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A 3D Coverage Path Planning Approach for Flying Cameras in Nature Environment under Photogrammetric Constraints

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Abstract: Coverage path planning is the operation of finding a path that covers all the points of a specific area. Thanks to the recent advances of hardware technology, Unmanned Aerial Vehicles (UAVs) have multiple use at present besides obvious military applications, such as nature environment 3D reconstruction. However most of the research focus on finding the coverage path in an planar coverage surface, without considering the photogrammetric constraints, such as constant distance for consistency resolution and normal orientation for orthophotograph. This paper present a modified back-and-forth 3D coverage path planning method for quadrotor with gimbal camera under photogrammetric constraints that can reduce the consumption of time and energy. First, the 3D terrain is modeled by quasi uniform B-spline surface for a mesh representation. Then, the center of the camera footprint on the terrain surface and the air points can be generated by photogrammetric constraints. Finally, a modified back-and-forth coverage path planning method has been used to calculate the scan direction and coverage path. The experiment results have showed that our method can cover all the waypoints in the air that satisfy all the photogrammetric constraints.

Key Words: Coverage Path Planning, Flying Camera, Photogrammetric Constraints

1 Introduction

Nowadays, Unmanned Aerial Vehicles(UAVs) are being used in many applications such as search or exploration, agriculture, and forest health monitoring [1] [2] [3]. Due to the advantages of hover capability, high maneuverability and decoupling between orientation and position, quadrotor with gimbal camera are eligible for nature environment 3D reconstruction and active surveillance in agriculture [4] [5].

The camera mounted on the quadrotor can fly over an area taking overlapped images, and these 2D images will used to 3D reconstruction. To speed up the 3D reconstruction and get a better reconstruction result, the camera path and perspective must satisfy some photogrammetric constraints, such as overlapping, constant distance for consistency resolution and normal orientation for orthophotograph. To satisfy the photogrammetric constraints, a lot of research have been done for finding the optimal path that can achieve complete coverage of the target area. This is known as coverage path planning(CPP) problem. However, the most research of CPP problem were based on using fixed-wing plane or quadrotor taking images in an 2D planar coverage surface, neglect constant distance and normal orientation for orthophotograph photogrammetric constraints.

In this paper, we focus on the CPP of nature environment 3D reconstruction under overlapping, constant distance and normal orientation for orthophotograph photogrammetric constraints. Firstly, The nature environment terrain was modeled by quasi uniform B-spline surface, the data points were from the the pre-measured digital terrain elevation data. Secondly, to reduce the consumption of time and energy, a modified back and force CPP method were used to cover the target area. We will calculate the optical scan direction, center points of camera footprints and air points those satisfy the photogrammetric constraints. Finally, the coverage path that consists of a set of smooth 3D curves variate with the 3D terrain will be derived.

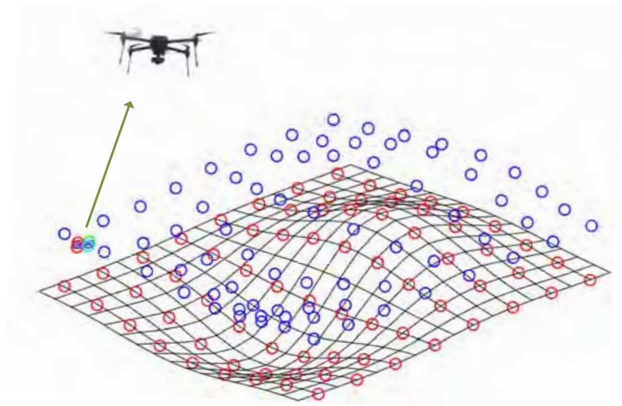

Fig. 1: The red points on the surface of nature environment is the center of flying cameras that satisfy the overlapping photogrammetric constraints, The blue points in the air derived from the red points can satisfy the constant distance and normal orientation photogrammetric constraints.

2 Related Work

Coverage Path Planning(CPP) is the task of determining a path that passes all points in a specific area while avoiding obstacles. Galceran and Carreras had done an excellent job for the survey on coverage path planning, in [6] they had reviewed the most successful CPP methods that made in the past decade such as cellular, grid-based, graph based, neural-network with online or off-line computation and for known and unknown areas.

