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Thesis Tittle Study on UAV-Enabled Real-Time Data Collection Method for Grassland Monitoring

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STUDY ON UAV-ENABLED REAL-TIME DATA COLLECTIONMETHOD FOR GRASSLAND MONITORING

Abstract

The new generation of information technology is the critical technology for grassland monitoring and the significant guarantee for the construction of intelligent grasslands. H owever, due to the difficulty of deploying information technology infrastructures, the high cost of data collection, the high data transmission delay, and the high energy consumption in the grassland, these problems seriously restrict the construction of grassland intelligence. UAVs have been widely used in grassland observation because of their high mobility and low cost, but there are few works on the grassland monitoring data collection. In this context, the content of this paper is as follows:

This paper adopts a three-tier edge networks architecture that consists of wireless sensors, access points and UAV, and investigates the real-time data collection method of edge networks for the short-distance of grassland monitoring. Firstly, we formulate the UAV-enabled real-time data collection model for the grassland monitoring under the constraints of UAV's energy, wind speed, and the real-time data volume of access points. Secondly, we propose a real-time dynamic trajectory planning algorithm for the UAV to collect the monitoring data at access points. At the same time, we design a novel passer-by strategy tailored to the characteristic of the problem to improve data collection efficiency and reduce the energy consumption due to the turnback of UAV. Simulation results show that the formulated model in this paper can better reflect the characteristics of the grassland monitoring data collection problem. The effectiveness of the proposed data collection algorithm is also verified. The passer-by strategy can further improve the efficiency of data collection and reduce the energy consumption of the UAV.

Key Words: Grassland monitoring; UAV; real-time data collection, path planning, Passer-By

Contents

Chapter 1 Introduction

1.1 Research Background and Significance

Grassland is an important constituent of national land resources and ecosystems. As one of the countries with the most abundant grassland resources in the world, China is home to grasslands ofapproximately 40,000 hectares, accounting for 40% of the country's total land area. Grassland resources are an essential part of China's ecological resources, providing people with the means of living and production needed in their daily lives. Grassland ecosystems play a pivotal role in climate regulation, water conservation, carbon cycling, and production of livestock products. Nevertheless, with the extensive development and exploitation of grassland ecological resources, the grassland ecosystem has been severely degraded. The management of grassland resources and the ecological conservation of grassland resources are in urgent need of efforts. Grassland monitoring is the fundamental work for scientific utilization and rational construction of grassland resources as well as the maintenance of grassland ecological balance. It is also core to grassland management[1]. In the face of the massive resources of grassland information, a large portion of them have not been collected, processed and utilized in time, limited by technologies including data collection. This has, to a certain extent, hindered the research on grassland resources and impeded sustainable agricultural development and the construction of national ecological environment.

At present, the application of Internet of things (IoT)-based data monitoring technology in the context of grassland is still in the development stage. It has been difficult to realize automatic backward transmission of monitoring data. Whereas direct manual collection will result in a long collection period, low collection efficiency, and poor timeliness, and is also highly constrained when it comes to complex grassland terrain, thus struggling to meet the actual demands and unable to adapt to complex environments. As a result, the limitations of manual operations have significantly hindered the construction and development of grassland ecology. In addition, there also exist problems such as difficult deployment of communication facilities, costly monitoring data collection process, high data transmission delay, poor reliability, and high network energy consumption. All of these problems make it difficult for conventional grassland data collection methods to achieve higher application value in practical scenarios, and neither can they meet the demands of real-time data collection in generic environments.

On the other hand, the rapid advancement of new information technology has provided novel solutions for the technical bottleneck facing traditional production. In 2019, The State Forestry and Grassland Administration of China issued the "Guiding Opinions on Promoting the Development of Artificial Intelligence for Forestry and Grassland", clearly highlighting the utilization of new-generation information technologies such as cloud computing, IoT, and unmanned aerial vehicles (UAVs) in driving the development of the new forestry and grassland management system towards the goal of synergy, efficiency, and intelligence, so as to afford new paradigms for various ecological protections to further modernize forestry and grassland industries. It is therefore evident that the construction of a novel, smart grassland IoT is the only way towards realizing the modernization of grassland industry and also the key task in building a beautiful China.

Realizing efficient and rational management and utilization of grassland resources through researching and constructing a novel, smart grassland IoT is of great significance to sustainable ecological development, ecological security maintenance, the structural adjustment of the agricultural industry, as well as the evolution of the animal husbandry industry. Meanwhile, UAVs have been widely employed in various fields such as agricultural production, smart transportation, and smart monitoring due to their convenience, flexibility, low cost, and ease of use[2]. The matured development of UAV technology provides both hardware and software support for real-time collection of grassland monitoring data. UAVs'real-time transmission technology is extensively used particularly in animal husbandry monitoring, agricultural management, ecological environment investigation, etc., making it possible to establish a large-scale intelligent IoT.

In light of the background, this paper adopts a UAV-enabled edge communication architecture for grassland IoT. On the one hand, an edge network communication model is built between the ground access point (AP) and UAVs to extend network life, optimize network data transmission, and fulfill data monitoring and transmission requirements in grassland scenarios. On the other hand, drones are applied to achieve a flexible, economical, and efficient data collection system.

Despite drones'irreplaceable role in the construction of the novel, smart grassland IoT, there exist many challenges in constructing a novel real-time monitoring IoT for the actual grassland environment. Among them, the most critical challenge is that the wind velocity cannot be ignored in the actual scenario, which has a major impact on the route planning of the UAV under energy-constrained conditions. In-depth analysis of the route planning problem under wind velocity interference reveals that this type of problems is often non-convex and typically obtain suboptimal solutions by variants of successive convex approximation (SCA) techniques[3]. Yet, these SCA-based solutions rely heavily on trajectory initialization and do not take into account disturbances by wind velocity. Neither do they consider effective real-time data monitoring or collection. Furthermore, for the task of real-time UAV dispatching to acquire a large amount of AP data, their computational complexity and flight trajectory complexity become intractable.

In this paper, a novel method for UAV-enabled real-time collection of monitoring data is proposed, which provides a new solution for achieving higher UAV flight energy efficiency under wind velocity interference. Meanwhile, concerning the timeliness and effectiveness required for real-time collection of monitoring data, a new data collection strategy named Passer-By is proposed. Simulation experiments validate the effectiveness of the proposed model and algorithm.

1.2 Status Quo of Domestic and International Research

The UAV-Enabled real-time data collection method for grassland monitoring is designed as per the actual grassland monitoring scenario, taking account of the characteristics of the meadow ecological environment and cutting-edge communication technology. Due to their relatively weak development foundation, there exists a significant deficiency in existing grassland monitoring technologies. The key techniques adopted by the proposed method and the core problems to be solved mainly include research on a UAV-Enabled real-time data collection method, and the UAV energy efficiency optimization and route planning under wind velocity interference conditions. Hence, a review on the research status quo of these three aspects is presented next.

1.2.1 UAV-Enabled Real-Time Data Collection Methods

In large-scale monitoring of wireless sensor networks (WSNs), utilizing UAVs as mobile data collectors for ground wireless sensor nodes has received widespread attention as an energy efficient way to extend network lifetime[4].

As one of the earliest integrated approaches to study UAV-WSNs, Martinez et al. [5] utilized UAV systems to collect data in sensor networks and extended lifetime of energy-constrained WSNs through cooperative communication between WSNs and UAVs. Corke et al.[6] employed AVATRA autonomous helicopters for node deployment of WSNs, establishing a communication link between WSN nodes and helicopters to transmit feedback information from the deployment algorithm to the UAV for timely decision-making. Khan et al.[7] proposed a mobile Sink data collection strategy that can both adjust the load and improve the network's energy efficiency. It collects sensing data by sending data inflow signals to Sink via each node, and abstract it as a TSP problem to determine each data collection point. However, their method does not match the actual application scenario. Vasisht et al.[8] proposed FarmBeats, an end-to-end data-driven agricultural IoT platform, to achieve seamless data collection.

