Research on Automatic Path Planning of Wind Turbines Inspection Based on Combined UAV

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***Abstract*—Wind energy is a clean and widely deployed alternative to reduce human's dependence on fossil fuels for power generation. Under this trend, more turbines and wind farms will be built all around the world. Inspecting the turbines of wind farms is a challenging task due to the difficult conditions, which puts workers at high risk who need to work at considerable heights. Increasing number of turbines also requires longer time which may bring huge cost. In this regard, unmanned aerial vehicles (UAVs) can play an important role in the automatic inspection of turbines. In this paper, we propose a method to inspect wind turbines based on combined UAV, which is able to plan the inspection path of the wind turbine and combine image processing technology to identify wind turbine defects, so as to make wind turbines inspection more efficient.**

***Index Terms*—combined UAV, path planning, wind turbines detection**

Fig. 1. UAV is detecting wind turbine

I. Introduction

Wind power is an efficient and environmentally friendly way to generate electricity which has a positive significance for improving the environment and reducing energy pressure [1]. As a result, there are increasing number of wind farms being built all over the world to make the full use of it. The basic structure of the wind turbine includes four parts: blades, nacelles, hubs and towers, among which the parts that are most vulnerable to damage and need to be inspected are blades, as their surfaces can be damaged by many factors [2].

With the development of UAV technology, UAVs have been widely applied for the automated inspection for wind turbines [3] [4]. Many researchers have been devoted to the research of the UAV inspection technology. The team at the Polytechnic University of Madrid applied image-based object tracking technology to the inspection of UAVs [5]. The team at the GSRIO Technology Center in Australia has developed a UAV that can achieve autonomous obstacle avoidance, which is much more stable and propulsive than the previous UAV, and can complete 3D mapping within 50 meters using its own camera [6]. Research [7] proposes a mobile edge computing (MEC) driven UAV routine inspection scheme, in which the UAV not only detects WTs in multiple sorties, but also provides computing and offloading services. The studies mentioned above reflect the essential role of UAVs in inspecting wind turbines, which can reduce inspection time, improve inspection efficiency, and reduce manual risks.

The inspection of wind turbines is divided into shutdown inspection and in-service inspection [8]. Shutdown inspection will greatly reduce the efficiency of wind power generation and lose all wind resources during inspection. So we consider in-service wind turbines inspection by UAV, using image stitching technology to reconstruct the wind turbine and identify the defects.

In order to inspect the wind turbine when it is in the working state, the UAV must not only be able to avoid obstacles autonomously, shoot and collect images on the designated route, but also needs to have stronger wind resistance and endurance. However, a single UAV has limited load capacity [9] and endurance, so we propose an automatic path planning method based on combined UAV to ensure collect enough images and increase the inspection efficiency.

The remainder of this paper is organized as follows. In Section II, we provide the basic description of wind farm inspection and wind turbine inspection system and formulate

This work was supported in part by the National Natural Science Foundation of China (62071294, 61671295, 61671128), and the Shanghai Key Laboratory of Digital Media Processing and transmission; it is also partly sponsored by Shanghai Pujiang Program (16PJD029) , the 111 Project (B07022), Open Foundation of State key Laboratory of Networking and Switching Technology (Beijing University of Posts and Telecommunications) (SKLNST-2021-1-08). (Corresponding author: Junqi Wu)

the mathematical model. Then we describe the algorithms and principals of each problem in Section III. The simulation and analytical results are presented in Section IV, while Section V gives the conclusion of the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