Maza et al. proposed a terrain coverage algorithm that divided the target area taking into account UAV's relative capabilities and initial locations. Each subarea is assigned to a UAV which will cover it using a zigzag pattern to minimized

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the number of turns. The proposed algorithm has a low complexity, can operate in near-real time [7]. Huang [8] presented a time optimal line-sweep coverage path planning algorithm by decomposing the coverage region into subregions, selecting a sequence of those subregions, and generating a path that covers each subregion in turn by minimizing the number of turns in every subregion. Xu et al. presented an application of the optimal Morse based boustrophedon decomposition method for unmanned aerial vehicles [9]. Barrientos et al. proposed a one-phase automatic task partitioning manager for team of UAVs based on negotiation among the vehicles, considering their state and capabilities [10]. Santamaria et al. presented an algorithm for multiple heterogeneous UAVs with different sensors footprints [11]. Jimenez et al. proposed to use an genetic algorithm to achieve optimal coverage [12].

To get 2D images that used for terrain 3d reconstruction, Torres et al. proposed an algorithm by minimizing the number of turns and the total flight distance in both convex and non-convex regions to reduce the battery consumption. And they also proposed the coverage alternatives and the interrupted path concept to improve the line sweep path generation and the polygon decomposition problems [13]. Franco et al. proposed an energy-aware coverage path planning algorithm that not only considered the coverage area geometrical constraints but also the image resolution and the flying speed based on an energy model that derived from real measurements [14].

However, the purpose of the above algorithms is to find a path that covers all points of interest in 2D plane surface, not considering the 3D situations. An off-line approach for planning time-optimal trajectories for UAVs performing 3D urban structure coverage was presented by Cheng et al., they simplify the structure to be covered, named buildings, into hemispheres and cylinders. Then the 3D trajectories are planned to cover these simpler surfaces [15]. Li et al. considered the consistent resolution constraint and proposed an energy optimal coverage path planning algorithm that the UAV will coverage the terrain at an adaptive offset distance according to the terrain elevation [16].

3 Constraints and Modeling

In order to introduce our CPP method for UAVs in 3D nature environment under photogrammetric constraints, we first formulate two sections below:

3.1 Photogrammetric Constraints

In our 3D reconstruction work, the images that used for 3D reconstruction, must satisfy the following Photogrammetric Constraints:

Overlapping: Consecutive pictures should have a given percentage of overlapping, the percentage of overlap can be decided by users. The greater the overlap is, the higher the accuracy of the 3D model will be. It means that the footprint of the camera on the nature environment surface, should keep a desired percentage of overlapping in their length l and width w like Fig.2.

constant distance and normal orientation: The distance between the camera and the center of the camera footprint on the nature environment surface should have a constant distance. It will supply a consistent sensing resolution for the 3D reconstruction. And the orientation of the flying camera should be perpendicular to the the projection of the camera view on the smoothed 3D terrain surface.

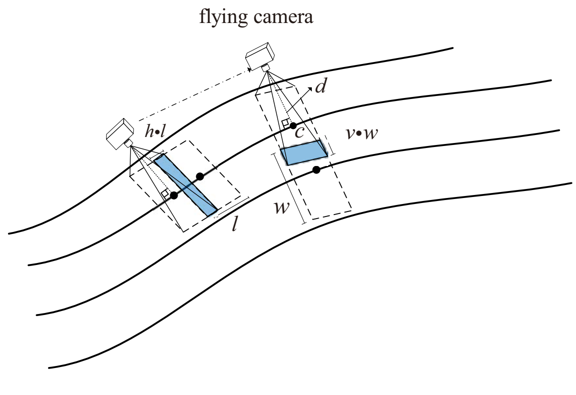

Fig. 2: The flying camera footprint on the nature environment surface. While h and v denote the overlapping percentage of the pictures in their length and width, c denote the center of the footprint, d is the constant distance photogrammetric constraints.