Zhan et al. [9] investigated the UAV-Enabled distributed estimated trajectory design with minimizing the mean square error of the estimation as the objective. By formulating the task as the equivalent problem of maximizing the number of wireless sensor nodes while successfully collecting data through UAVs. the authors further proposed a low-complexity greedy algorithm based on TSP and convex optimization to obtain a suboptimal trajectory solution. Sun et al.[10] studied the coverage and target monitoring probability of WSN-UAV in sparse networks, which proved that linear motion is the optimal scanning route for UAVs to detect random moving targets. Gong et al. [11] examined the problem of minimum UAV flight time when performing data collection for one-dimensional sensor networks. The data collection interval, UAV velocity, and sensor transmit power were jointly optimized by a dynamic programming approach.

To reduce the load and energy consumption on UAV data acquisition caused by redundant data generated by wireless sensors, many researchers have proposed various data collection methods[12]. For instance, Ebrahimi et al. [13] proposed a UAV-enabled dense WSNs data collection method based on projection compression data collection. You et al.[14] considered the more precise, angle-correlated Rician fading channel between UAVs and sensor nodes. Samir et al.[15] leveraged UAVs to collect data from time-constrained IoT devices with guaranteed performance. They offloaded traffic from existing wireless networks and, by jointly optimizing UAVs'route and wireless resource allocation, maximally increased the number of IoT device services with target data upload deadlines.

Nasir et al.[16] considered a single-antenna UAV-BS multi-user communicaiton system using the non-orthogonal multiple access (NOMA) technique to provide service to a large number of terrestrial users. Hu et al.[17] deployed a single UAV to provide computing services for terminal devices and minimized the sum of maximum delays between users by optimizing offload rate, user scheduling, and UAV route planning. Although the above studies exploited various communication technologies to realize UAV-Enabled data collection, research on key characteristics of large-scale data collection and combination problems in specific application scenarios is relatively limited. The majority of existing literature is not directly applicable to grassland monitoring data collection and transmission.

At present, there is little research on UAV route planning under wind velocity interference conditions. The existing UAV-Enabled data collection can be roughly divided into two segments, namely data collection and route planning.

On the data collection segment, Zeng et al.[18] paid less attention on the key characteristics of large-scale data collection and combination problems in specific application scenarios, and are therefore not directly suitable for grassland monitoring data collection and transmission. In terms of UAV route planning, the existing work by Zhang et al. [19] only assumes a single fixed response sequence, which cannot solve the real-time changing response problem. Their route planning was performed from a lowest energy consumption perspective, which lacks consideration of actual needs and key elements, thus incapable of directly extending to grassland monitoring data collection and transmission.

The research content of this paper is depicted in Figure 1.1. Through the description of the problem of UAV-Enabled real-time collection of grassland monitoring data, a real-time collection model of grassland monitoring data is constructed. The UAV flight path is planned in the windy environment, and the ground AP is covered in a more extensive and timely manner during the collection process, so as to achieve real-time and efficient collection of more APs under an energy-constrained condition.

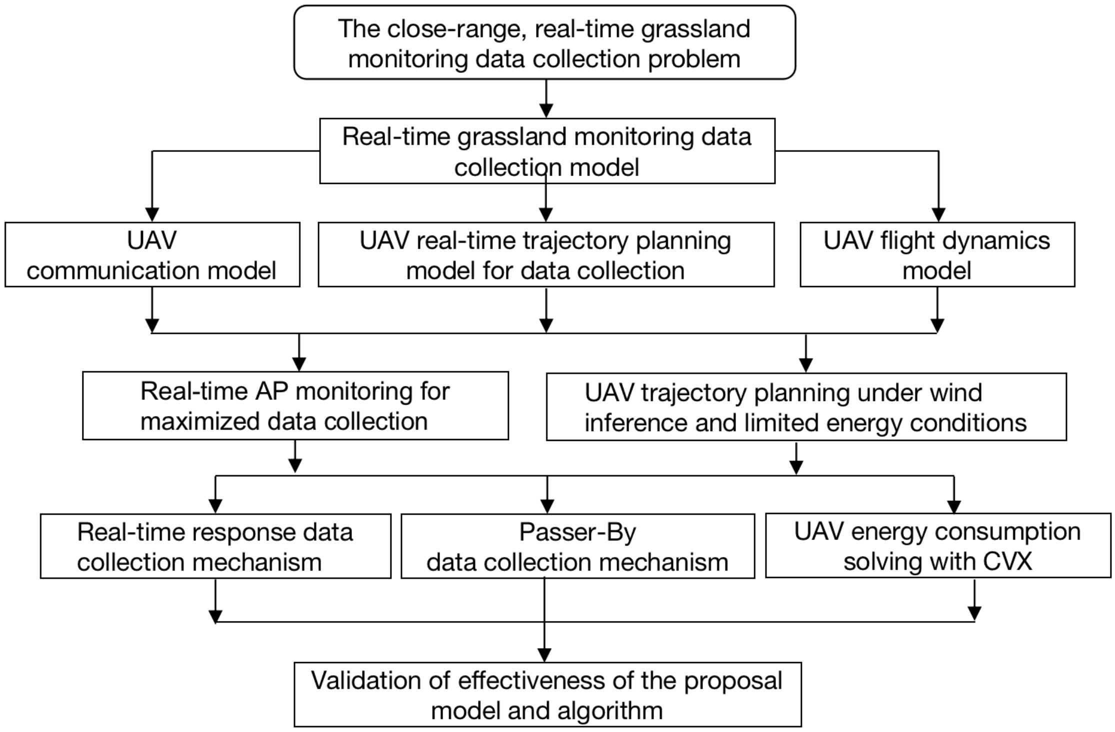

Figure 1.1 Research content of this study

1.3 Thesis Organization

This paper consists of five chapters and is organized as follows.

Chapter 1 starts by outlining the research background and briefly describing the challenges facing grassland informatization, highlighting that its advancement is of great significance to China's economic development. The chapter then introduces existing research on grassland monitoring data collection and analyzes certain technical defects and limited application value of existing works, leading to the research question of UAV-Enabled real-time grassland monitoring data collection. The proposed method is designed to address the problem of real-time large-scale data collection and related combinatorial issues in practical scenarios. Finally, the organization of this paper is described.

Chapter 2 first describes the UAV-based real-time data collection method. Next, the model for UAV-Enabled data collection system is established by considering the problems of data acquisition, UAV energy efficiency optimization, and route planning under wind velocity interference conditions. The objective function and associated constraints of the probloem's mathematical model are defined.

In Chapter 3, the defined mathematical problems are solved and a Passer-By data collection strategy is proposed through in-depth analysis of the model and the queue initialization algorithm in order to further improve UAVs'flight energy efficiency. Meanwhile, the specific UAV flight status in the actual scenario is discussed in depth. The non-convex problem of flight energy consumption under windy conditions are converted into a convex problem and the flight energy consumption is solved by the CVX solver. A Stall algorithm for hovering collection is also proposed to derive the dynamic optimization algorithm for UAV flight trajectory.

Chapter 4 validates the effectiveness of the proposed real-time data collection model and UAV dynamic optimization algorithm with simulation experiments, and analyzes the merits of the proposed method through experimental results.

Finally, Chapter 5 concludes the paper with a summary of the key points and an outlook on future research work.

Chapter 2 UAV-Enabled Real-Time Grassland Monitoring Data Collection Model

This chapter first defines the UAV-based real-time data collection problem under wind velocity interference. It then establishes the corresponding mathematical model and considers it in analyzing the mathematical form of the problem. To overcome the key technical bottleneck facing grassland monitoring data acquisition in enhancing grassland monitoring intelligence and realizing a communication mechanism tailored for real-time grassland monitoring data acquisition, this paper constructs a UAV-assisted edge network communication architecture. It employs multi-rotor UAVs as data collectors for real-time gathering from each ground access point (AP) within the grassland monitoring area. The schematic diagram of the AP-UAV edge network model is presented in Figure 2.1.