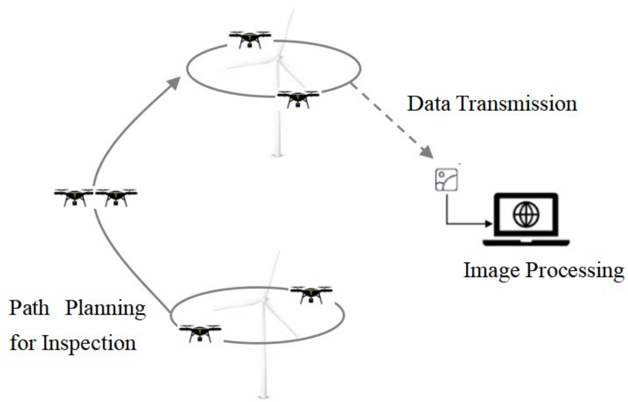

Fig. 2. The system of wind farm inspection based on combined UAV

The whole process of is as fig.3 shown: we divide the whole process into two stages: the first is to plan the path of the wind farm, which is carried out by the combined UAV. The second stage is to plan the path of the single wind turbine inspection, which is conducted by the two separated UAVs. Meanwhile, the UAVs transmit the image data back to the ground for processing. The collected data will be used to image stitching, through which three-dimensional reconstruction can be realized. After finishing the inspection of the current wind turbine, the two UAVs will recombined in the end points and then fly to the next target.

A. UAV and Wind Farm Models

The combined UAV(UAV-C) is composed of the host UAV (UAV-H) and the slave UAV (UAV-S). Since the UAVs is always in the wind farm M, at any time t($0 \leq$ t $\leq$ T), the position of UAV-C (which is the same as the position of UAV-H) and UAV-S is given by:

$$f(t) = (x_t, y_t) \in M \quad (1)$$

$$g(t) = (x_S, y_S) \in M \quad (2)$$

The inspection task in the first stage is to determine the traversal order of the wind turbines in wind farm for saving the energy of UAVs and time consumption of inspection. In order to minimize the distance traveled by the combined UAV while traversing all wind turbines. We established the following optimization model:

$$\begin{aligned} \min \quad & D \\ \text{s.t.} \quad & \mathcal{C}1: P_t = (x, y) \in M, \\ & \mathcal{C}2: f(t) = (x_t, y_t) \in M, \\ & \mathcal{C}3: D = \sum_{i=1}^{N_w} d\left\{P_t(i), P_t(i+1)\right\}, \end{aligned} \quad (3)$$

TABLE I
PARAMETERS LIST

Parameter	Definition
M	The map of wind farm
W_c	The horizontal resolution of the image
H_c	The vertical resolution of the image
θ_h	The field angle of view of the UAV camera when shooting horizontally
θ_v	The field angle of view of the UAV camera when shooting vertically
θ_d	The field angle of view of the UAV camera when shooting diagonally
D_{U-T}	The distance between UAV and turbine
L_B	The length of blade
W_B	The maximum width of the blade
L_N	The length of nacelle
R_N	The radius of nacelle
R_H	The radius of hub
H_T	The height of tower
R_T	The radius of tower
P_{hub}	The center point of hub
$P_{nacelle}$	The center point of nacelle (rear)
$V_{nacelle}$	The vector of nacelle
V_U	The direction vector of UAV
v_U	The average flight speed of UAV
P_U	The initial waypoint of UAV
t_c	The combination time of UAV
t_d	The separation time of UAV
T	The total time of the wind turbine inspection
ω	Wind turbine rotation speed

Where $\mathcal{C}1$ means that the wind turbines is in the wind farm M. $\mathcal{C}2$ means that the combined UAV is in the wind farm M. $\mathcal{C}3$ is the calculating method of the distance. $d\{,\}$ is Euclidean distance function.