3.2 3D Terrain and Flying Camera Model

Under the above constant distance and normal orientation for orthophotograph constraints, as the Fig.2 shows, the footprint of camera on the surface is same. Then a quasi uniform B-spline surface can be used to formulate and smooth the three-dimensional terrain as follows:

$$S(u,v)=\sum_{i=0}^{m}\sum_{j=0}^{n}P_{ij}N_{i,p}(u)N_{j,q}(v) \tag{1}$$

while P_{ij} is the control point that comes from regular grid DEM date, the basis B-spline $N_{i,p}(u)$ and $N_{j,q}(v)$ can be derived by Cox de-Boor recursion formula.

$$\begin{cases} N_{i,0}(u)=\begin{cases} 1 \text{ if } \mathrm{u}_i \le u \le u_{i+1} \\ 0 \text{ others} \end{cases} \\ N_{i,k}(u)=\frac{u-u_i}{u_{i+k}-u_i}N_{i,k-1}(u)+\frac{u_{i+k+1}-u}{u_{i+k+1}-u_{i+1}}N_{i+1,k-1}(u) \\ define\frac{0}{0}=0 \end{cases} \tag{2}$$

We can use $S(x,y,z)$ to denote the 3D terrain surface, and $C(xs,ys,zs)$ is the center of the camera footprint that discrete distributed on the surface of the terrain. For every C point, there is a normal vector that is perpendicular to the camera footprint, along the normal vector for constant distance d, there is a point $O(xo,yo,zo)$ in the air that can satisfy all the Photogrammetric Constraints. Our purpose is to cover all the points $O(xo,yo,zo)$, and the camera orientation should point to the $C(xs,ys,zs)$and at every air point. The flying camera's yaw angle will follow the quadrotor, the camera's pitch α and roll β angle can be stable at the desired angle, which satisfy the normal orientation photograph constraint like Fig.3.

4 Coverage Path Planning

In order to cover all the air points $O(xo,yo,zo)$ that needed to be covered, the flow diagram of the coverage path planning algorithm is presented in Fig.4.

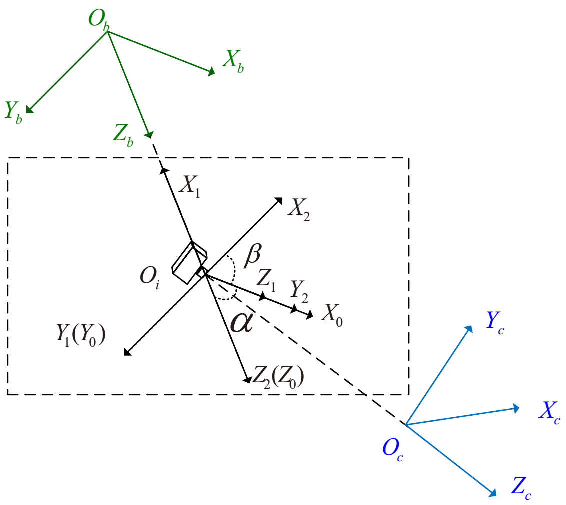

Fig. 3: Flying camera model consist of quadrotor body frame (green frame), gimbal camera frame (blue frame). Coordinate transformation in the dash box is the process that the camera rotate with a pitch angle α around Y and roll angle β around Z.

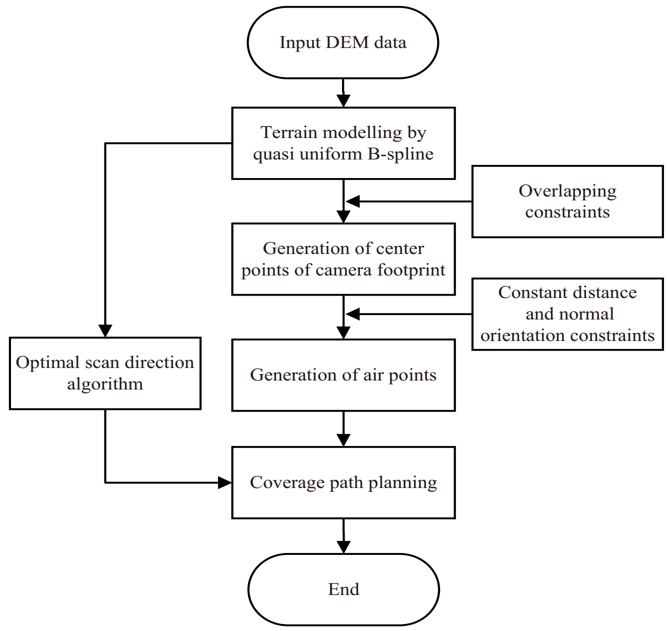

Fig. 4: The flow diagram of the coverage path planning algorithm.