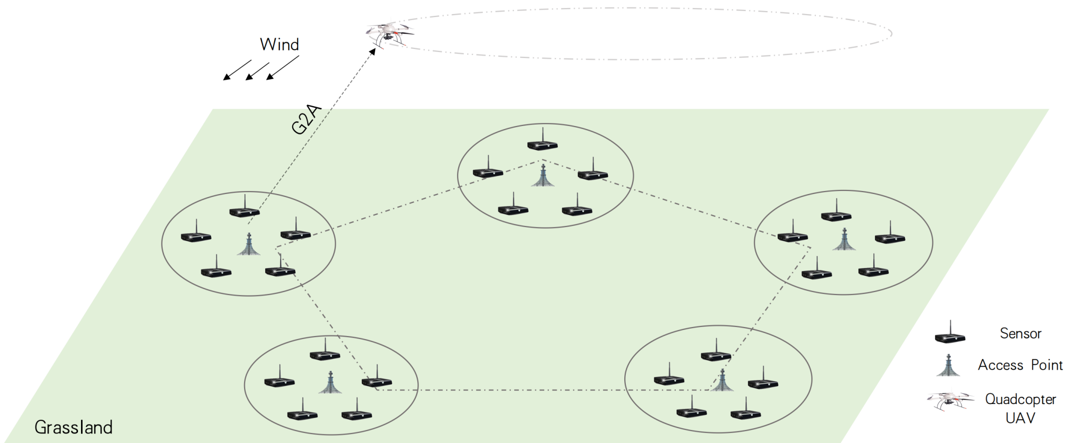

Figure 2.1 Schematic diagram of the AP-UAV edge network model

In this model, sensor nodes are deployed in the grassland area to be monitored. Each AP acts as an edge computing server to locally process the raw data collected from sensor nodes, filtering redundant data to reduce link load and improve data transmission rate. As a mobile base station, a UAV receives AP-processed data and store them in the storage device it carries. Once the UAV has collected all data from APs, it will send them back to the cloud computing center at the monitoring station for processing. In the AP-UAV edge network model, due to the limited battery capacity carried by the UAV, each AP has a limited storage capacity and different APs collect different amounts of monitoring data within a given period of time. Besides, the influence of environmental factors of grassland on UAV flight cannot be overlooked. To this end, this paper considers incorporating the wind velocity factor to enhance its research practicability.

2.1 System Model

A summary of the symbols involved and their connotations is presented in the following table before the description of the model.

Table 2.1 **Symbol & Description**

Symbol	Description
i	i-th AP node
L_i	Coordinates of AP_i
n	n-th time interval
τ	Time interval duration
$K_i(n)$	Total data growth rate of AP_i in the n-th time interval (in %)
$k_i(n)$	Natural data growth rate of AP_i in the n-th time interval (in %)
$D_i(n)$	Percentage of real-time data of AP_i in the n-th time interval
$\bar{D}_i(n)$	Percentage of real-time remaining capacity of AP_i in the n-th time interval
$k_i^{UAV}(n)$	UAV data collection rate for AP_i in the n-th time interval (in %)
Q	Numerical threshold for the early warning mechanism
n_f	Set of time-interval indexes of UAV flight
n_d	Set of time-interval indexes of UAV data collection
$T_f(i,x)$	UAV flight duration from AP_i to AP_x
$T_f(x)$	Total UAV flight duration of two trips with relay node AP_x
$T_{of}(i+1)$	AP_i+1's remaining time before data overflow
$T_c(x)$	UAV data collection time for AP_x
$\parallel dis(L_i,L_j) \parallel$	Straight-line distance of UAV flight from AP_i to AP_j
$q(t)$	Position coordinates of UAV at time t
$R_i(T_i)$	Total data transmission volume from AP_i to UAV
T_i	Total collection duration at AP_i
$t_i[n]$	UAV data collection duration at AP_i in the n-th time interval
P	UAV flight power
E_d	Energy consumption by hovering flight under UAV data collection
E_f	Energy consumption by straight-line flight under UAV dispatching
η	Energy efficiency
E_{max}	Total electrical energy carried by UAV to support flight

$\vec{v}[n]$	Flight velocity vector provided by UAV power in the n-th time interval
$\vec{V}_{wind}$	Wind velocity vector in the actual scenario
$\vec{v}_e[n]$	Resultant velocity vector of UAV in the n-th time interval
$\vec{a}[n]$	Flight acceleration vector by UAV power in the n-th time interval
a_{max}	UAV acceleration at maximum power

First, a number of sensor nodes are deployed within the grassland scene to be monitored, along with one AP for the corresponding area. AP_i denotes the ith AP, $L_i \in \mathbb{R}^2$ and $i \in \mathbb{I} \triangleq \{1,\cdots,i\}$.

Each AP acts as an edge computing server and performs local processing on the raw data collected from sensor nodes. The data are then collected by the UAV.

During data collection, the data volume at each AP dynamically grows over time. Let $k_i(n)$ and $D_i(n)$ denote the data growth rate and real-time data volume at AP_i in the nth time slot. Since consistent data volume growth at all APs, Equation (2) can be obtained, that is, the data volume at AP_i at time n (i.e. $D_i(n)$) is equal to the the sum of data volume at time n-1 (i.e. $D_i(n-1)$) and the data growth volume; the data growth volume is the product of the corresponding data growth rate $K_i(n)$ and time interval τ. For the total AP growth rate $K_i(n)$, during the UAV flight stage, the AP data volume grows at the rate of $k_i(n)$; during UAVs'data collection from APs, the total AP growth rate $K_i(n)$ equals to the AP growth rate $k_i(n)$ minus the UAV data collection rate $k_i^{UAV}(n)$. When all APs operate normally, the data volume collected increases gradually. To prevent overflow of collected data, a corresponding AP threshold Q can be set (according to the actual condition) for early warning response.

$$D_i(n) <= Q \tag{1}$$

$$D_i(n) = D_i(n-1) + K_i(n)\tau \tag{2}$$

$$K_i(n) = \begin{cases} k_i(n), n \in n_f \\ k_i(n) - k_i^{UAV}(n), n \in n_d \end{cases} \tag{3}$$

The UAV takes off from the base station, with a preset flight duration of T (i.e., carried battery power must be able to support a flight duration T). A priority ranking is built according to all the amounts of AP data volume requested to be collected within the grassland monitoring area. The UAV performs data collection according to the AP priority. After reaching each AP, the UAV hovers over the AP and collect data, after which it continues on to the next AP assigned for data collection. This process repeats until the UAV has collected the data of each AP once and the return status is satisfied, this is when the UAV starts to return. Here, the return status is defined as the condition that UAV's remaining power is just enough for its return to the starting point. Next, the UAV flies back to the starting point BS for charging and data offloading, which completes one full process of data collection. The course of UAV's flight can be divided into two parts: the first part is UAV's flight between APs, and the second part is the hovering data collection at designated APs.

For easier problem solving, this paper splits the total flight duration T into N+1 intervals of equal length. Thus the UAV flight trajectory $q[n] = q(n\tau), n = 0, \cdots, N$. According to the UAV flight status, these N+1 intervals can be grouped into the two sets of n_f and n_d, where n_f represents the set of indexes of the intervals spanned by the UAV flight stage, and n_d those by UAV data collection stage.

