Optimal path planning for UAV based inspection system of large-scale photovoltaic farm

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***Abstract*—Small scale quad-rotor unmanned aerial vehicle (UAV) has attracted much attention in recent years and has been widely adopted in many civil applications, e.g. inspection of critical infrastructure spanning over a large geographical area. In a typical UAV based inspection system for large-scale photovoltaic farm, it is required to control the mounted gimbal camera taking pictures of all the PV modules and eventually accurately identify the ones with defects through efficient image processing techniques. Given a series of waypoints without an effective path generation algorithm, the image acquisition can be not satisfactory and even miss some areas that should be inspected. In this paper, a Bezier curve and particle swarm optimization (PSO) joint approach is presented to address the UAV path planning challenge. The path generation process fully takes flight attitude, gimbal limitation and path length into consideration with the aim to improve the efficiency and the reliability of the inspection system. The performance of the proposed solution is assessed through a set of simulation experiments and the numerical result demonstrates the effectiveness of the proposed optimal path planning solution.**

Keywords—Quad-rotor UAV, PV inspection, path planning, Bezier curve, particle swarm optimization

I. Introduction

Currently, much research effort with the pursuit of low carbon energy provision and technological advances has driven a great boom in the utilization of various forms of renewable energy resources [1]. The solar photovoltaic (PV) energy is playing an increasingly important role in the transition to clean and low-carbon energy provision globally. The statistics from International Energy Agency (IEA) indicates that, China became world's largest producer of photovoltaic power in 2015 and the cumulative photovoltaic capacity reached at least 178 GW by 2014 which is sufficient to supply 1% of global electricity demands. The worldwide deployment capacity of about 55 GW is accomplished in 2015, and installed capacity is projected to more than double or even triple beyond 500 GW between 2015 and 2020. By 2050, solar power is expected to become the world's largest source of electricity, with solar photovoltaic power contributing 16%. This will require PV capacity to grow to 4,600 GW, of which more than half is forecasted to be deployed in China and India [2].

The new advances of renewable energy technologies, e.g. solar photovoltaic, have received increasing attentions and the reliability of the large-scale PV farms needs to be guaranteed. In reality, the PV farms are constructed over a large geographical area and located in the places with complex topographies, as illustrated in Fig. 1. This implies that the manual inspection and operational condition monitoring of such PV farms can be time-consuming, and even not possible in practice.

The significant interest and research in quad-rotor unmanned aerial vehicles (UAVs) have been increasingly growing in recent years due to the simple structure, low cost and the flexibility of motion mode of UAVs, especially for the capability of flexible hovering as well as vertical take-off and landing (VTOL). Currently the quad-rotor UAVs have been widely adopted in various civil applications, including geological survey, search and rescue, meteorological observation, air traffic control and field patrolling, and so forth.

Fig. 1. The illustration of a large-scale PV farm

The quad-rotor UAV is adopted in such condition to carry out the asset assessment and defect detection for large-scale photovoltaic systems [3]. The UAV-based inspection system can perform flight task automatically in PV systems which are generally located in remote areas with transportation problems and detect the faults of PV modules. In our previous work [4], two most typical visible defects of PV modules (snail trails and dust shading) are characterized and the defect detection through image processing algorithms based on FDOG function and feature matching is carried out for the aerial PV module images captured by visible light cameras. Therefore, it is required to guarantee that the picture taken eventually shows exactly what was expected. Under the circumstance that a number of dispersed waypoints are given without an identified appropriate trajectory generation algorithm, the acquisition of useful PV module images can be hardly carried out for fault detection and condition monitoring purposes. This indicates that the accuracy of UAV location, including the flight attitude and the gimbal angle, need to be properly managed during the inspection process.

One of the key issues of UAV based inspection system is the trajectory planning generation which aims to identify the trajectories that are feasible of being executed by the target vehicle. Series of trajectory generation algorithms have been proposed in literature. There are traditional methods including simulated annealing (SA) [5] and Tabu search algorithm (TGA) [6], graph-based methods including Voronoi diagram searching method [7], A* search [8] and D* lite algorithm [9], population-based evolutionary algorithm including genetic algorithm (GA) [10] and ant colony optimization (ACO) [11]. However, trajectories generated from the aforementioned methods need to be further smoothed considering the movement restriction of UAVs. An alternative approach of modelling UAV flight paths is to use a selection of available curves, e.g. Dubins curves [12], clothoid curves [13] and B-splines [14], that are designed to ensure the smoothness of trajectories and some of which are infinitely differentiable.

