtain high-precision terrain data, and pilots need to manually assist in route correction to reduce operation risks.

2.4 Processing of Multi-source Operation Data

Spraying operations mainly store operation records including flight trajectory, operation area and pesticide consumption. Remote-sensing images need stitching and correction to generate orthophotos of tea gardens, invert vegetation indices and identify regions with abnormal growth. Inspection images are used for manual review of locations with frost damage or pest outbreaks. Various types of data are aggregated to support decision-making for fertilization, pesticide application and disaster disposal in tea gardens.

At present, various types of data in most UAV systems are independent of each other. Spraying records are stored in the flight control backend, while remote-sensing images are stored in camera memory cards, lacking a unified data management platform. Data export and organization require manual operations, and the threshold for data utilization is high. Many tea gardens only retain images after operations and do not truly apply the data to production management.

3. Main Practical Missions of Multi-task UAV Management

3.1 Plant-protection Spraying Operations in Tea Gardens

Chemical pest control is the most fundamental production requirement for tea gardens, mainly targeting major pests such as tea leafhopper and tea geometrid. Manual pesticide application is difficult on sloped hilly tea gardens, while UAVs can finish large-area spraying rapidly. Nevertheless, dense branches and leaves of tea-tree canopy make it difficult for droplets to penetrate to leaf back. Mountain gusts may cause droplet drift. Direct adoption of field-crop operation parameters will lead to insufficient pesticide deposition inside canopy and weakened pest-control performance.

Tea-garden spraying differs from field-crop operations. Tea leaves are mostly distributed inside the canopy and on leaf backs, which are the main habitats of pests. UAVs adopt a top-down spraying method, making it difficult for droplets to reach leaf backs. In production practice, methods such as adjusting atomized particle size, adding spray adjuvants and reducing flight speed are used to improve deposition effect. Meanwhile, wind directions differ on different slopes of sloped tea gardens: droplets on windward slopes are easily blown away, while liquid easily accumulates on leeward slopes, further increasing operation difficulty.

3.2 Remote-sensing Monitoring of Tea-tree Growth

UAVs equipped with multispectral cameras fly over tea gardens to acquire large-scale image data. Vegetation indices can be inverted from images to distinguish tea-tree plots with vigorous growth, fertilizer deficiency stress and drought damage. Differentiated management zones can be divided to guide partition fertilization of tea gardens. Compared with manual field survey plot by plot, UAV remote-sensing greatly shortens investigation cycles and realizes rapid general survey of tea-garden growth status.

However, tea-garden remote sensing also has many limitations. Tea-tree canopy heights are uneven, and bare soil exists between tea rows, which interferes with vegetation index calculation results. Overcast weather and strong direct sunlight both affect image quality. Relying solely on UAV remote-sensing images can only identify abnormal growth but cannot distinguish whether it is caused by pests, fertilizer deficiency or drought. Reliable conclusions can only be obtained in combination with ground field investigations.

3.3 Disaster Inspection Operations for Tea Gardens

Spring frost damage, summer high-temperature drought and local pest outbreaks will severely harm tea yield and quality. UAVs can quickly inspect large-scale tea gardens, capture on-site images, and locate positions and scope of disasters. Especially for steep-slope tea gardens hard for human access, UAV inspection can obtain disaster information in the first place and win time for disaster mitigation.

Frost damage inspection is suitable for using thermal-infrared payloads, as frost-damaged tea trees show obvious differences in surface temperature. In the early stage of pest outbreaks, the affected area of individual tea trees is small and difficult to identify from high-altitude UAV images. Only when the disaster spreads to a regional scale can it be clearly distinguished in images. Therefore, UAV inspection is more suitable for large-scale initial screening, while subtle pest conditions still require ground manual recheck.

4. Practical Problems of Multi-task UAV Operations in Hilly Tea Gardens

4.1 Lack of Scenario-adapted Operation Standards for Tea Gardens

Current domestic UAV operation parameters are mostly formulated for field crops such as rice and wheat. Special parameter systems for hilly tea gardens are insufficient. Parameters such as flight altitude, flight speed and nozzle atomization pressure are mostly adjusted relying on operators' experience. Operation quality varies greatly among different operators, which easily leads to droplet drift, insufficient canopy penetration and unstable quality of remote-sensing images.

