Consider no-fly zones and calculate unloading UAV power line autonomous patrol track planning technology

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ABSTRACT

In transmission line inspection, using UAV inspection technology will help improve the quality and efficiency of transmission line inspection and reduce the error and security risk of manual inspection. After the UAV collects a large amount of data during the inspection of power lines, when passing the ground station with stronger computing power, the data can be unloaded to the ground station to help it complete the calculation to make sure the task is finished within a specific limited time. The flight starts and finish points of the UAV patrol are fixed, and are constrained by factors such as flight, communication, and energy. In the paper, the flight trajectory planning scheme of UAV is proposed to minimize the total of its communication and flight energy or power consumption while completing the unloading of computing data within the specified time, and the experiment shows that the design scheme can greatly dwindle the UAV energy consumption in the mission execution process.

Keywords: Power line inspection, unmanned aerial vehicle, no-fly zones, calculate unload, patrol track planning

1. INTRODUCTION

Under the current situation of rapid development of the national economy and the record high amount of electric energy, the safety and stability of power supply have higher standards. The traditional mode of manual inspection of transmission lines exposes problems such as low efficiency and difficulty in ensuring the safety and security of personnel. Therefore, the development of power inspection to automation and intelligence is an inevitable trend [1].

UAVs (Unmanned Aerial Vehicle) mainly combine infrared technology sensing technology, remote sensing technology and other high-tech performance of the flying aircraft, can observe some areas with relatively high hazard factors or areas with relatively complex situations, and use the high-tech performance carried by them for picture analysis and shooting [2].

(1) Efficiency improvement. UAV inspection in mountainous areas and other areas affected by geographical environment, weather conditions and other factors, can give full play to its flexible and fast, high work efficiency characteristics, to achieve rapid access to clear image data and through analysis and processing, to judge the operation of the line, is dozens of times the efficiency of manual inspection [3].

(2) Wide coverage. Through the inspection of unmanned aerial vehicles, overhead transmission lines can be detected at close range, achieving zero dead ends, zero blind spots, and accurately finding defects such as wire breakage and insulator damage [4].

(3) Reduce casualties. The use of UAV inspection can eliminate manual climbing, wiring and other operations, which can effectively reduce labor intensity, improve operation and maintenance efficiency, and control the risk of casualties. Therefore, the application of UAVs is an effective solution for the intelligent development of line inspection [5].

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The key technologies of autonomous inspection of UAV power lines include

(1) Lidar detection technology, which obtains accurate spatial location information of power lines and surrounding environments, provides accurate location information for subsequent UAV autonomous inspection route planning, and can also obtain accurate distance from buildings, trees and cross-crossing objects near power lines.

(2) UAV flight attitude control technology, stable control of UAV flight attitude, to ensure that the task can be performed in accordance with the pre-set route during autonomous inspection [6].

(3) Wireless communication technology, UAV flight data transmission and UAV image transmission must rely on wireless communication technology [7].

(4) UAV track planning technology is fundamental to ensuring that UAVs can safely complete their tasks. The basic track planning is mainly 3 parts: the first fully combines the actual on-site environmental impact, and conducts the preliminary planning of the flight track; Second, the optimal trajectory is calculated using the optimization search algorithm; The third is track smoothing. When planning the trajectory, it is essential to reckon the performance constraints of the UAV itself, as well as the mission requirements and environmental constraints. At present, the constraints on the state of the UAV itself cannot be better handled, so the track planning technology must be continuously improved [8].

(5) Image data analysis and processing technology, the current UAV autonomous inspection is mainly in the fixed point to take photos and carry out backhaul, the ground server through the photo image analysis and processing of the line inspection, to obtain the health of the transmission line and identify defects or fault points [9].

This paper studies the trajectory planning technology of autonomous patrol of UAV power lines. Airports, temporary take-off and landing points, military management areas, party and government organs, supervision sites, observatories, satellite ground stations, meteorological radar stations, large enterprises that produce and store inflammable and explosive dangerous goods, large warehouses, bases, power plants, substations, gas stations and large stations, wharves, ports, large-scale event sites, high-speed railways, ordinary railways and other areas have no-fly zones [10]. Meanwhile, thanks to the limited UAV computing power, consider that the UAV will unload the computing tasks to the ground station that passes by to calculate, and the ground station returns the calculation results to the UAV before the UAV flies away [11-12]. Therefore, the UAV can bypass the no-fly zone and complete the calculation task before reaching the end point, so as to plan the UAV power line autonomous patrol track as a constraint.