To this end, this paper presents a Bezier curve [15, 16, 17] based smooth quad-rotor UAV trajectory generation algorithm combined with particle swarm optimization (PSO) [18], achieving the balance between path length, kinematic constraints of the vehicle and flight attitude, especially taking the gimbal angle limitation into consideration, to finally solve the problem of area missing when performing flight tasks in the asset assessment and defect detection for PV systems.

The rest of the paper is organized as follows: section II discusses the major technique issues in quad-rotor UAV trajectory generation; section III presents the proposed trajectory generation algorithm based on the combination of Bezier curve and particle swarm optimization; section IV carries out a set of simulation experiments to validate the feasibility and effectiveness of the proposed method; and finally the conclusive remarks are given in section V.

II. Technical Challenges of Quad-rotor UAV Path Generation

A. *UAV-based PV Inspection System*

A typical UAV based PV inspection system consists of a quad-rotor unmanned aerial vehicle (UAV) boarded with an on-board processor, a digital light visible single-lens reflex (SLR) camera and a set of corresponding sensors, as shown in Fig. 2. After accessing a series of waypoints by offline or online path planning, the quad-rotor UAV can perform flight tasks automatically, control the camera mounted on a three axis gimbal to take pictures of PV modules and finally accomplish the goal of locating defective PV modules and identifying the type of failures and defects by processing these images. Thus, it is one of the major issues that the picture taken eventually shows exactly what was expected. This is a problem that concerns with several factors including the accuracy of UAV location, the flight attitude and the gimbal angle. For the quad-rotor UAVs, the flight attitude is always related to its velocity and acceleration.

In the process of PV farm inspection, it is necessary to make sure that every PV module will be detected. Accordingly, the waypoints are pre-defined by geographical information or photos portrayed the detection area, most of which are aligned or in other parallel lines and all need to be photographed. However, the endurance of the quad-rotor mounted with current additional payload and a power battery carrying energy of 100Wh is only about 15 minutes based on previous testing experiments and fluctuates depending on the ambient temperature. If the quad-rotor UAV hovers over each waypoint before taking pictures, then it is inescapable that the vehicle needs to experience the process of accelerating, flying uniformly and decelerating between any two waypoints. Obviously, it is a great waste of either time or energy. The proposed solution is to generate a curve makes all the waypoints along the trajectory and guarantees the smoothness of the acceleration profile.

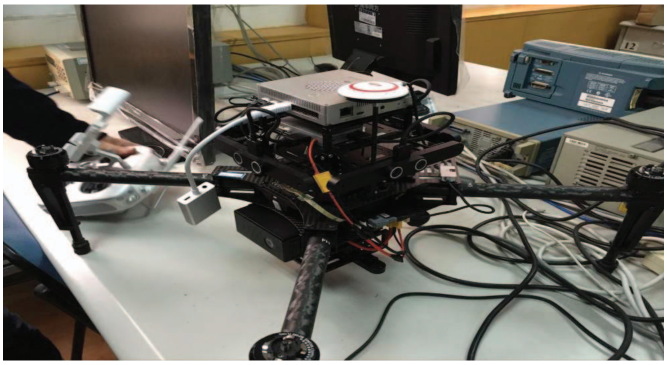

Fig. 2. UAV hardware platform and components

B. *Problem Formulation*

Due to the fact that the quad-rotor UAV will fly at a height of 100 meters in areas which are mostly flat and open, the flight tasks will be performed without consideration of the movement in the vertical direction. Therefore the model can be simplified to a two dimensional as well as an obstacle-free one.