B. Wind Turbine Model

we consider that the blade surface is flat and the UAV and camera use one same coordinate by default. The resolution of the image and the field angle of view of the UAV camera are meet the following equations:

$$\tan\left(\frac{\theta_h}{2}\right) = \frac{2 \cdot \tan\left(\frac{\theta_d}{2}\right) \cdot W_c}{\sqrt{H_c^2 + W_c^2}} \quad (4)$$

$$\tan\left(\frac{\theta_v}{2}\right) = \frac{2 \cdot \tan\left(\frac{\theta_d}{2}\right) \cdot H_c}{\sqrt{H_c^2 + W_c^2}} \quad (5)$$

To ensure that the UAV can detect the entire wind turbine through the path, the distance $(DU - T)$ between the UAV and the wind turbine blades during patrol inspection should meet the following requirements:

$$\frac{W_B}{D_{U-T}} < \min\left\{\tan\left(\frac{\theta_d}{2}\right), \tan\left(\frac{\theta_h}{2}\right), \tan\left(\frac{\theta_v}{2}\right)\right\} \quad (6)$$

$$\min\left(D_{U-T}\right)=\frac{W_B}{\min\left\{\tan\left(\frac{\theta_d}{2}\right),\tan\left(\frac{\theta_h}{2}\right),\tan\left(\frac{\theta_v}{2}\right)\right\}} \tag{7}$$

We specify the front and rear of the wind turbine as the positive and negative sides. The UAVs judge the positive and negative of the wind turbine by calculating the angle between its direction vector and the nacelle vector:

$$V_{\text{nacelle}} = P_{\text{hub}} - P_{\text{nacelle}} \tag{8}$$

$$V_U = P_U - P_{hub} \tag{9}$$

$$\cos A = V_{\text{nacelle}} \cdot V_U \tag{10}$$

$$\begin{cases} positive & \text{i}f A>0 \\ negtive & \text{e}lse \end{cases} \tag{11}$$

As shown in the fig.3, the UAVs inspects two sides of the wind turbine respectively, (a) depicts the separation of the combined UAVs to detect wind turbine, (b) describes the path of each UAV to detect and leave (vertical view).

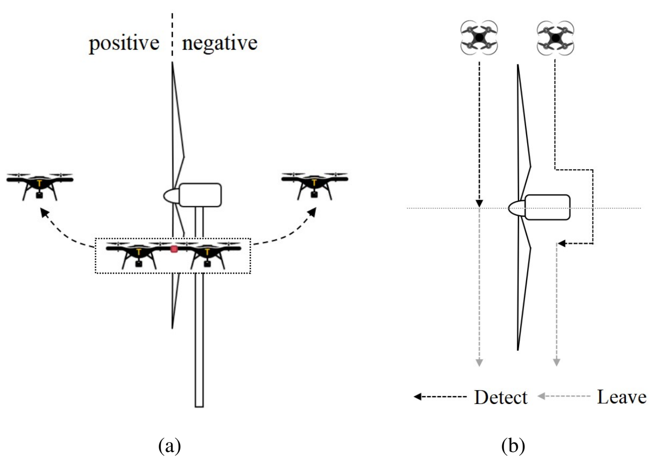

Fig. 3. The separation of the combined UAV and the inspection path

C. Problem Formulation

The UAV needs to select shooting points and hover for a while in shooting points to take photos of the blades. Three images will be taken during a hover time Δt. The interval between taking three images equals to the time interval for the blade rotate 120°, so that the three images correspond to the three blades of the wind turbine in order, which will be labeled as Blade I, Blade II and Blade III for subsequent image stitching.

The time interval $\Delta T(i)$ between the i_{th} shooting point and the $(i+1)_{th}$ shooting point during the flight should meet the following requirements:

$$\Delta T(i)=n(i)\cdot 2\pi/\omega \quad (i=1,2,\ldots) \tag{12}$$

The value of $n(i)$ is a positive integer.