In this paper, the UAV is set to fly at a constant altitude H. Therefore, the UAV flight trajectory $q(t)$ is represented by the three-dimensional coordinates $[x(t), y(t), H]$. Provided a constant H, it is simplified to the two-dimensional coordinates $[x(t), y(t)]$, where $0 \leq t \leq T$.

$$T = (n+1)\tau, n = 0, \cdots, N \tag{4}$$

$$q(t) = [x(t), y(t)], 0 \leq t \leq T \tag{5}$$

$$q[n] = q(n\tau), n = 0, \cdots, N \tag{6}$$

In the UAV hovering data collection stage, the UAV's collection time for AP_i in its time interval τ is $t_i[n]$. If the data volume to be collected is large, the time slice occupied by data collection for AP_i will increase accordingly. Thus, the total collection time for AP_i is T_i. During data collection, the UAV keeps hovering at a constant altitude above the corresponding AP with a constant data collection rate. Therefore, the amount of data collected is proportional to the collection time. Through analyzing the UAV hovering status, since the influence of strong wind in the flight scene cannot be neglected, the UAV needs to provide a flying momentum same in magnitude and in opposite direction to the wind.

On the other hand, to maximize flight energy efficiency, the UAV must maintain a straight path as much as possible when flying between each pair of APs. Meanwhile, in light of the impact of wind velocity in the grassland scenario, in the course of UAV's constant-velocity flight, the combined velocity by the UAV must coincide with the straight-line trajectory. During UAV's acceleration, the resultant velocity vector equals the sum of the original velocity vector, the wind velocity vector and the UAV acceleration vector, and the resultant velocity direction must also coincide with the straight-line trajectory. The schematic diagram of the flight state is shown in Figure 2.2.

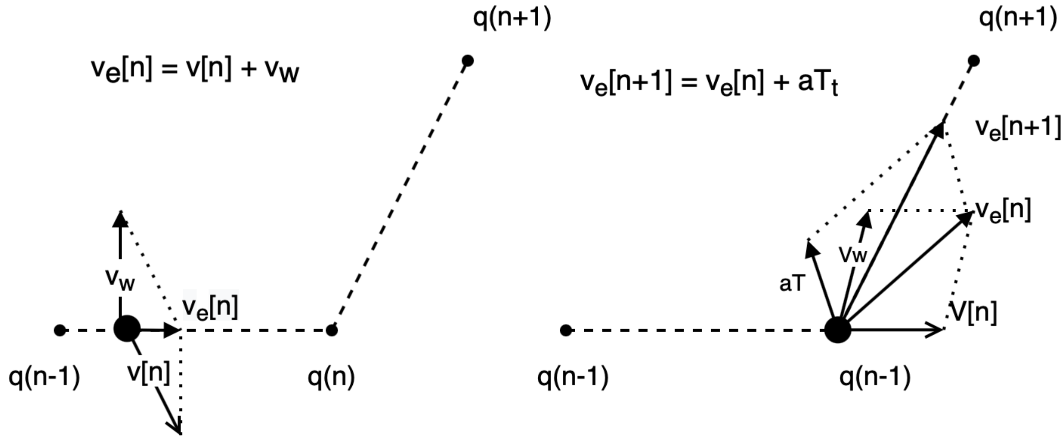

Figure 2.2 Schematic diagram of UAV flight status in windy conditions

In terms of the UAV flight system model, to ensure that the UAV can return to the starting point upon the completion of data collection, this paper adopts UAV's total energy as the main constraint. It is necessary to analyze UAV's energy consumption in specific flight state when subject to wind velocity interference. According to the expression for rotor UAV's instantaneous power (given in Equation (7)) derived by Dorling et al.[20], it can be noticed that UAV's instantaneous flight power is independent of its instantaneous velocity and instantaneous acceleration; instead, it is only related to UAV's mass. Integrating the instantaneous power over the time interval yields the energy consumed by the UAV in each time interval. UAV's energy gradually decreases until meeting the return state; the UAV then returns and one collection cycle completes.

$$P_{UAV} = M^{\frac{3}{2}} \sqrt{\frac{g^3}{2\rho\zeta h}} \tag{7}$$

Here, the power consumption equation of H-rotor UAV derived by Dorling et al. [20] is provided, where denotes UAV's mass (in kg); g denotes the standard gravitational acceleration (in N); ρ represents the fluid density of air (in kg/m3); ζ is the area of the rotary blade disk (in m^2); h is the number of rotors; P is in watts. In this grassland environment model, this paper sets the UAV to fly at a constant altitude. Since there are no obvious obstacles in the grassland environment, it is assumed that the communication path between the UAV and the ground AP is a Line Of Sight (LoS) communication link that obeys the network's free path loss.

$$h_k[n] = \beta_0 d_k[n]^{-2} = \frac{\beta_0}{H^2 + ||q[n] - b_k||^2} \tag{8}$$

where β denotes the channel power gain at a reference distance of 1m. Assuming that each AP transmits at constant power, the transmission rate between the AP and the and UAV is expressed as:

$$R_k[n] = B\log_2(1+\frac{\gamma_0}{H^2+\parallel q[n]-b_k\parallel^2}) \tag{9}$$

where B denotes the channel bandwidth in Hertz (Hz); γ_0 is defined as the received signal-to-noise ratio (SNR) at a reference distance of 1m; σ_2 is the noise power at the receiver ;d>1 is the channel capacity discrepancy caused by actual modulation and coding.

In view of the difference in the amount of raw data collected by each AP, the UAV needs to plan the route dynamically in real time as per the service request of each AP to avoid the overflow of collected data which may lead to lost monitoring data. To this end, it is of paramount importance to design an early warning mechanism for AP. When the amount of data processed by each AP hits a certain threshold, the AP sends a service request signal to the UAV. The UAV then stores the received signals from each AP in a response queue according to their sequence of arrival, and serves each AP in turn based on priority. A schematic diagram of the data collection mechanism for real-time response is depicted in Figure 2.3.

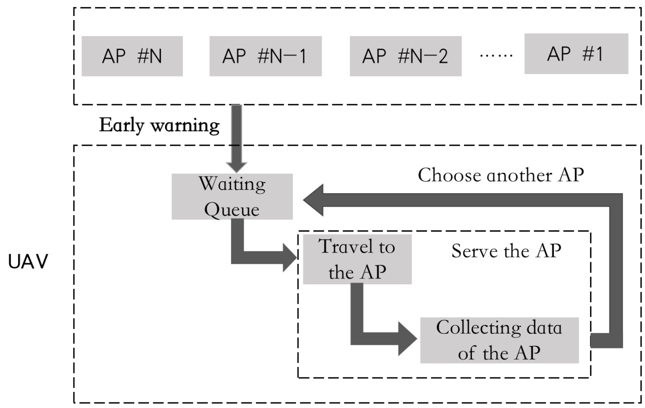

Figure 2.3 Schematic diagram of the data collection mechanism with real-time response

Targeting the complex scenarios, this paper proposes the Passer-By data collection mechanism which extends the original priority algorithm to further improve the energy efficiency of UAV data collection. Compared to the original algorithm, the proposed mechanism enables the UAV to reach the next node with longer remaining time before the deadline. To make full use of this remaining time, this paper proposes that if there exists other secondary nodes with lower priority in the vicinity of the straight-line route to a primary node with the highest priority, the Passer-By data collection mechanism should be adopted. In other words, on the premise of not significantly deviating from the planned route and not hindering the data collection of the primary node, the UAV collects data from secondary nodes along the linear route en passant to save the round-trip flight time and energy consumption, as well as to improve the collection energy efficiency.

For each AP that demands UAV data collection, it is necessary to consider both the temporal and the spatial priority. The Passer-By data collection mechanism balances the two constraints of time and space. Compared with the time priority queue algorithm that only considers the temporal priority, the Passer-By mechanism strives for a trade-off between temporal and spatial priority. For instance, in the presence of a closer secondary node with low data volume and a further primary node with high data volume at the same time, the mechanism replaces two round-trip flights (i.e., visiting the further node first and the closer node next) with one flight to save both time and energy consumption, dramatically improving data collection efficiency.