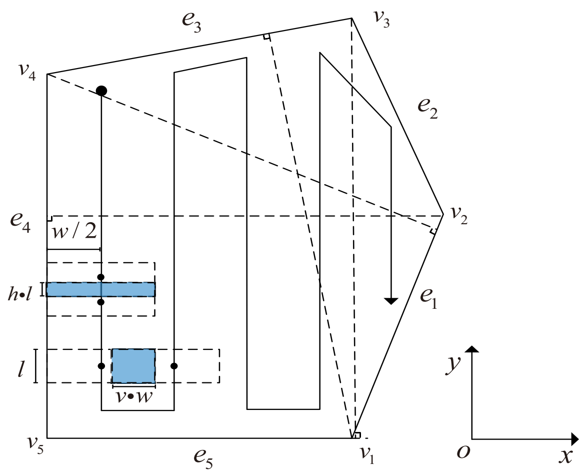

Fig. 5: The 2D polygon of the 3D terrain.

The back-and-forth algorithm creates a set of waypoints that can scan the entire area back-and-forth along one direction. As started in [8] the fuel consumption can be reduced by decreasing the number of turns. Also the number of turns during the survey impacts the time needed to accomplish the entire path since the UAV need to decelerate, turn and accelerate.

4.1 The Algorithm of Optimal Scan Direction

Usually the back-and-forth algorithm was used for the 2D coverage path planning, we can apply the back-and-forth algorithm to this 3D coverage path planning, except the altitude of UAV will change with the terrain variation. Firstly the 3D terrain was projected to the XOY 2D planar surface to form a polygon. The polygon was always a simple convex or concave polygon, since the area needed to be covered is often manually defined and we can assume that there are no obstacles.

For the convex polygon like Fig.5, an optimal scan direction can be selected to minimize the number of turns using the following Algorithm 1. In this example, the optimal scan direction is edge e_4 pointing to vertice v_2.

If the polygon to cover is no-convex, the no-convex polygon can be decomposed by the recursive greedy algorithm [17] or the heuristic algorithm [18].

4.2 The generation of the center of the camera footprint and air points

After the optimal scan direction was selected, the air points that satisfy photogrammetric constraints and coverage path can be generated by the following Algorithm.

As the Fig. 5 shows, we establish reference frame along the scan direction. Consider that the width of the camera footprint is much smaller than the *od distance*, the scan line can be computed by the 2D XOY projection of the nature environment.

1) Compute the number of lines n_1 that parallel to the *optimal edge*:
let $\Delta d = od\ distance - w/2$

$$n_1 = \begin{cases} \Delta d / w(1-v) & \Delta d \bmod w(1-v) \leq w/2 \\ \Delta d / w(1-v) + 1 & \Delta d \bmod w(1-v) > w/2 \end{cases} \tag{3}$$

while the scan lines can be denoted as:

$$\mathrm{xs}_i = \mathrm{xs}_0 + w/2 + (i-1)(w(1-v)) \quad i = 1, 2, 3, ..., n_1 \tag{4}$$

2) For every line, the altitude changing with the nature terrain, the length of curve line can be computed as:

$$S_i = \int_{zs_{i,0}}^{zs_{i,boundary}} \int_{ys_{i,0}}^{ys_{i,boundary}} dydz \tag{5}$$

while $ys_{i,0}$, $zs_{i,0}$ and $ys_{i,boundary}$, $ys_{i,boundary}$ is the

Algorithm 1 The algorithm of optimal scan direction

Input: The area needed to be covered $A = (v_1, v_2, ...v_n, e_1, e_2, ...e_n)$, while v and e denote the vertices and edges; $d_{\max} = 0$

Output: The optimal scan direction $od = (optimal\ edge, optimal\ vertice)$;

procedure OPTIMAL SCAN DIRECTION(A)
  for $e = 1; e <= n; e++$ **do**
    for $v = 1; v <= n; v++$ **do**
      Calculate the euclidean distance $d(e, v)$
      if $d_{\max} \leq d(e, v)$ **then**
        $d_{\max} = d(e, v)$
        $opposite\ vertice = v$
      end if
    end for
    if $e = 1$ **then**
      $od\ distance = d_{\max}$
    else
      if $d_{\max} <= od\ distance$ **then**
        $od\ distance = d_{\max}$
        $optimal\ edge = e$
        $optimal\ vertice = opposite\ vertice$
      end if
    end if
  end for
  return The optimal scan direction $od = (optimal\ edge, optimal\ vertice)$
end procedure

two boundary point of the n_i line. In every curve line the center of the camera footprint can be get at intervals of hl. The number of center of the camera footprint in every curve can be computed as :

$$n_2 = \begin{cases} (S_i - l/2)/hl & (S_i - l/2) \mod hl \leq l/2 \\ (S_i - l/2)/hl & (S_i - l/2) \mod hl > l/2 \end{cases} \tag{6}$$