Field crops have uniform plant height and flat plots, while tea trees of different ages have significantly different canopy heights. Young tea gardens, mature tea gardens and old tea gardens have completely different operation conditions. Existing industry specifications do not provide detailed parameters for tea gardens of different tree ages, and pilots can only rely on trial and error. Meanwhile, different slope orientations in tea gardens result in different suitable operation conditions for windward and leeward slopes, further increasing parameter adjustment difficulty.

4.2 Low Coordination Level of Multi-task Switching

In actual production, spraying, image acquisition and disaster inspection are mostly carried out separately. Replacing payloads and re-planning routes consume much preparation time after spraying missions. Disassembly and assembly of payloads are cumbersome. Operation data are independent of each other, and spraying records cannot be automatically associated with remote-sensing data. The advantages of integrated multi-task operations are not fully exerted.

At the hardware level, most plant-protection UAVs on the market are not designed for multi-task scenarios. Payload interfaces have poor universality, and replacing cameras or spraying components requires screw removal and wiring, with a single replacement taking a long time. At the software level, flight control systems mostly only support single operation modes and cannot set compound tasks of "photography-spraying-photography" in segments within the same route. After operations, spraying logs and image data belong to different software and require manual spreadsheet organization, which is difficult for ordinary tea garden operators to complete complex data processing.

4.3 Interference of Mountain Local Wind Fields on Operation Quality

Local gusts tend to form among mountain valleys in hilly zones, with obvious diurnal variations of mountain-valley winds. During the day, valley heating causes upward airflow, while wind direction reverses in the evening. Gusts result in drift of spraying droplets and reduce pesticide deposition effect on tea-tree canopy. Meanwhile, gusts disturb UAV flight attitude and blur remote-sensing images, degrading accuracy of subsequent image stitching and interpretation.

Wind fields in hilly mountainous areas are characterized by suddenness and locality. Within the same tea garden, wind speed at the valley bottom and on the upper slope differs significantly. General weather stations provide regional meteorological data that cannot reflect real-time wind conditions in small-scale tea gardens. Many pilots only refer to weather forecasts and encounter sudden gusts after entering the tea garden, causing spray drift, image blur, and even operation safety hazards.

4.4 Uneven Professional Competence of Operators

Most UAV operators for tea-garden work only master basic flight operations, lacking compound knowledge of tea-garden plant protection and remote-sensing data analysis. Some pilots merely focus on flight completion while ignoring spraying effect and image quality. The collected data cannot effectively support production decision-making of tea gardens.

Many pilot trainings only focus on flight safety, with little coverage of tea pest occurrence patterns, pesticide characteristics, and basic interpretation of remote-sensing images. Some operation teams only pursue operation area, flying too fast and resulting in substandard spraying effects. After collecting a large number of remote-sensing photos, they cannot perform stitching and interpretation, and the photos are directly archived without being converted into usable information for tea-garden management.

4.5 Prominent Contradiction Between Equipment Cost and Input-Output

The complete set of multi-task UAV equipment includes the airframe, multispectral camera and thermal-infrared payload, with high acquisition costs. Small and medium-sized tea gardens have limited operation scale, and directly purchasing a full set of equipment imposes great economic pressure. If outsourcing services are chosen, spraying and remote-sensing monitoring are charged separately, and the comprehensive cost of multiple operations is relatively high. Most tea gardens value the direct effect of pest spraying more and have insufficient awareness of the value of growth monitoring and disaster inspection, and are unwilling to pay for remote-sensing tasks, which restricts the promotion of multi-task modes.

5. Optimization Countermeasures for Multi-task UAV Operations in Hilly Tea Gardens

5.1 Promote Construction of Special Operation Parameters and Standards for Tea Gardens

Field experiments shall be carried out targeting different tea varieties, canopy heights and mountain wind conditions. Young tea gardens, mature tea gardens and old tea gardens shall be distinguished, and slope orientations shall be differentiated, to establish graded recommended operation parameters for UAV spraying and remote-sensing collection in hilly tea gardens, forming industrial operation guidelines to reduce quality fluctuation caused by empirical operation.