The Passer-By data collection mechanism is detailed as follows. Upon UAV's completion of data collection of AP_i, it selects the next AP by calculating through the prediction system. Given the data growth rate $K_{i+1}(n)$ and the real-time data volume $D_i(n)$ of the next primary node AP_{i+1}, the node's remaining time to data overflow $T_{of}(i+1)$ can be calculated according to its remaining capacity. During this remaining time, the UAV needs to fly first to AP_x and then to AP_{i+1}. Its priority is to be able fly for the total flight duration $T_f(x)$ of these two trips. On this basis, it should collect as much data from the lower-priority AP_x as it can. In other words, it must maximize the time $T_c(x)$ for collection from secondary node AP_x. Upon the completion of data collection at AP_x. the UAV heads to secondary node AP_{i+1} to continue data collection. Until this point, the Passer-By data collection completes. A schematic diagram of the Passer-By data collection mechanism is given in Figure 2.4

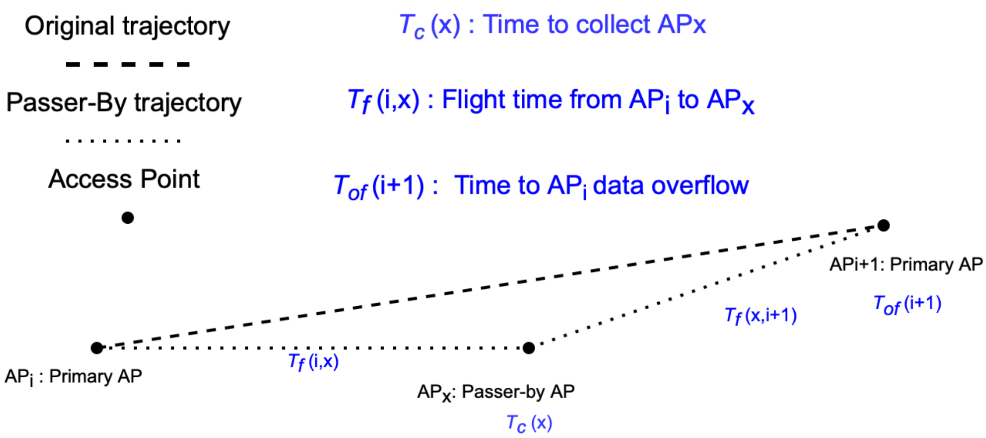

Figure 2.4 Schematic diagram of the Passer-By data collection mechanism

During the UAV flight, primary nodes are always of higher priority than secondary nodes in selecting nodes as targets. The primary node refers to the AP with the next highest priority in the AP queue during UAV's flight phase. Secondary nodes refer to all APs covered by the circular area whose diameter is defined by the current node and the primary node. Should Passer-By data collection be performed on secondary nodes, this paper stipulates that at most one secondary node can be included provided that data collection of the primary node is not hampered. If there exist multiple secondary nodes, the optimal one must be selected by means of an optimal secondary node selection algorithm.

Regarding AP_i and AP_{i+1} as the primary nodes in UAV's flight from the former to the latter, a circular area can be defined by setting $d_{(AP_i\ ,\ AP_{i+1})}$ as its diameter. All remaining nodes within this circular area are considered secondary nodes and are sorted via the optimal secondary node algorithm. The node with the highest priority AP_x is then selected for Passer-By data collection. The collection duration is the difference between the estimated data overflow time of primary node AP_{i+1} and the time taken by the UAV to fly through the secondary node and then to the primary node.

In the circular area, the secondary node AP_x is a node near the trajectory of AP_i - AP_{i+1}. Since the position coordinates of the secondary node are known and fixed, the corresponding distance (space) and time constraints can be calculated according to the UAV flight state. Also, as the real-time data volume is known, the AP data time constraint can be calculated from the AP data growth rate. It can be found through analyzing the time and space constraints of the secondary nodes that they are all time-dependent. Hence, they can be reduced to a single time constrain to simplify the solving process. Moreover, if a secondary node is selected for Passer-By data collection, it must be ensured that the collection at the primary node is not affected. Time allocation is done for the optimal secondary node on the premise that no data flow occurs at the primary node. Here, if total flight time $T'_{(x,f)}$ incurred by data collection at the secondary node exceeds the time constraint of the primary node data overflow $T_{(i,of)}$, this node will be deemed as an illegitimate secondary node and is therefore discarded.

2.2 Mathematical Model

Concerning the UAV data collection model, this paper aims to design a dispatching optimization algorithm catered to the problem's key characteristics under the constraint of the total UAV energy. The designed algorithm should solve the problem P of maximizing the total data volume collected by the UAV as well as the energy efficiency η. The total data volume R collected by UAV is the sum of the collected data volume at each AP during a flight, in which the data transmission volume of AP_i is denoted by R_i. Energy efficiency η represents the ratio of the energy consumed by the UAV during the data collection state to the total energy consumption throughout the entire process. E_d denotes the total energy consumption of the UAV when hovering over each AP to collect data. E_f denotes the energy consumed by the UAV flying between pairs of APs. E_{max} denotes the total energy that the UAV carries to support its flight, where the energy consumption of UAV communication and data transmission are assumed negligible. Furthermore, as a priority is to prevent overflow in AP data collection, this paper sets an early warning threshold Q on the AP real-time data collection volume D_{AP} (which can be set according to actual scenarios), providing an early warning response in order to avoid lost data.

In the process of data transmission between UAV and AP, since the transmission rate is subject to UAV-AP distance (including flight altitude and flight trajectory), the data transmission volume can also be affected by it. The data transmission volume of AP_i is denoted by R_i, and is equal to the integral of the transmission rate. Its expression is given by:

$$R = \sum_{i=1}^{I} R_i(\mathbf{T}_i) = \sum_{i=1}^{I} \int_0^{T_i} B \log_2 \left(1 + \frac{\gamma_0}{H^2 + \| \mathbf{q}_t \|^2}\right) dt \tag{10}$$

In light of the computational complexity associated with this problem, this paper adopts a discrete approach towards the total energy consumption of UAV flight. It first solves for the energy consumption in each time interval before summing over all the time intervals to yield the total energy consumption of UAV flight. The energy consumption in each time interval is equal to the multiplication of power and time duration of corresponding intervals. The expression is given by:

$$E\left(\left\{v\vec{[n]}\right\}, \left\{a\vec{[n]}\right\}\right) \approx \sum_{n=0}^{N} P\left(\left\{v\vec{[n]}\right\}, \left\{a\vec{[n]}\right\}\right) \tau \tag{11}$$

In this paper, the energy efficiency η is set to denote the ratio of the energy consumed by the UAV in the state of collecting data to the total energy consumption throughout the entire flight, which is given by:

$$\eta = \frac{E_d}{E_d + E_f} \tag{12}$$

Let E_{max} denote the total energy of the UAV's power source to support flying. The total power consumption of UAV flight should be less than the total energy of the power source, which is expressed as:

$$E_d + E_f <= E_{max} \tag{13}$$

For UAV's uniform-speed flight, the resultant velocity vector is the resultant vector of the flight velocity and the wind velocity. Besides, for UAV's hovering state, $v[n] = -v_w$, $v_e[n] = 0$ and relevant expressions are given as follows:

$$\vec{v}_e[n] = \begin{cases} \vec{v}[n] + \vec{v}_w, n \in n_f \\ 0, n \in n_d \end{cases} \tag{14}$$

Concerning the momentary UAV velocity change near AP, the resultant speed vector equals the vector sum of the original velocity vector, wind velocity vector, and UAV acceleration vector. As for the hovering phase, since the UAV is nearly stationary relative to the AP, the resultant velocity is considered zero. The velocity variation expression is given by:

$$\vec{v}_e[n+1] \approx \begin{cases} \vec{v}_e[n] + \vec{a}[n]\tau, n \in n_f \\ 0, n \in n_d \end{cases} \tag{15}$$