For the positive side inspection, which is inspected by UAV-H, it determines the starting point P_0 and the path length of the inspection:

$$L=L_B+R_H \tag{13}$$

The valid range of the UAV camera corresponds to the actual scene range $M_c * N_c$. We are supposed to set N shooting points during the inspection process to collect enough image data. The related parameters meet the following unequal relationships:

$$\sum_{i=1}^{N-1}\Delta T(i)\cdot v_U+M_c/2\geqslant L_B \tag{14}$$

$$\sum_{i=1}^{N-1}\Delta T(i)\cdot v_U\leqslant L \tag{15}$$

$$\Delta T(i)\cdot v_U\leqslant M_c \tag{16}$$

If the total shooting range of the N points exceeds L, we will set the last shooting point as the hub center point P_{hub}. In that case, we have to add time compensation t_c to ensure the order of the blade images, which means the UAV has to hovering for another interval of time to wait for the rotation of the blades.

$$t_c=\Delta T(i)-\frac{\left|L-\sum_{i=1}^{N-1}\Delta T(i)\cdot v_U\right|}{v_U} \tag{17}$$

Otherwise, we will add a shooting point to the hub center to ensure that the starting point and end point in the UAV inspection process are determined.

In order to minimize the positive side inspection time, we can formulate the following optimization problem:

$$\begin{aligned}\min_{N,n(i)} \quad & T_P=T_{P-d}+T_{P-l}\\ \text{s.t.} \quad & \mathcal{C}1: f(t)=(x_t,y_t)\in M,\\ & \mathcal{C}2: T_{P-d}=\Delta t\cdot N+\sum_{i=1}^{N-1}\Delta T(i),\\ & \mathcal{C}3: T_{P-l}=L/v_U,\\ & \mathcal{C}4: D_{U-T}(t)\geqslant\min\left(D_{U-T}\right),\end{aligned} \tag{18}$$

Where $\mathcal{C}1$ means that the UAV-H is in the wind farm M. $\mathcal{C}2$ means the detection time of the positive side of the wind turbine. $\mathcal{C}3$ means the leaving time. $\mathcal{C}4$ guarantees that the distance between the UAV-H and the wind turbine is greater than the minimum safe distance.

Regarding the negative side of the wind turbine, which is detected by UAV-S, as the rotation of the wind turbine blades can be ignored when detecting the nacelle, we divide the detection path into two parts: blade detection and nacelle detection. The blade detection process is identical to the positive side. The nacelle detection is supposed to adjust the shooting angle according to the shape and size of the nacelle.

The shooting points N set in blade detection meets the following constraints:

$$\sum_{i=1}^{N-1}\Delta T(i)\cdot v_U+3\cdot M_c/2\geqslant L_B \tag{19}$$

$$\sum_{i=1}^{N-1}\Delta T(i)\cdot v_U\leqslant L_B-D_{U-T} \tag{20}$$

$$\Delta T \cdot v_U \leqslant M_c \tag{21}$$

Similarly, if the total shooting range of the N points exceeds $L_B - D_{U-T}$, we will set the last shooting point to the corner point. The time compensation is:

$$t_c = \Delta T(i) - \frac{\left| L_B - D_{U-T} - \sum_{i=1}^{N-1} \Delta T(i) \cdot v_U \right|}{v_U} \tag{22}$$

We can formulate the following optimization problem to minimize negative side inspection time:

$$\begin{aligned} \min_{N,n(i)} \quad & T_N = \Delta t \cdot (N+1) + (L + L_B)/v_U \\ \text{s.t.} \quad & \mathcal{C}1: g(t) = (x_S, y_S) \in M, \\ & \mathcal{C}2: D_{U-T}(t) \geqslant \min\left(D_{U-T}\right), \end{aligned} \tag{23}$$

Where $\mathcal{C}1$ means that the UAV-S is in the wind farm M. $\mathcal{C}2$ guarantees that the distance between the UAV-S and the wind turbine is greater than the minimum safe distance.

Based on the analysis above, the optimized mathematical model of the whole inspection problem is established as:

$$\begin{aligned} \min_{N,n(i)} \quad & T \\ \min_{N,n(i)} \quad & T_P, T_N \\ \text{s.t.} \quad & \mathcal{C}1: f(t) = (x_t, y_t) \in M, \\ & \mathcal{C}2: g(t) = (x_S, y_S) \in M, \\ & \mathcal{C}3: T = \max\left\{T_P, T_N\right\}, \end{aligned} \tag{24}$$

Where $\mathcal{C}1$ and $\mathcal{C}2$ mean that the UAV-H and UAV-S are in the wind farm M. $\mathcal{C}3$ means that the inspection time of single wind turbine is the larger one of the inspection time of the positive side and that of the negative side.