3) The air points can be denoted as:

$$(xo_i, yo_{i,j}, zo_{i,j}) = (xs_i, ys_{i,j}, zs_{i,j}) + d\nabla F(xs_i, ys_{i,j}, zs_{i,j}) \tag{7}$$

while $i = 1, 2, 3, ..., n_1$, $j = 1, 2, 3, ..., n_2$, d denote the constant distance photogrammetric constraints, $\nabla F(xs_i, ys_{i,j}, zs_{i,j})$ denote the unit normal vector of every center of camera footprint. $\nabla F(xs_i, ys_{i,j}, zs_{i,j})$ can be derived by the cross product.

4) At every air point,the orientation of the flying camera can be denoted as following pitch and roll angular : pitch angular:

$$\alpha_{i,j} = \arctan \frac{\nabla F | zs_{i,j}}{\nabla F | xs_i} \tag{8}$$

roll angular:

$$\beta_{i,j} = \arctan \frac{\nabla F | zs_{i,j}}{\nabla F | ys_{i,j}} \tag{9}$$

while ∇F is the logogram of $\nabla F(xs_i, ys_{i,j}, zs_{i,j})$.

4.3 Path planning

Now all the air points and the orientation of flying camera can be denote as $p_{i,j}(xs_i, ys_{i,j}, zs_{i,j}, \alpha_{i,j}, \beta_{i,j})$. Every scan path can be denoted as $\gamma_i = \{p_{i,1}, p_{i,2}...p_{i,j}\}$, while one curve of the coverage path can be seen as Fig.6. For the back-and-forth coverage approach the full coverage path can be denoted as $\gamma = \{\gamma_1, \gamma_2...\gamma_i\}$.

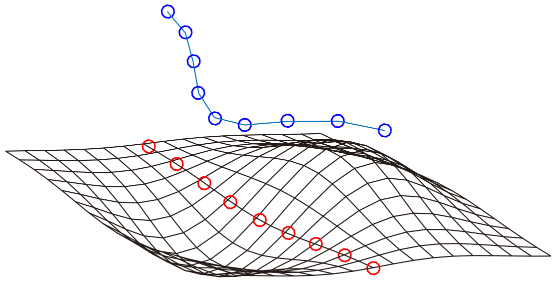

Fig. 6: The red point is the center of the camera footprint, the blue point is the air points that corresponding to the red point through photograph constraints. The curve of the connection of blue points is the back-and-forth coverage path.

Fig. 7: Flight platform

5 Experiment

In this paper, a self-stability gimbal camera was mounted on the quadrotor, the gimbal use a PID controller and can communicate with the Pixhawk flight controller board (with the ardupilot v3.4 firmware) through MAVlink communicate protocol. In the world coordinates, the position of flying camera is same to the quadrotor neglect the installation error, the camera orientation can be controled through flight controller board to desired angular, so the whole system can be seen as flying camera. The UAV flight data and gimbal data can be get from the dataflash log, the whole flight platform is as shown in Fig.7.

The environment that needed to be coveraged was shown in Fig.8, in this experiment we use the total station to get 116 DEM datas. The 3D terrain was modeled by quasi uniform B-spline as shown in Fig.9. The overlap was set as $h = 0.356$, $v = 0.5$ and the constant distance $d = 15$. Using our coverage path planning method, we can get 269 air points and gimbal angle, the coverage path form and gimbal angle that satisfy all the photogrammetric constraints above can be generated. The coverage path can be seen in Fig.10. The experiment result can be shown in Fig.11 and Fig.12.

Fig. 8: The environment needed to be coveraged. The left picture is realistic picture of the 3D environment terrain, the right picture is the polygon that manually defined need to be coverged.