For UAV's distance constraint, the UAV in this system model satisfies the ordinary distance derivation formula. During the data collection phase, the UAV can be considered to be in a stationary state as it remains hovering. The corresponding expression is given by:

$$\vec{q}[n+1] \approx \begin{cases} \vec{q}[n] + \vec{v}_e[n]\tau + \frac{1}{2}\vec{a}_n\tau^2, n \in n_f \\ \vec{q}[n], n \in n_d \end{cases} \tag{16}$$

This paper also gives the coordinates representation of the start and end points of the UAV flight trajectory, as well as the start and end velocities:

$$\vec{q}[0] = \vec{q}_0, \vec{q}[n+1] = \vec{q}_F \tag{17}$$

$$\vec{v}[0] = \vec{v}_0, \vec{v}[n+1] = \vec{v}_F \tag{18}$$

The UAV flight velocity constraints and acceleration constraints are also outlined. The flight velocity must be less than the velocity V_{max} under its maximum power. The flight acceleration must be less than the acceleration a_{max} under its the maximum power.

These constraints, whose expressions are given below, must be met for normal flight of the aircraft.

$$0 \le ||\vec{v}[n]|| \le V_{max}, n = 0, \cdots, N \tag{19}$$

$$||\vec{a}[n]|| \le a_{max}, n = 0, \cdots, N \tag{20}$$

In summary, the mathematical model of the UAV-Enabled real-time grassland monitoring data collection can be formulated as:

$$(P): \max_{\{q[n]\},\{v[n]\},\{a[n]\},\{t_i[n]\}} \{R, \eta\} \tag{21}$$

s.t.(1)——(20)

2.3 Summary

This chapter designs a UAV-Enabled real-time monitoring data collection method targeting the grassland data collection problem at hand. The system model is analyzed in detail to derive the corresponding mathematical form of the problem.

Chapter 3 Solving the problem of UAV-Enabled real-time grassland monitoring data collection

Following the above discussions, this chapter proposes a solution method for UAV energy efficiency optimization and route planning under windy conditions.

3.1 Dynamic Dispatching Algorithm for UAV Flight Trajectory

To solve the complex model described above, this paper designs a specific dynamic optimization algorithm for UAV flight trajectory. First of all, to simplify the solution procedure, this paper assumes a constant wind velocity vector $\vec{v}_{wind}$ in the grassland scene, constant data growth rate $k_i(n)$ at ground APs, and constant UAV collection rate $k_i^{UAV}(n)$ at ground APs. The solution steps of Algorithm 1 can be divided into five parts, namely initial queue generation (steps 1-3), starting point selection (steps 4-10), Passer-By node update (step 12), UAV straight-line flight (steps 9 and 15), and UAV hovering data collection (steps 10 and 16) .

The procedures of the UAV flight trajectory dynamic optimization algorithm are as follows. First, the initial priority queue of APs is obtained from the InitialQueue algorithm and an ordered set AP_u of uncollected APs are updated. According to the queue priority, the highest priority AP AP_{First} in the ordered set AP_u is selected as the first AP to be visited by the UAV. Upon receiving the instruction, the UAV immediately heads to AP_{First}. At this time, it marks AP_{First} and updates the uncollected ordered set AP_u. During the UAV flight, to solve the non-convex problem of energy consumption under wind velocity interference, this paper employs the CVX solver to solve the convex problem transformed from the original non-convex problem. When the UAV is above the AP to be collected, the Stall algorithm is called to keep the UAV hovering while collecting data from the AP. Upon completing the collection from the first node, the Passer-By data collection mechanism is introduced to realize real-time node update through a new priority sorting of nearby nodes, thereby further improving UAV collection efficiency.

Algorithm 1 : Trajectory Optimization

Input: L_i, $i \in \mathbb{I}$, wind velocity $\vec{V}_{wind}$, real-time data volume $D_i(n)$.

Output: Energy efficiency η, data collection volume R, UAV flight velocity $\vec{v}\,[n]$, UAV flight acceleration $\vec{a}\,[n]$, UAV flight trajectory $\vec{q}\,[n]$.

1: Initialization: set of uncollected APs A_u, set of collected APs $N = \varnothing$.

2: Assume constant wind velocity $\vec{v}_{wind}$, constant AP data collection rate $k_i\ (n)$, constant UAV transmission rate $k_i^{UAV}\ (n)$.

Call **InitialQueue** $(D_i(0))$ and update set of uncollected APs A_u.

while $A_u \neq \varnothing$ or return state reached $E_{left} = E_{return}$ **do**

  Select the 1st node AP_{First} from set of uncollected APs A_u;

  if $N = \varnothing$ **then**

    $N \leftarrow N \cup \{AP_{First}\}$;

    $A_u \leftarrow A_u \backslash \{AP_{First}\}$;

    Call **Cvx** (v_{wind}). Solve wind velocity interference problem with CVX and update flight information E_f, $q\ (t)$;

    Call **Stall** (AP_{First}). Solve data collection problem and update collected data volume R, E_d;

  else

    Call **passer-by** (AP_x). Update set of uncollected APs A_u. Obtain the collection $T_c(x)$ of Passer-By node AP_x.

    $N \leftarrow N \cup \{AP_x\}$;

    $A_u \leftarrow A_u \backslash \{AP_x\}$;

    Call **CVX** (v_{wind}). Solve wind velocity interference problem with CVX and update flight information E_f, $q\ (t)$;

    Call **Stall** (AP_x). Solve data collection problem and update collected data volume R, E_d;

  end if

end while

Classify constraint conditions $U_n - T_n$ of uncollected APs through E_n;

Delete unreachable nodes E_n from queue and output energy efficiency E_n;

return E_n;

3.1.1 Queue initialization algorithm

To ensure the UAV can fully collect all AP data and avoid AP data overflow, this paper sorts the APs according to the initial AP data volume $D_i(0)$ and outputs the new ordered set of AP queue.

Algorithm 2 : InitialQueue

Input: AP initial data volume $D_i\ (0)$.

Output: Ordered set of initial AP queue A_u.

Generate ordered set of AP sequence to be collected according to the initial AP data volume in descending order.

for a = 0 to i-1 **do**

for b= a+1 to i **do**
    if $D_a\ (0) < D_b\ (0)$ **then**
        $t = D_a\ (0)$;
        $D_a\ (0) = D_a\ (0)$;
        $D_b\ (0) = t$;
    end if
end for
end for
Obtain AP index AP_i and store in ordered set of AP sequence A_u^*;
$A_u \leftarrow A_u^*$;
return A_u

3.1.2 Solving UAV flight energy consumption under wind velocity interference with CVX

In dispatching UAV flight, in light of the wind velocity factor in the actual grassland scenario, the non-convex problem is approximated as a convex problem to be solved by the CVX solver. Meanwhile, to simplify its solution, this paper considers only straight-line flight. Specific parameters of the UAV are determined in the experiment.

Algorithm 3 : CVX (V_{wind})

Input: Start coordinates L_i, end coordinates L_{i+1}, wind velocity vector $\vec{V}_{wind}$.
Output: Energy consumption of dispatching straight-line UAV flight E_f
Assume constant wind velocity.
Solve non-convex problem of the model with convex solver
Obtain straight-line flight energy consumption E_f in windy conditions.

3.1.3 Hovering collection algorithm

Upon arrival at the designated AP AP_i to be collected, the hovering collection algorithm performs time planning for AP_i by its real-time data volume $D_i(n)$ and calculates the actual time required for the data transmission. Meanwhile, the UAV remains hovering over AP_i. Based the calculated time, the energy E_d consumed by UAV data collection can be calculated and E_d can be updated.