D. Performance Evaluation

As is mentioned above, the optimization goal of our model is to reduce the time consumption of the UAV inspection. So in this paper, we use the optimization result *T* as the performance evaluation metrics of different algorithms, which is an apparent reflection of the efficiency of the combined UAV.

III. PROBLEM SOLUTION

A. Wind Farm Inspection Path Planning

When the combined UAV is looking for the optimal path for the wind farm, it starts from the starting wind turbine, visits each wind turbine, and finally returns to the starting point, seeking the shortest path to access all the wind turbines. We can regard the process as Traveling Salesman Problem (TSP). We use the ant colony optimization (ACO) algorithm to find the shortest path.

In ACO algorithm, the walking path of ants represents a feasible solution to the optimization problem, and all the paths of the entire ant colony form the solution space of the optimization problem. when an ant, at its current wind turbine (WT), selects the next WT, the transition probability p_{ij} is composed of two parts: the concentration of pheromone τ_{ij} and the distance from the current WT to the next one η_{ij}. α is the importance factor of pheromone, and β is the importance factor of the heuristic function. At time t the transition probability of ant k from wind turbine i to wind turbine j is calculated according to the following formula:

$$p_{ij}^k(t) = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha [\eta_{ij}]^\beta}{\sum_{k \in \text{allowed}} [\tau_{ik}(t)]^\alpha [\eta_{ik}]^\beta}, & j \in \text{allowed}_k \\ 0, & \text{else} \end{cases} \tag{25}$$

During the iteration process, the concentration of pheromone on all paths in the problem space will change. The first part is the evaporation of pheromone, where ρ is the evaporation factor representing the rate of pheromone evaporation. Then, each ant releases pheromone on the edges it passes through this round, based on the length of the path it constructs. The formula is as follows:

$$\tau_{ij}(t) = (1-\rho)\tau_{ij} + \sum_{k=1}^{m} \Delta \tau_{ij}^k \tag{26}$$

Our optimization goal is to minimize the path length of the UAv inspection and choose the optimal order to inspect wind turbines. Algorithm 1 is the ant colony optimization algorithm process for wind farm inspection path planning.

Algorithm 1 Ant Colony Optimization Algorithm for Wind Farm Inspection Path Planning

```
Input: the wind farm map M, the number of wind turbines N_w
Output: the shortest path for UAV inspection
Set the number of ants m and the maximum number of iterations iter_max, initialize the taboo table Table and pheromone for each edge Delta_Tau
for iter_max = 1 to iter do
  for i = 1 to m do
    Randomly choose an initial wind turbine
    for j = 1 to n do
      Calculate the transfer probability p_ij^k(t)
      Use the roulette method to choose the next wind turbine
      Put j into the table
    end for
  end for
  Calculate the path length of each ant
  Update the pheromone for each edge
end for
Return the shortest path
```

B. Wind Turbine Detection path

After the UAV-C arrives at each of the wind turbine, it separates into UAV-H and UAV-S to start inspect the single wind turbine. For planning the path and the position of hovering points, the horizontal range of wind turbine blade has to be entirely covered by the shooting range of the UAV camera. Thus we can consider this problem as a variant of the interval-coverage problem. The interval of the shooting points are line segments of varying lengths. Our optimization goal is to cover the entire inspection path by UAV camera in the shortest possible time. Here, we use greedy algorithm to seek the optimal solution.

When selecting a line segment, the longest one will be used as the local optimal solution. Determine whether the sum of the iterated optimal solution satisfies the limiting conditions to select the final optimal solution.