Given a pair of waypoints $< P_i, P_j >$ representing the initial position and destination, the flight path can be expressed as a parametric curve $r(t)$ in $\mathbb{R}^3$ where t is a continuous variable in $\mathbb{R}$ and presents as follows:

$$\begin{aligned} P_i(x_i, y_i) &= r(t_i) \\ P_j(x_j, y_j) &= r(t_j) \end{aligned} \tag{1}$$

where the x axis points to the north and the y axis points to the east.

If there are totally N waypoints, a feasible path will be the union of each $r(t)$ calculated between each sequence pair of waypoint, which is formulized as follows:

$$\Re = \left\{ \bigcup_{k=1}^{N-1} r_k \in \mathbb{R} \right\} \tag{2}$$

III. Bezier Curve-PSO based Trajectory Generation Algorithm

This section presents the proposed trajectory generation algorithm based on the Bezier curve and PSO technique in details.

A. Bezier Curve

Bezier curves are widely used to model smooth curves and can be defined for any degree n. An explicitly definition for Bezier curve of degree n expresses as follows:

$$\begin{aligned} B(t) &= \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i} t^i P_i \\ &= (1-t)^n P_0 + \binom{n}{1}(1-t)^{n-1} t P_1 + \\ &\cdots + \binom{n}{n-1}(1-t) t^{n-1} P_{n-1} + t^n P_n \qquad 0 \le t \le 1 \end{aligned} \tag{3}$$

where P_i is the i_{th} control point of the targeted Bezier curve, $\binom{n}{i}$ are the binomial coefficients which also expressed as ${}^n\mathrm{C}_i$ or C_i^n .The proposed algorithm is implemented in cubic Bezier curves which function is presented as follows:

$$r(t) = (1-t)^3 P_0 + 3(1-t)^2 t P_1 + 3(1-t) t^2 P_2 + t^3 P_3 \tag{4}$$

where $0 \le t \le 1$ and Bezier curve can be uniquely calculated by the four control points.

Assuming that the UAV heads towards the north in a fixed yaw angle all the time and moves along the east-west direction before switching to another row.

The Bezier curve can provide a number of advantages in addressing the path planning problem, as follows: (1) the Bezier curve is infinitely differentiable so that the path produced will be absolutely smooth; (2) the first and last control points are always the end points of the curve which makes it possible for the designed curve passing through all the specified waypoints; (3) the Bezier curve is straight if and only if all the control points are collinear; and (4) the direction of UAV velocity can be set by the control points of Bezier curve.

The path length is defined as the length of the designed Bezier curve which can be generally expressed with the Leibnitz notation as:

$$L = \int_0^1 \sqrt{(dx/dt)^2 + (dy/dt)^2}\, dt \tag{5}$$

The general solution uses Legendre-Gauss quadrature omitting the derivation is given as follows:

$$\begin{cases} L \simeq \dfrac{1}{2} \cdot \sum_{i=1}^{n} C_i \cdot f(\dfrac{1}{2} \cdot t_i + \dfrac{1}{2}) \\ f(t) = \sqrt{(dx/dt)^2 + (dy/dt)^2} \end{cases} \tag{6}$$

where the values of C_i and t_i can be found in many available tables and $n = 3$ in this paper.

TABLE I. Weights and Abscissae Table for n=3

i	**Weight-** C_i	**Abscissa-** t_i
1	0.888888888888888	0.0000000000000000
2	0.555555555555556	-0.7745966692414834
3	0.555555555555556	0. 7745966692414834

It is expected that the quad-rotor UAV flying at a constant speed $V_{\max}$. Given the total flight distance L calculated by Eq. (6), the total flight time T can be calculated according to:

$$T = \frac{L}{V_{\max}} \tag{7}$$

However, the velocity of UAV including the magnitude as well as the directions related to the derivative of the path needs to be known. The variable t_{real} represents the actual time. The parameter t mentioned above is independent from time or the coordinate system, so we choose curve fitting to build the relation between parameter t and real time and finally find a polynomial equation like this:

$$t = g(t_{real}) \tag{8}$$

The procedure will be done every single time given a pair of waypoints. Thus the velocity can be expressed as follows:

$$\begin{aligned} v_x(t_{real}) &= \frac{r_x'(g(t_{real})) \cdot V_{\max}}{\sqrt{r_x'^2(g(t_{real})) + r_y'^2(g(t_{real}))}} \\ v_y(t_{real}) &= \frac{r_y'(g(t_{real})) \cdot V_{\max}}{\sqrt{r_x'^2(g(t_{real})) + r_y'^2(g(t_{real}))}} \end{aligned} \tag{9}$$

