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Real-time Trajectory Planning for Autonomous Parafoil in Obstacle-Rich Environment

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Abstract—**Parafoil system is suitable for large-area and long-time surveillance and airdrop missions and has the advantages of simple structure, low cost and high load capacity. The system is utilized for delivery mission in open area, where there is no obstacles or few obstacles. After released from the airplane, the system performs a classical three-phases landing strategy consisting of homing, energy management and terminal landing. This paper utilizes the classical guidance framework and presents a revised method of terminal landing using Bezier curves to solve obstacles avoidance problems in obstacle rich environment for parafoil system. With the definition of Bezier curve and cost function, the terminal landing path generation problem is converted to an optimization problem and is solved using nonlinear optimizer. To deal with different environments, a terminal landing strategy is developed. The simulation results show its effectiveness on parafoil system terminal path planning.**

Keywords—parafoil system; trajectory planning; obstacle avoidance; Bezier curve; three-phases landing; terminal landing

I. INTRODUCTION

A. Introduction of Parafoil System

Parafoil system is a small unpowered equipment, which is widely utilized in precision delivery missions. It provides a unique capability for air-transport of heave payloads according to the high payload-weight-ratio [1]. The system is compact before parafoil deployment and lightweight, and it flies at low speed and impacts the ground with low velocity. Parafoil system is often considered to be safer than normal fixed-wing aircraft because of its inherent stability, limited response to control inputs, and stall resistance [2]. All of the above advantages make it a suitable platform for field investigations, search and rescue, and delivery [3].

However, parafoil has the characteristics of complexity, uncertainty, nonlinearity, time-varying, control delay and large inertia, and is easily affected by the atmospheric environment [4]. The system is strongly influenced by apparent mass because of its light weight [5]. A unique feature of parafoil system is the high degree of variability of flight dynamic, which make its practical applications be a great challenge [6].

B. Control mechanism

The general control mechanism for parafoil is left and right brake deflection. The asymmetric deflection of left or right brake makes parafoil system to turn. Deployment of the right brake causes a significant drag rise and a small lift rise on the right side of the canopy with slight right tilt. The above effects cause the system to turn right when a right brake is deployed [7].

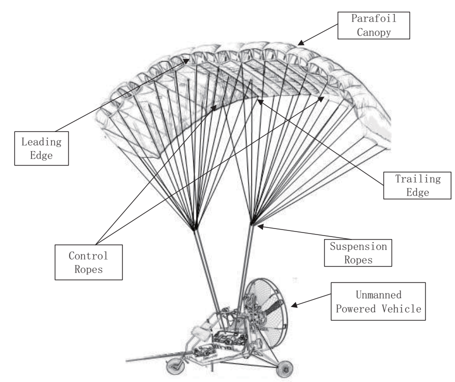

Fig. 1 Structure of parafoil system

The platform we built has the engine to provide thrust to get the system off the ground and the engine is switched off to perform precision landing. The structure of the system is shown in Fig. 1.

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C. Guidance strategy

Guidance strategies for different parafoils delivery missions may vary significantly based on the purposes, but most parafoil systems follow the same procedure, which is called three-phases landing [8] to ensure safety and accuracy. After being released from an airplane, the system inflates and go directly to the destination; then the system starts to circle until the altitude is below a specified value; finally terminal landing will be implemented to make the system upwind. As to terminal landing, several ways of planning a trajectory is realized. Turning upwind and then perform a final flare maneuver is the most common strategy for terminal landing. To reduce the landing error, smooth trajectory generation based on Bezier curves [9] and “T-approach” [10] were developed. There are some other guidance strategy developed in high wind conditions [11-14]. All these methods take wind disturbances into account but neglect the obstacles which are very common in urban areas.

This paper presents a method of terminal landing using Bezier curves to solve obstacles avoidance problems for parafoil system. In Sec. II the three-phases landing strategy is presented to accomplish long-distance delivery missions. Definitions of Bezier curve and cost function and terminal landing strategy are given to solve obstacle avoidance problem in obstacle rich environment in Sec. III. Simulation results in Sec. IV shows the effectiveness of the method. The paper ends with conclusions and recommendations for the future development.

II. THREE-PHASES LANDING

For non-powered parafoil system, the glide ratio can be considered constant [15] and we can design a desired path for parafoil system and finally deal with the landing error, which is caused by wind disturbance and other uncertainty, by revising the desired terminal landing path. The three-phases landing strategy consists of homing, energy management and terminal landing as shown in Fig. 2. While dropped with a long distance from the destination, the unpowered parafoil system tends to approach the terminal point in xy-frame, called homing. After the system enters the cone, energy management will be utilized to reduce the height preparing for the final landing. Finally, terminal guidance will perform to ensure landing accuracy and the desired heading angle.

Homing can be achieved by simply following the line from the release point(R) to the middle point(M). Then circling or “T-approach” method [16] can be applied during the phase of energy management. Finally, terminal guidance to the target(T) using Bezier curves is used to achieve minimal landing error, desired heading angle and obstacles avoidance.

III. TERMINAL LANDING

A. Bezier curve definition

A cubic Bezier curve is defined by a starting point, a terminal point and two control points. In parafoil terminal guidance scenario, Bezier curves are utilized to provide a smooth path from an initial position to the destination upwind.