2. SYSTEM MODEL

When the UAV completes the circuit inspection and photography task, it collects a heap of data, and the energy and computing resources carried by it cannot guarantee the completion of the computing task in a limited time, affecting the timeliness of the application [13]. The UAV passes through a ground station with more computing power during the flight to the end point, and the UAV can offload data to the ground station to help it complete the calculation. In this process, the flight starting point and the finish point are fixed, the time for mission completion is limited, and it is constrained by factors such as flight speed, acceleration, and radius of curvature [14]. This paper studies the UAV to complete the unloading of computational data within a specified time while minimizing the sum of its communication and flight energy consumption.

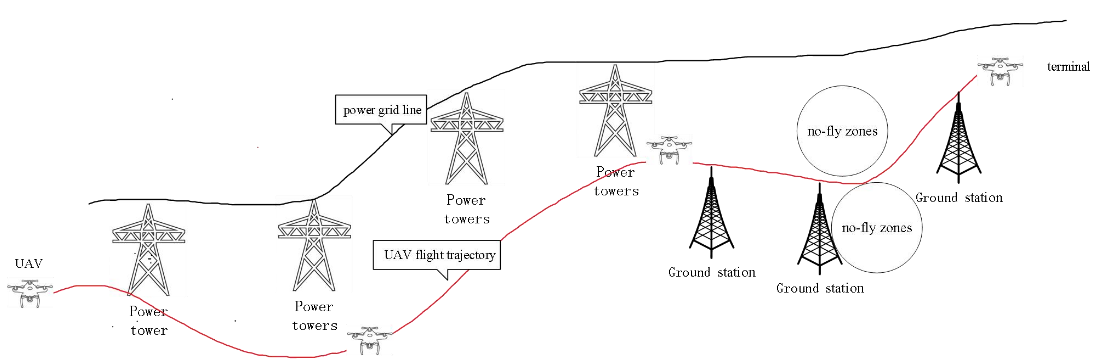

Figure 1. UAV power line inspection scenario

The system's model can be seen in Figure 1. Including a UAV and K ground stations. The UAV acts as one mobile data node, offloading all the data to the ground station. Suppose the UAV needs to finish calculating all its data as a task within a given time period T. In the UAV continuous flight, the trajectory can generate many numbers of continuous variables. Under this circumstance, it is hard to solve those infinite variables. Hence, the UAV trajectory is discretized.

Time period T can be divided to serval equally time slots N, each with a length of δ_t. Formula (1) is used to calculate the value δ_t,

$$\delta_t = T/N. \tag{1}$$

The trajectory of the UAV is modelled as a three-dimensional Cartesian coordinate system, where the XYZ axis is in meters. Then the coordinates $q_u[n]$ of the UAV in the n-th time slot can be expressed as

$$q_u[n] = \left(x_u[n], y_u[n], H\right), n \in \{1, \cdots, N\}. \tag{2}$$

H is the UAV flight hight on Z-axis, which remains unchanged during flight. $x_u[n]$ is the X-axis coordinates of the UAV in the No. n-th time slot. $y_u[n]$ is the Y-axis coordinates of the UAV in the No. n-th time slot.

For the UAV, the location of all K ground stations are known in advance. The location coordinates of the k-th ground station are expressed as

$$w_k = (x_k, y_k, 0), k \in \{1, \cdots, K\}. \tag{3}$$

The X-axis coordinate of the k-th ground station is is expressed as x_k, and the Y-axis coordinate is y_k.

The objective of this paper is to optimize the UVA flight energy consumption and communication energy consumption. The premise is to ensure that the UAV can complete the data offloading and calculation tasks within a specified time T, and then minimize the flight energy consumption and communication energy consumption.