The curvature of Bezier curve is calculated by the following formulation:

$$\kappa(t_{real}) = \frac{r_x'(t) \cdot r_y''(t) - r_x''(t) \cdot r_y'(t)}{\left[r_x'^2(t) + r_y'^2(t)\right]^{3/2}} \quad (10)$$

The module of acceleration is:

$$\mathrm{acc}(t_{real}) = V_{\max}{}^2 \times \kappa \quad (11)$$

As long as the module of velocity doesn't change with time, there is only normal acceleration that is perpendicular to velocity.

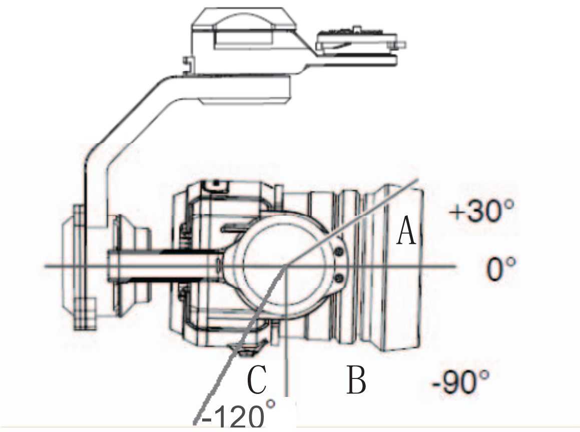

Fig. 3. the structure and the pitch range of the gimbal

Based on the dynamic and kinematic model of quad-rotor UAV, even the slightest tilt of the quad-rotor will induce translational motion. Thus, there is a strong correlation between attitude angle, velocity and acceleration.

The gimbal motors have already designed to respond instantly to subtle movements of the airframe and neutralizes it to keep the camera stable combined with high speed processing. In most cases, the three-axis gimbal is able to handle tasks taking images vertically, but there are also some limitations. The structure of the gimbal shows in Fig. 3.The mechanical range of pitch is $\left[-120^\circ, 30^\circ\right]$ where 0° pointing to the nose of the aircraft, $\angle A = 30^\circ$ and $\angle B = \text{-}90^\circ$. The gimbal is set to be perpendicular to the ground, that is, the pitch angle of the gimbal is -90° when the quad-rotor is hovering. Assume a windless environment. When the quad-rotor moves backwards, the head of UAV will raise and cause deflection. To maintain the status of taking vertical pictures, gimbal pitch angle should be adjusted towards $\angle C$. But a problem always occurs if the deflection is larger than $\angle C$. After UAV returns, the gimbal pitch angle will not return to -90° as expected and adjust to an angle smaller than $\angle B$. Furthermore, error will accumulate every time the large deflection arises. Thus, the constraint needs to be fully taken into the consideration of path planning.

B. Calculating Control Points using Particle Swarm Optimization

The Particle swarm optimization (PSO) technique is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to given measure of quality. In this proposed method, PSO is used to find the optimal control points P_1 and P_2 of a cubic Bezier curve, given two adjacent waypoints P_0 and P_3.

Taking velocity direction into consideration and ignoring the initial point and the last point, there are two types of path curves need to be exploited as follows.

1) Straight lines: If the velocity at P_0 points directly to the destination point P_3, the path curve will be a straight line, which is common in our patrolling scheme. As it mentioned above, the UAV keeps heading towards north all the time so the pitch angle is always zero during these periods and obviously satisfies the demand.

2) Cubic Bezier curves: If the quad-rotor needs to turn off at P_0 and heads towards P_3, two more control points P_1 and P_2 should be given to produce a Bezier curve. PSO algorithm is introduced to solve this problem by generating an optimal path that takes path length, kinematic constraints of the vehicle and flight attitude, especially the gimbal angle limitation into account. Although, there are a number of factors that need to be considered.