Algorithm 4 : Stall (AP_i)

Input: Real-time data volume $D_i\ (n)$, early warning mechanism data threshold Q, AP_i's total data growth rate (%) in the n-th time interval $k_i\ (n)$, AP_x's passer-by collection allocation time $T_c\ (x)$
Output: UAV energy consumption E_d under data collection state.

while $Di\ (n) > Q$ **do**
    Update AP's real-time data volume $Di\ (n)$ from equation (2.2) of data collection and obtain collection time from equation (2.2) or call Passer-By algorithm;
    Update collected data volume R_i from equation (2.11);
    Update energy efficiency E_d from equation (2.12);
end while
return The latest UAV flight energy efficiency E_d

3.1.4 Passer-By collection strategy

This paper considers including nearby nodes in the Passer-By algorithm to improve UAV collection efficiency. Upon completion of the collection at the current node A_i, the UAV calls the Passer-By algorithm to search for the next to-be-collected AP A_j in the original queue. It plots a circle with these two APs as the diameter. The AP with the highest data volume within the circle, AP_{max}, is identified and set as a Passer-By node. This node is then inserted into the original queue and A_u is updated. In addition, the transmission time allocated to AP_{max} is also computed based on the data transmission rate and UAV flight status to ensure that data of the next to-be-collected AP A_j in the original queue does not overflow.

Algorithm 5 Passer-By

Input: Set of AP coordinates $L_i, i \in \mathbb{I}$, current AP A_i and its data growth volume $k_i\ (n)$, next AP in the original path A_j and its $k_j\ (n)$, UAV's current remaining energy E_{left}.

Output: Passer-By node A_x and its allocated collection time T_x .

Calculate distance between APs i and j, $D_{i,j}$;
Plot a circle with diameter $D_{i,j}$;
while no suitable secondary node has been found **do**
    Search for AP A_{max} with the highest data volume within the circle;
    Calculate new path distance $D_{i,max}$, time duration of $D_{max,j}$ and the new path, $T_{i,max}$ and $T_{max,j}$;
    $T_{max} = T_{of}(j) - T_{i,max} - T_{max,j}$;
    Calculate energy consumption $E_{i,max}$, E_{max} and $E_{max,j}$;
    $E_{left} = E_{left} - E_{i,max} - E_{max} - E_{max,j}$;
    if $T_{max} \geq 0$ and $T_{of}\ (max) \geq T_{i,max}$ and $E_{left} \geq E_{return}$ **then**
        $A_u \leftarrow A_u \cup A_{max}$;
        return A_{max} ;
    else
        Discard secondary AP nodeA_{max} with the highest data volume;

    end if
end while

3.2 Summary

This chapter first proposes the method by analyzing the specific system model, in which the initial queue algorithm is responsible for UAV path planning in the initial state. Once the approximate path has been determined, the grassland environmental statistics is updated in real time, after which the Passer-By mechanism is employed for the real-time environmental data collection and the updating of the original path, resulting in a real-time optimal flight path with higher energy efficiency. The non-convex problem in the windy environment during actual flight is approximately transformed into a convex problem, for which the flight energy consumption is solved by the CVX solver. Real-time consideration of ambient wind power maximizes the flight energy efficiency. Specifically, the UAV saves energy in downwind conditions, and adjusts the power direction in upwind conditions to minimize the energy loss caused by wind resistance.

After the UAV arrives at the designated AP, hovering collection is performed and the Stall algorithm is called. The UAV is set to a fixed flight altitude for data transmission via the communication link. When the UAV's remaining energy equals the energy required for an immediate return, the UAV return procedure is performed for automatic UAV recovery under limited energy conditions, which marks the completion of one automatic flight.

Chapter 4 Numerical Experiments and Analysis

4.1 Parameter Settings

Through field investigation at the CAS Haibei National Field Research Station of Alpine Grassland Ecosystem, the real-time monitoring and collection of grassland data is planned with the construction of a three-layer edge network model consisting of the UAV, ground APs, and sensors. Among them, the sensors perform 24/7 collection of environmental data such as temperature and humidity; the ground base station locally processes the sensor-collected raw data; the filtered data are collected by the cruising UAV. In conjunction with this model, the grassland area is set to 500m $\times$ 500m and the number of APs to 25. Ground coordinates of the AP set are randomly generated by the algorithm, and each AP_i is given a randomly initialized data percentage $D_i(0)$. Moreover, considering the practical application needs, this paper sets a fixed data growth rate of $0.2\%/s$ for each AP to ensure the real-time dynamic data update of APs.

For easier solving, this paper neglects the small proportions of the acceleration and deceleration processes of the UAV, that is, the UAV is assumed to fly at a constant speed throughout its entire journey. $v[n]$ is set to be 20 m/s. Meanwhile, to account for the windy condition, $\vec{V}_{wind}$ is set to be = [0][5], that is, the wind blows due north at a speed of 5 m/s. According to the energy formula of rotor UAV [20], UAV's energy consumption rate in the uniform linear motion or the hovering state is only a function of its mass. Hence, the UAV mass is set to $M = 5\ kg$ and the total energy is $2 \times 10^3 kj$.

25 random AP coordinates and their corresponding data volume are generated with a uniform random number generator, shown in Table 4.1, and are diagrammed in Figure 4.1 as a scatter plot.

Table 4.1 **AP coordinates and initial data volume in grassland**

AP index	AP coordinates	Initial data volume（%）	AP index	AP coordinates	Initial data volume (%)
0	（482，126）	79	13	（321，179）	57
1	（137，500）	6	14	（55，292）	72
2	（357，147）	31	15	（444，310）	35
3	（144，491）	65	16	（187，327）	68
4	（440，381）	76	17	（297，211）	66
5	（36，360）	77	18	（419，91）	68
6	（283，3）	24	19	（422，437）	36
7	（48，25）	71	20	（295，82）	22

8	（320，398）	36	21	（182，309）	76
9	（56，362）	54	22	（390，222）	45
10	（192，112）	42	23	（305，283）	68
11	（178，237）	45	24	（161，287）	51
12	（318，90）	71			

As shown in Figure 4.1, the UAV takes off from the station with coordinates (0, 0). It returns to this station upon completion of data collection, which marks one complete flight process. In this way, automatic data collection and automatic aircraft recovery are realized with a high degree of automation.

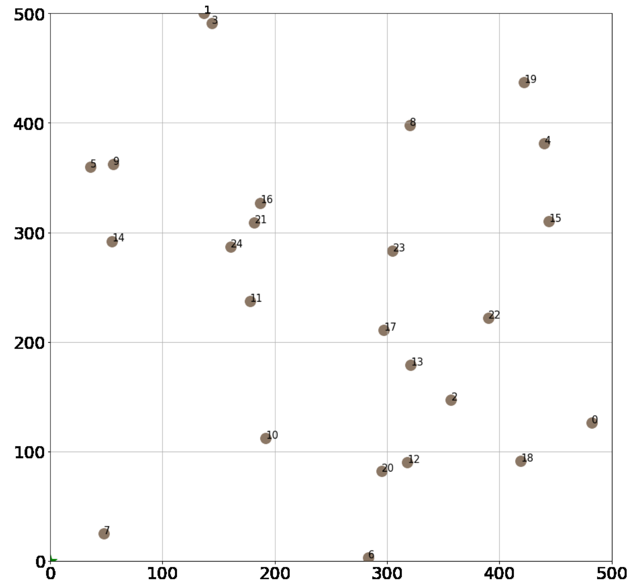

Figure 4.1 Random scatter plot of APs in the simulation experiment

4.2 Simulation Results

This paper implements both the: the original queuing algorithm and the proposed Passer-By data collection mechanism whose trajectories are visualized in Figures 4.2 and 4.3 respectively. It can be observed that the the original queuing algorithm results in a more rigid, erratic trajectory. A large number of APs are not reached or not collected even when the trajectory passes in close proximity. There are also more overlappings of the trajectory. These greatly deviate from the research objective of realizing UAV data collection in a limited energy condition for higher energy efficiency.