Based on the given restriction condition and combined with the greedy algorithm, the optimal path and the shortest time can be obtained. The optimization algorithm is summarized in Alg.2

Algorithm 2 Algorithm for Calculating the Number and Position of Hovering Points

Input: the start point P_0, the end detect point P_d, the end point P_e, the wind turbine rotation speed ω
Output: $S = \{x_1, x_2, x_3, ..., x_N\}$, the number of hovering points N
$d = dist\{P_0, P_d\}$
GREEDY-INTERVAL-SELECTOR (ω, d, v_U)
  Let S be a new set, $n_{allowed}$ be a new set
  for each k is positive integer **do**
    if $k \cdot \frac{2\pi}{\omega} \cdot v_U \leqslant M_c$
      $n_{allowed} = n_{allowed} \cup \{k\}$
  end for
  Arrange the elements in descending order, obtain $n_{allowed} = \{n_1, n_2, ..., n_k\}$
  $i = 1$
  $s = 0$
  for each j in k **do**
    while (i)
      $n(i) = n_{allowed}(k - j)$
      $m(i) = n(i) \cdot v_U \cdot 2\pi/\omega$
      if $(s + m(i) \leqslant d)$
        $prev = s$
        $x[i] = prev + m(i)$
        $s = x[i]$
      else
        break
      $i = i + 1$
      $N = i + 1$
      $S_i = S_i \cup \{x[i]\}$
    $j = j - 1$
    $x[N] = P_d$
    return S_i
  end for
  return S

We consider the inspection time T is the optimization object, and n and N are the optimization variables. Based on the corresponding constraints, we can find the optimal solution.

IV. SIMULATION AND DISCUSSIONS

During the simulation, we assume that the UAV camera is supposed to be able to rotate the lens direction according to the position so that it can scan all parts of the wind turbine from the front and back sides.

Table II gives some detail information about the wind turbines and the UAV for simulation.

TABLE II
PARAMETERS LIST

Parameter	Value
L_B	85
L_N	15
R_H	5
R_N	5
v_U	1
M_c	10
ω	$2\pi/3$
$\min(D_{U-T})$	5

We selected part of the geographic data of an offshore wind farm in China for visualization, and used the ACO algorithm to determine the shortest path of its complete traversal, which is as shown in fig.4.

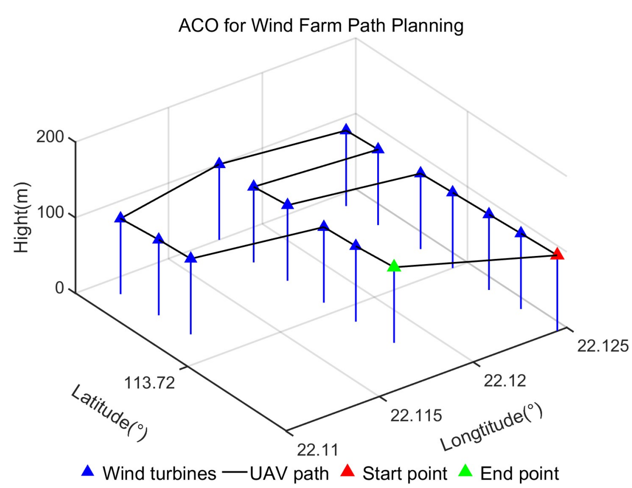

Fig. 4. UAV detection path of wind farm based on ACO

Based on the given parameters and values, we calculate the optimal number of the hovering points for collecting the images of wind turbine blades, hub and nacelle as table III shows.