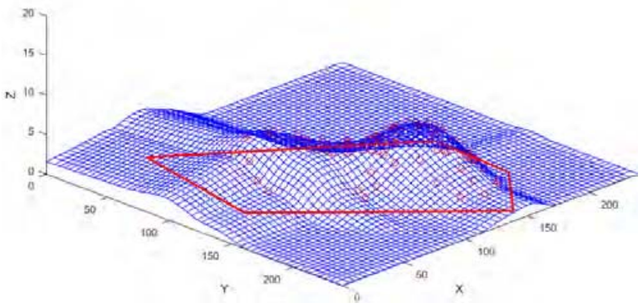

Fig. 9: The 3D terrain modeled by quasi uniform B-spline. The polygon is the area needed to be coveraged and the red point is the DEM data.

These results show that, through our coverage path planning method and the flight platform, we can get the images that satisfy the overlapping, constant distance and normal orientation photogrammetric constraints.

6 Conclusion

In this paper, a quasi uniform B-spline surface was used to modelling the 3D environment terrain, besides the overlapping photogrammetric constraint, the constant distance and normal orientation photogrammetric constraints were presented to get a better 3D reconstruction result. Then a modified back-and-forth 3D coverage path planning method for

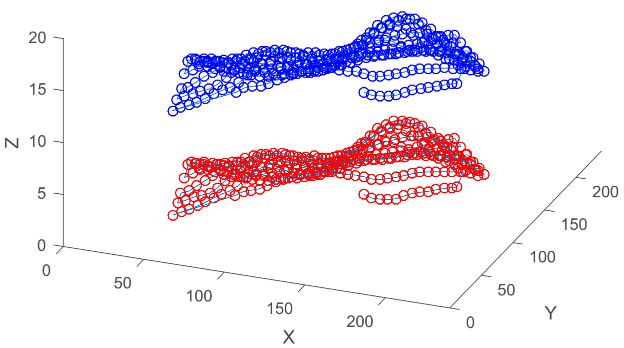

Fig. 10: The red points is the center of the camera footprint, and the blue points is the air points that derived from our 3D coverage path planning method.

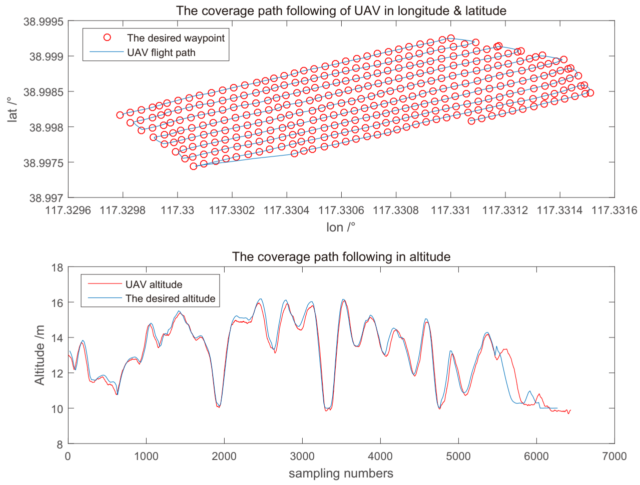

Fig. 11: The coverage path following of UAV. From the above result, it showed that the UAV can reach the desired waypoint.

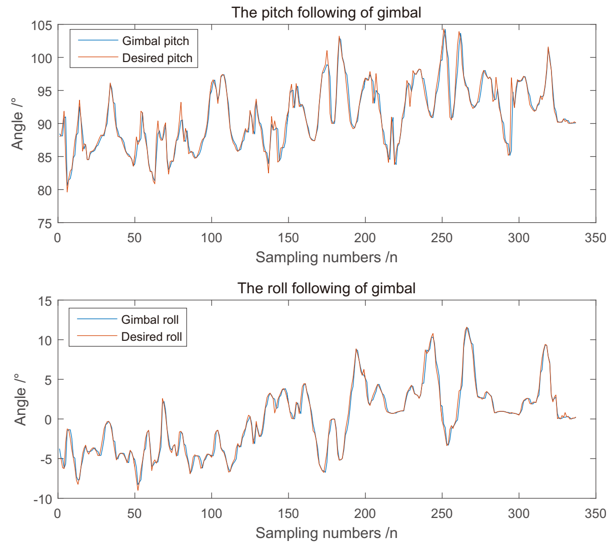

Fig. 12: The angle following of gimbal, in every waypoint the gimbal can reach the desired pitch and roll angle.

quadrotor with gimbal camera was presented, and the experiment results have showed that, our method can get the desired images that satisfy all the three photogrammetric constraints.

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