For more effective optimization, this paper implements the new trajectory optimization algorithm powered by the Passer-By data collection mechanism. From Figure 4.3, it can be noticed that the proposed method yields a more ideal flight trajectory in the same grassland setting as in

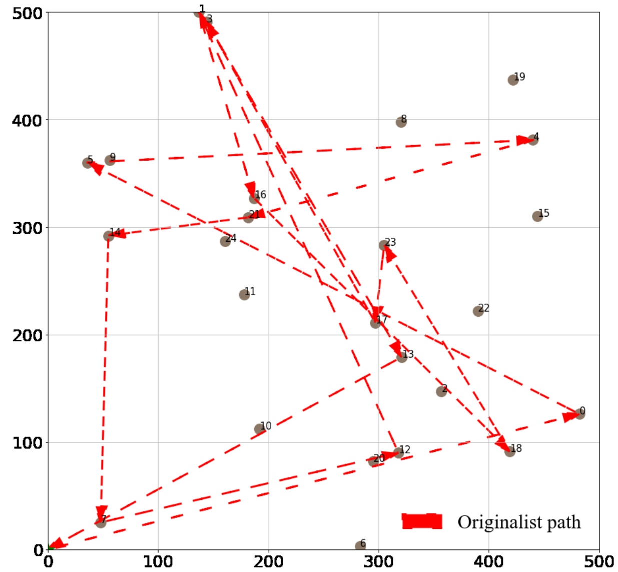

Figure 4.2 Trajectory diagram of the Originalist data collection mechanism

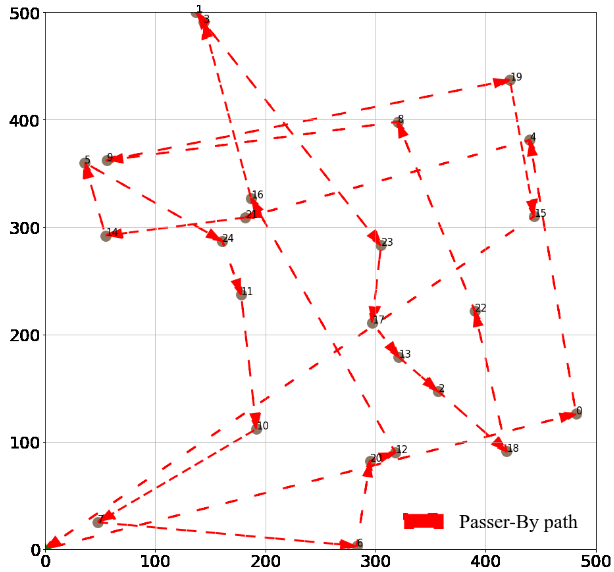

Figure 4.3 Trajectory diagram of the Passer-By data collection mechanism

Figure 4.2. It covers more AP_i under the same limited energy constraint. In the meantime, when a lower-priority AP is near the original flight trajectory, it is pre-determined to be included in the collection process with a lifted priority, thereby significantly enhancing flight efficiency.

Table 4.2 Analysis of simulation results

	OriginaList	**Passer-By**
UAV trajectory during data collection	[0, 5, 4, 21, 14, 7, 12, 1, 16, 18, 23, 17, 3, 13]	[0, 4, 21, 14, 5, 24, 11, 10, 7, 6, 20, 12, 16, 3, 1, 23, 17, 13, 2, 18, 22, 8, 9, 19, 15]
Number of collected APs	14	25
AP coverage (%)	56	100
Data volume collected (%)	789.9074	1071.8208
Total collection time (s)	394.9537	535.9104
Total flight time (s)	1231.9615	1375.6424
Flight efficiency (%)	32.0598	38.9571

By analyzing the above simulation results, it can be argued that compared with the original queuing algorithm, the Passer-By strategy enjoys remarkable advantages in terms of AP coverage. This is of great significance for effective AP collection in practical scenarios. On the one hand, the AP data is collected in a timely and effective manner before it overflows. On the other hand, it can evenly alleviate the overall data deficiency of the grassland. While maintaining the advantage in terms of AP coverage, the Passer-By strategy also has greatly increases the the total amount of data collected with higher collection efficiency.

In summary, the proposed algorithm allocates more energy for the UAV hovering collection stage while guaranteeing more APs are covered. It simplifies the flight path by avoiding switch-backs and repeated routes to a significant extent. This validates the effectiveness of the proposed method in achieving data collection with more optimal energy efficiency.

4.3 Summary

This chapter sets the relevant parameters of the UAV and the grassland environment by strictly adhering to the actual scenario. It implements the proposed algorithm and the original algorithm and evaluates their results with comparative analysis. This chapter validates the feasibility of the proposed UAV-Enabled real-time data collection model and the solution of UAV energy efficiency and route planning optimization problems. Simulation results demonstrate that the proposed method outperforms the original algorithm in terms of flight energy efficiency, flight coverage, and collected data volume. The proposed method therefore provides a promising technical solution to UAV-based real-time monitoring data collection.

Chapter 5 Conclusion and Prospect

5.1 Conclusion

This paper addresses the three key problems of UAV real-time data collection, UAV energy efficiency under wind interference, and UAV route planning through the invention of a novel UAV-Enabled real-time collection method in the grassland scenario. A sound data acquisition mechanism is designed that works for different monitoring area and ranges. The characteristics of grassland monitoring and principles of communication are taken into account in planning the optimal UAV trajectory and improving UAV energy efficiency, thereby achieving maximal collection volume and flight duration. In this paper, the objective function that maximizes data collection volume under limited energy is defined. The Passer-By mechanism is proposed to update the optimal collection route in real time which further improves UAV's data collection efficiency and reduce energy consumption in switchback journeys. The simulation results demonstrate the effectiveness of the proposed real-time grassland monitoring data collection system whose performance surpasses that of the original algorithm.

5.2 Research Prospect

This research aims to solve the problem of real-time monitoring data collection and transmission in proximity to the monitoring station. However, due to the limited capacity of the battery carried by a single UAV, it is challenging for the proposed method to work in a larger monitoring area with longer flight duration. Thus, it is necessary to investigate data collection and transmission methods that are applicable to long-range and blind spot monitoring. Also, the grassland environment setting adopted in this study's experiments is relatively simple, and the flight status of the UAV is unvaried. Therefore, the proposed model and algorithm are not directly applicable to the real grassland scenario. For future work, the characteristics of the grassland environment will be more extensively considered to investigate a more practical grassland monitoring data collection mechanism.

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Thanks

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毕业论文（设计）成绩表

过祖煜同学自 2021 年 02 月份进入本人课题组，在本人的指导下从事草原监测数据收集方面的研究工作。该同学学习认真，刻苦钻研，能够较好的完成本人布置的科研任务，并能积极主动的与本人交流讨论。

过祖煜同学的本科毕业论文具有较大的创新性，论文中的模型和算法都是他在本人的指导下先后经过一年时间完成的，论文书写较为规范，表述较为准确。高质量的完成了本科论文的要求，这对一个本科生实属不易。

本人认为过祖煜同学的毕业论文达到了优秀论文的标准和要求，特此推荐为优秀论文。

建议成绩 优　　　　**指导教师（签字）**

答辩委员会意见

答辩委员会负责人（签字）

成绩 优　　　　**学院（盖章）**

2022 年 5 月 30 日

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建议成绩 优　　　**指导教师（签字）** [illegible]

答辩委员会意见

答辩委员会一致建议成绩优.

答辩委员会负责人（签字） [illegible]

成绩 优　　　**学院（盖章）** 兰州大学 信息科学与工程学院

2022年5月30日