TABLE III
RESULT OF THE OPTIMIZATION PROBLEM

	N	Δt	$\Delta T(1) \backsim \Delta T(N-1)$	$\Delta T(N)$	t_c	T_d	T_l	T
P-side	11	3	9	9	0	113	90	203
N-side	10	3	9	8	1	125	80	206

From the result of the experiment we know that for the positive side of wind turbine, the shortest inspection time can be obtained when the number of hovering points is set to 11,

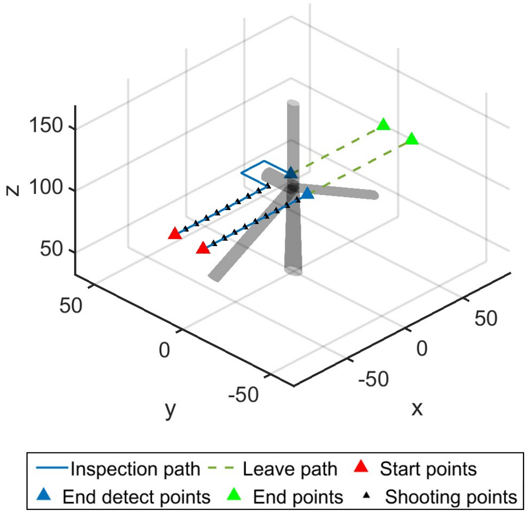

Fig. 5. The frontal perspective of wind turbine inspection path

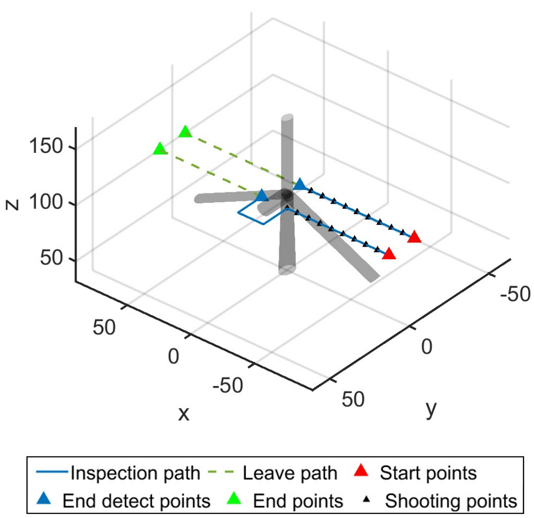

Fig. 6. The rear perspective of wind turbine inspection path

and for the negative side, we can get the optimal number of hovering points 10. Combined with the two optimal solution, the shortest inspection time is $\max\{T_P, T_N\}$, which is equal to 206.

The visualization of the inspection path is shown in the fig.5,6,7, displaying three perspectives from the front, back, and top views respectively.

V. CONCLUSION

This paper proposes a wind turbine inspection strategy based on the combined UAV that allows for in-service inspection of the wind turbine. Through the cooperative approach of combining and separating the UAVs, synchronized detection of the positive and negative sides of the wind turbine

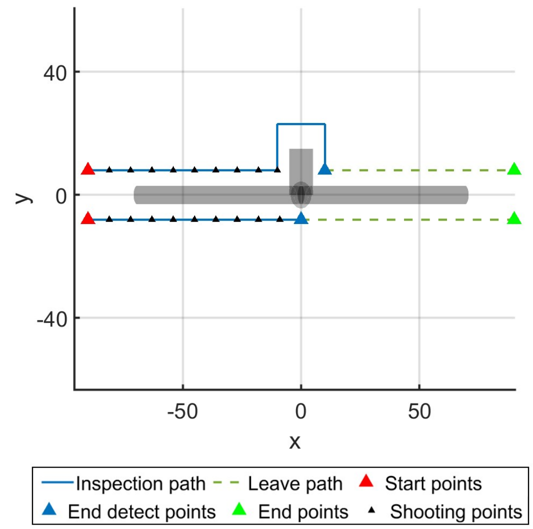

Fig. 7. The aerial perspective of wind turbine inspection path

is conducted. Compared to the single UAV inspection, the combined UAV greatly improves inspection efficiency, and the continuous operation of the wind turbine ensures that the wind energy is not wasted. Finally, the effectiveness and feasibility of this strategy are verified through the algorithm experiments.

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