Firstly there is acceleration constraint. The quad-rotor UAV system is a complicated nonlinear system and even though it is known that there is correlation between acceleration and attitude angle, it is difficult to build a precise model of them. Due to the uncertainty inflight, we choose an equation roughly describe this as follows:

$$\begin{aligned} pitch &= \theta = \arcsin(-ax / g) \\ roll &= \gamma = \arctan(ay / az) \end{aligned} \quad (12)$$

According to the mechanical constraint of quad-rotor, we can get the limitation of acceleration.

Given the UAV flying with the constant speed, the shorter the path implies less time cost.

There are two key steps when applying PSO to optimization problems: the representation of the solution and the fitness function. In this paper, the solution is the coordinate value of $P_1(x1, y1)$, $P_2(x2, y2)$. Given $P_0(X0, Y0)$, $P_3(X3, Y3)$ the particle can be set as $(y1, y2)$ .The fitness function of PSO in this paper is defined like this:

$$F = \min\left[\mathrm{L} + \mu \cdot \kappa \max + \lambda(a_x \max + a_y \max)\right] \quad (13)$$

where L and κ has been introduced above. μ , λ is the adjustment coefficient of curvature and acceleration respectively, increasing their weight in this function. The flow chart of PSO algorithm for Bezier curve generation is given in Fig. 4.

IV. Simulation Experiment and Numerical Result

This section presents and discusses the numerical result of proposed path generation algorithm based on PSO and Bezier curve to assess the path planning performance. Given a series of waypoints as given in TABLE II, the proposed method is implemented to generate a trajectory that passes all the waypoints for the expected inspection process.

Fig. 5 shows the performance curve that represents the average fitness value and the max fitness value of PSO algorithm in each iteration. It can be seen that the fitness value convergence very fast as the iteration progress.

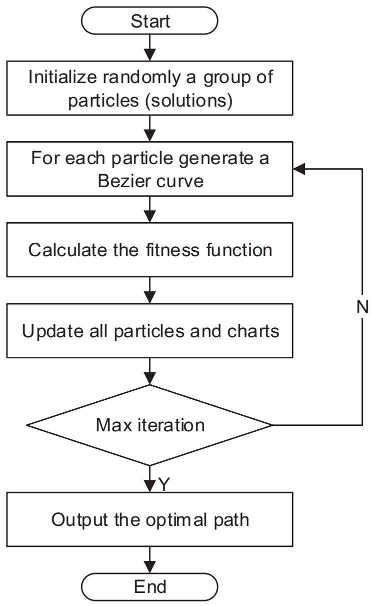

Fig. 4. The flow chart of PSO algorithm for Bezier curve generation

TABLE II. GIVEN WAYPOINTS

Index	X	Y	Index	X	Y
1	0	0	8	80	75
2	0	75	9	80	150
3	0	150	10	120	150
4	40	150	11	120	75
5	40	75	12	120	0
6	40	0	13	160	0
7	80	0	14	160	75

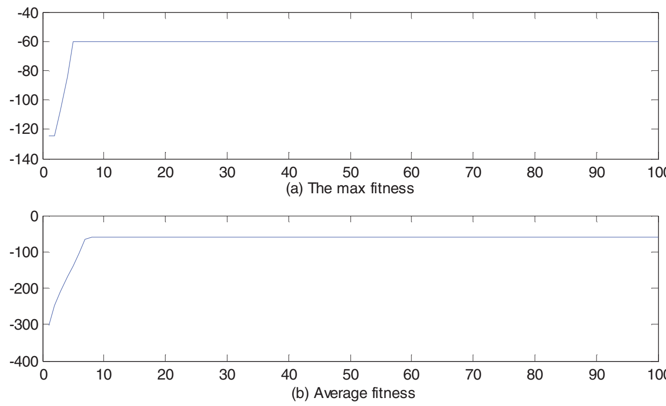

Fig. 5. Average fitness value and max fitness value

An optimal path can be produced after PSO algorithm and the properties like velocity and acceleration between two turning points are shown in Fig. 6. It can be seen that the max acceleration is kept less than $5m/s^2$ and all the curves are smooth.