For spraying operations, requirements for atomized particle size, flight altitude, flight speed and adjuvant usage shall be clarified. For remote-sensing operations, requirements for lighting conditions, flight overlap rate and terrain-following flight accuracy shall be specified. Meanwhile, operation effect evaluation methods shall be improved, not only assessing operation area but also incorporating pesticide canopy deposition rate and image stitching quality into operation evaluation indicators.

5.2 Optimize Multi-task Operation Procedures and Hardware Adaptation

Quick-disassembly structures for payloads shall be optimized, and equipment interface standards shall be unified to shorten replacement time between different tasks. Terrain-following route-planning functions shall be improved to support segmented spraying and image acquisition in one flight mission. Operation task sequences shall be optimized, prioritizing image collection before spraying operations to avoid pesticide contamination of optical lenses.

Simple data-management tools shall be built to correlate and archive flight trajectories, spraying records and remote-sensing images, lowering the threshold for data processing. For small and medium-sized tea gardens, data analysis output results shall be simplified, directly outputting a list of abnormal plot locations without requiring tea garden operators to master professional remote-sensing knowledge.

5.3 Establish Operation-timing Selection Mechanism for Mountainous Environment

Operation time slots with low wind speed shall be selected according to mountain meteorological conditions. Before operations, in addition to referring to regional weather forecasts, on-site field wind observation shall be added to avoid gust-prone periods in valleys. Tea-garden operation meteorological thresholds shall be established: when on-site instantaneous wind speed exceeds the threshold, spraying operations shall be stopped, and inspection and photography tasks unaffected by wind fields shall be prioritized.

Based on the diurnal variation characteristics of mountain-valley winds, suitable operation time periods for hilly tea gardens shall be summarized. Generally, early morning and evening have lower valley wind speeds and are suitable for spraying; noon with good lighting conditions is suitable for remote-sensing image collection, matching different tasks to appropriate meteorological windows.

5.4 Improve Compound-skill Training for Pilots and Promote Human-machine Collaborative Mode

Special training targeting tea-garden scenarios shall be developed, covering not only UAV flight safety, but also basic knowledge of tea-garden plant protection and remote-sensing image recognition. Training content shall include tea-garden scenario cases, explaining the influence of wind fields on spraying and operation key points for tea gardens of different tree ages.

The human-machine collaborative mode combining UAV operations and ground recheck shall be popularized: UAVs finish large-scale rapid operations, and ground personnel conduct on-site verification for abnormal plots identified by UAVs, verifying whether it is pest damage, fertilizer deficiency or drought, forming a complete management chain of "air-borne data acquisition-ground recheck-production disposal", avoiding erroneous production judgments based solely on UAV data.

5.5 Develop Diversified Service Modes and Lower the Threshold for Tea Garden Use

To address the high cost of independent equipment purchase for small and medium-sized tea gardens, socialized outsourcing services shall be vigorously developed. Professional operation service teams shall be established, equipped with a full set of multi-task UAV equipment, to provide packaged services for scattered tea gardens, completing spraying, growth survey and disaster inspection in one go, spreading equipment costs. Meanwhile, science popularization shall be carried out for tea garden operators, explaining the practical value of remote-sensing monitoring and disaster inspection, and improving tea gardens' acceptance of multi-task operations. Cooperatives shall be encouraged to centrally organize contiguous tea gardens to purchase services uniformly, improving operation scale and reducing per-unit-area operation costs.

6. Conclusion

Restricted by terrain conditions, traditional manual-operation modes restrict modernization of hilly tea gardens. UAVs can realize multi-task operations including plant-protection spraying, remote-sensing growth monitoring and disaster inspection, acting as an important tool for modernized hilly tea-garden management. In practical application, there still exist practical problems such as lack of operation standards, low multi-task coordination level, mountain wind-field interference, insufficient comprehensive competence of operators, and input-output contradictions.

By formulating scenario-oriented operation parameter standards for tea gardens, optimizing multi-task hardware and operation procedures, selecting proper meteorological windows for operations, conducting compound-skill training, and developing socialized service modes, the application potential of UAVs in hilly tea gardens can be further released. it can be seen that the multi-task UAV mode has obvious efficiency advantages in contiguous hilly tea gardens, but cannot be completely separated from manual ground recheck. More field comparative experiments are required in follow-up research to continuously improve integrated multi-task operation schemes and promote in-depth integration of UAV technology into production and management of hilly tea gardens.

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