The optimization problem P_0 is defined as follows [15]:

$$P_0: \min_{\mathrm{Q,P}} \sum_{n=1}^{N}\left(c_1 \cdot \| v[n] \|^3 + \frac{c_2}{\| v[n] \|}\left(1 + \frac{\| a[n] \|^2}{g^2}\right)\right) \cdot \delta_t + \sum_{n=1}^{N}\sum_{k=1}^{K} P_{u,k}[n] \cdot \delta_t \tag{4}$$

$$\text{s.t.} \quad q_u[n+1] = q_u[n] + v[n] \cdot \delta_t + \frac{1}{2} a[n] \cdot \delta_t^2 \tag{5}$$

$$v[n+1] = v[n] + a[n] \cdot \delta_t \tag{6}$$

$$\| v[n] \| \le V_{\max} \tag{7}$$

$$\| a[n] \| \le a_{\max} \tag{8}$$

$$q_u[0] = q_0, \; q_u[N+1] = q_F \tag{9}$$

$$(x_u[n] - x_{\mathrm{NF}}^j)^2 + (y_u[n] - y_{\mathrm{NF}}^j)^2 \ge \left(Q_{\mathrm{NF}}^j\right)^2 \quad \forall n, j \tag{10}$$

$$\frac{\| v[n] \|^4}{\left(\frac{\| v[n] \|^2}{R}\right)^2 + \frac{\left(\| v[n+1] \| - \| v[n] \|\right)^2}{\delta_t^2} - \frac{\left(\| v[n+1] \| - \| v[n] \|\right)^2}{\delta_t^2}} \ge \left(R_{\min}\right)^2 \tag{11}$$

$$0 \le \sum_{k=1}^{K} P_{u,k}[n] \le P_{\max} \quad n \in \{1, \cdots, N\} \tag{12}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{K}\delta_t \cdot B \cdot \log_2(1+\frac{P_{u,k}[n]\cdot \mathrm{h}_{u,k}[n]}{\left(\sum_{j\neq k} P_{u,j}[n]\right)\cdot \rho \cdot \mathrm{h}_{u,k}[n]+\sigma^2}) \geq L_{\text{total}} \tag{13}$$

The formula (4) indicates minimize the flight power consumption sum and communication energy consumption of the UAV. Where, c_1 and c_2 represent constants related to load coefficient, wing span efficiency, and wing area, the gravitational acceleration is given by g. The flight energy consumption of UAV is bound up with its speed and acceleration. When $\| v[n] \| = 0$, the UVA flight energy consumption is infinite. Therefore, fixed wing UAVs are different from rotary wing UAV， it cannot hover at a speed of 0 and must always fly in the air. Q represents the flight path of the UAV, Q={$q_u[1]$,…, $q_u[n]$,…, $q_u[N]$}. Q represents the flight path of the UAV, Q={$q_u[1]$,…, $q_u[n]$,…, $q_u[N]$}. P represents the transmit power vector set of each time slot, P={$P_u[1]$,…, $P_u[n]$,…, $P_u[N]$}, $P_u[n]$= {$P_{u,1}[n]$,…, $P_{u,k}[n]$,…, $P_{u,K}[N]$}.

The formula (5) indicates the change in the trajectory of the UAV. $v[n]=[v_x[n], v_y[n]]$ ， $a[n]=[a_x[n], a_y[n]]$ represents both speed and acceleration at the n-th time slot, severally. $v_x[n]$ and $v_y[n]$ are the flight speeds of UAV on X and Y axis at the n-th time slot severally. The The acceleration of the UAV on the X and Y axes at the n-th time slot is expressed as $a_x[n]$ and $a_y[n]$.

The formula (6) indicates the speed change of the UAV during flight, maintaining a uniform acceleration movement between adjacent two time slots.

The formula (7) indicates the maximum speed constraint of the UAV during flight， where $V_{\max}$ as the flight speed maximum.

The formula (8) indicates the maximum acceleration constraint of UAV during flight. $a_{\max}$ is the maximum acceleration of UAV.

The formula (9), coordinates of the specified start and finish locations of the UAV are q_0 and q_F .

The formula (10) represents the trajectory constraint. Assuming that N_{NF} is the number of the no-fly zones, the set of the no-fly zones will represented as $\{1,\cdots,N_{\text{NF}}\}$. For ease of calculation, the No. j-th no-fly zone is modelled as cylinders with a center on the ground as $\{x_{\text{NF}}{}^j, y_{\text{NF}}{}^j\}$, a height of $H_{\text{NF}}{}^j$ and a radius of $Q_{\text{NF}}{}^j$, $j\in\{1,\cdots,N_{\text{NF}}\}$. Based on the existence of the No. j-th no-fly zone, the distance between the center of it and the UVA during flight must always be larger than its radius $Q_{\text{NF}}{}^j$.