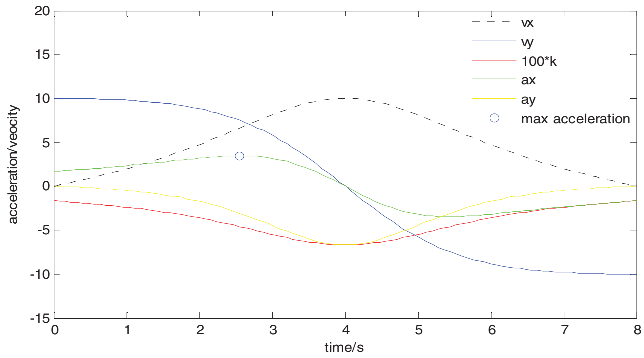

Fig. 6. The properties of the targeted path

This proposed method is implemented in the on-board processor carried by the quad-rotor UAV. The whole path trace when finished the sample task in flight simulator shows in Fig. 7, those red dots are expected waypoints.

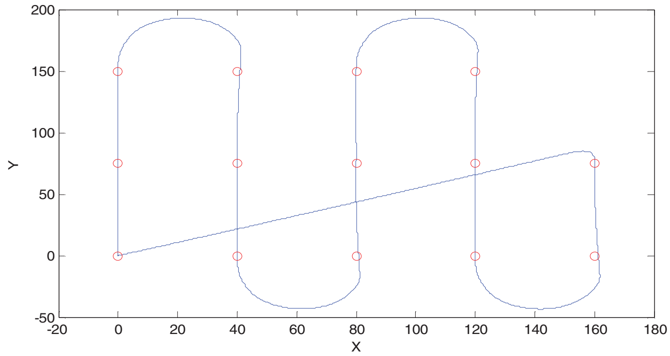

Fig. 7. The whole path trace of the sample task

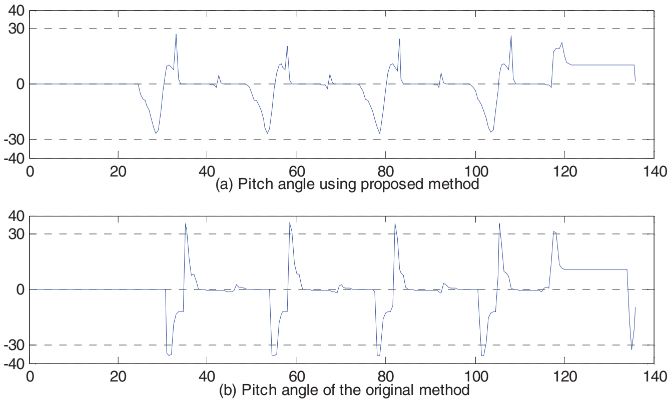

Fig. 8. Changes of pitch angle in the sample task

One of the key factors of this method is to keep pitch angle below 30° all the time so that the three axis gimbal can work properly and photographs ideal pictures. Fig. 8 shows the changes of pitch angle in the sample task and it can be seen that pitch angle in the proposed method is acceptable, while in the original method there are always times that the pitch angle is out of range.

V. Conclusions and Remarks

This paper presented a path planning solution for the quad-rotor UAV based inspection system for condition monitoring of large-scale PV farms. The proposed algorithm is based on Bezier curve and particle swarm optimization algorithm. This method takes main consideration of the gimbal angle in order to accomplish the PV inspection tasks ideally. The numerical result obtained from the simulation experiments clearly demonstrates the effectiveness of the proposed path planning solution.

Based on the observations obtained from this work, the following aspects are considered need further research effort. It should be noted that, there is more concern in the UAV-based PV patrolling system. Although most of the areas are flat and open so the problem can be simplified to be in an obstacle-free environment, the strong wind is still an assignment problem. It should be noted that the proposed method works effective only in a windless environment. The optimal approach that is able to adjust velocity of the aircraft constantly according to the current wind velocity is considered more appropriate for the inspection system of large-scale PV farms, rather than traveling with a constant speed. This can further improve the reliability and efficiency of the inspection process with a reduced complexity and cost.

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