The formula (11) represents the minimum radius in curvature constraint, that is, the arc formed by the flight turn of the UAV will be limited by its own flight performance, and the UAV can only turn within a specific turning radius. $R_{\min}$ is the minimum turning radius of UAV.

The formula (12) represents the constraints on UAV transmitting power, and in the n-th time slot, the UAV transmit power for data transmission to the k-th ground station is expressed as $P_{u,k}[n]$. $P_{\max}$ is the maximum transmitting power of UAV.

The formula (13) indicates that to ensure the UAV can successfully complete the data offloading and calculation task under a given time, the sum total of data volume of the UAV unloaded to all ground stations during the entire time period must be greater than or equal to L_{total} . L_{total} indicates the sum amount of data that the UAV needs to unload. B means the bandwidth of communication channel in Hz.

From the n-th time slot to the k-th ground station, the UVA channel power gain can be expressed as

$$h_{u,k}[n]=\frac{\beta_0}{d_{k,n}^2}=\frac{\beta_0}{(H^2+\| q_u[n]-w_k \|^2)} \qquad k\in\{1,\cdots,K\}, n\in\{1,\cdots,N\}\cdot \tag{14}$$

$d_{k,n}$ suggests the distance between the *n*-th time slot UAV and the *k*-th ground station. β_0 indicates the channel gain at one meter distance.

3. SIMULATION RESULTS AND ANALYSIS

The comparison of UAV flight trajectory using Time Division Multiple Access (TDMA) unloading data and UAV flight trajectory using Code Division Multiple Access (CDMA) unloading data is shown in Figure 2. For ease of observation, the location of the ground station is marked with a five-pointed star. As can be seen from Figure 2, in code-division multiple access mode, the UAV is able to complete the task with a smaller trajectory offset. This is also due to the use of spread spectrum in the code division multiple access mode, which can realize that multiple ground stations can receive data at the same time in the entire time period, without too much shortening the ground station distance and improving the channel gain. It should be noted that in the code division multiple access mode, the UAV trajectory is biased to the ground station less, its trajectory length is shorter, the average speed is smaller. And in the model of the UAV flight power consumption here, the UAV flight power consumption is also large and small than the time-division multiple access scheme.

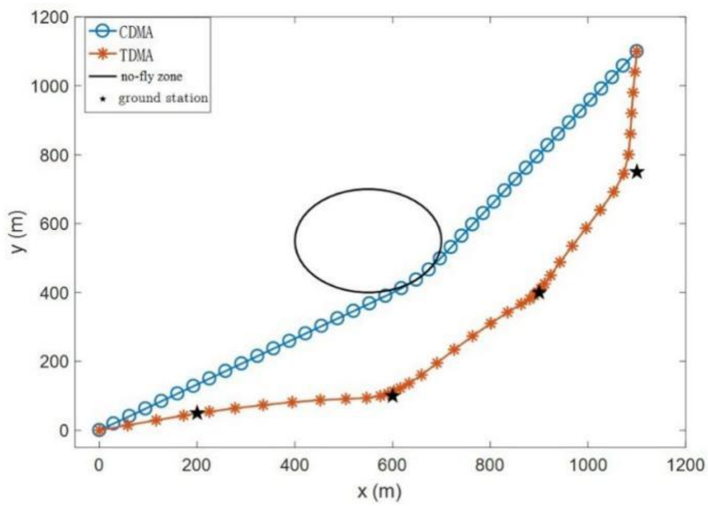

Figure 2. Comparison of optimized trajectory in TDMA and CDMA modes

4. CONCLUSION

The simulation results of this paper display that the design scheme can effectively lower the power consumption of UAV during task execution, and the joint optimization algorithm used in the experiment has the best effect. In order to make the optimized result more in line with the authentic flight scenario of UAV, and different from the existing work to consider the simple flight model and flight scenario, this paper adds the design of the UAV no-fly zone and the minimum flight curvature radius, and the experiments show that the scheme proposed in this paper can get a more practical flight scheme that meets the conditions.

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