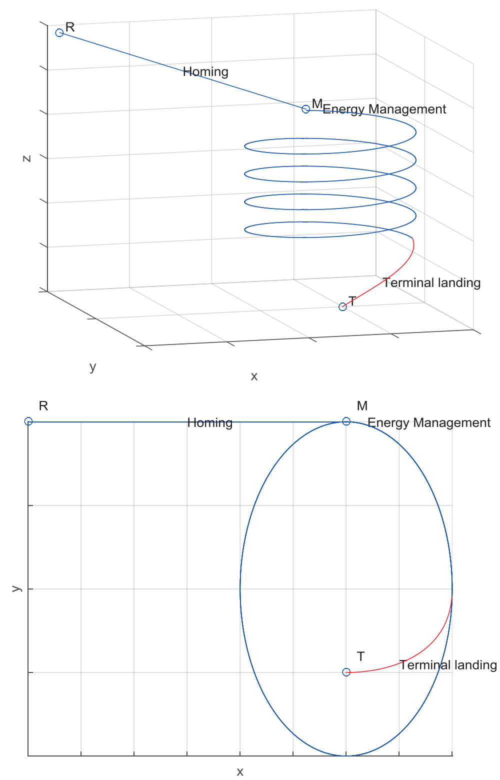


Fig. 2 Three-phases landing

Comparing with a quadratic Bezier curve, which has a single control point, a cubic Bezier curve has two control points and thus is able to guarantee the initial and terminal heading angles. Given initial position $b_0(x_1, y_1)$, terminal position b_2 (x_2, y_2) and two control points c_1 (x_1^*, y_1^*) and c_2 (x_2^*, y_2^*), a cubic Bezier curve can be defined as follows:

$$x = a_x\tau^3 + b_x\tau^2 + c_x\tau + x_1 \tag{1}$$

$$y = a_y\tau^3 + b_y\tau^2 + c_y\tau + y_1 \tag{2}$$

Where $\tau \in [0,1]$ is the parameter that describes the position of a point on the Bezier curve ($\tau = 0$ stands for initial position and $\tau = 1$ stands for the terminal position). The coefficients in Eq. (1) and Eq. (2) are given as follows:

$$a_y = y_2 - y_1 - c_y - b_y \tag{3}$$

$$c_x = 3\left(x_1^* - x_1\right) \tag{4}$$

$$b_x = 3\left(x_2^* - x_1^*\right) - c_x \tag{5}$$

$$a_x = x_2 - x_1 - c_x - b_x \tag{6}$$

$$c_y = 3\left(y_1^* - y_1\right) \tag{7}$$

$$b_y = 3\left(y_2^* - y_1^*\right) - c_y \tag{8}$$

Fig. 3 shows an example of single cubic Bezier curve. Using all the coefficients given above, we can draw some conclusions of a cubic Bezier curve $B(\text{t})$ that: 1) $B(0) = \text{b}_1$, 2) $B(1) = \text{b}_2$, 3) $B'(0) = 3(\text{c}_1 - \text{b}_0)$ and $B'(1) = 3(b_2 - c_2)$. These properties make Bezier curve proper for parafoil terminal guidance and the detailed description can be found in [9].

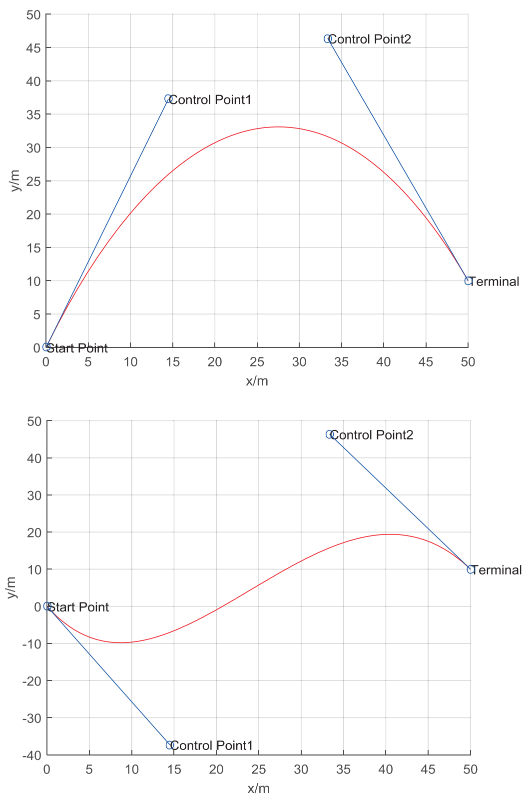


Fig. 3 Single cubic Bezier curve

B. Cost function definition

Three-phases guidance method is usually effective for delivery mission and Bezier-curve based terminal guidance is utilized to reduce landing error while satisfying the physical limitation of turning rate in an open environment, which means no obstacles are taken into account. However, there are usually obstacles where parafoil systems are expected to land for delivery missions. Terminal guidance using Bezier curves gives it a way to produce smooth path for parafoil system to follow directly, instead of using path planning method to gain desired positions and then path smoothing method to make the trajectory able to be followed.

A cubic Bezier curve is determined by the position of two control points ($c_1(\text{x}_1^*, \text{y}_1^*)$ and $c_2(\text{x}_2^*, \text{y}_2^*)$), which corresponds to four parameters $(\text{x}_1^*, \text{y}_1^*, \text{x}_2^*, \text{y}_2^*)$. Given the constraint of initial and terminal heading angles, the number of undetermined parameters is reduced to two. The distance (d_1) between the starting point(S) and c_1 and the distance (d_2) between c_2 and target (T) can be calculated by minimizing the cost function.

In [7], Bezier curves are designed to give smooth trajectory for parafoil to follow in windy conditions. In our research, area description is introduced to the cost function to conquer obstacle avoidance problems as shown in Fig. 4. Occupied area (OA) is the revised building area by taking the size of parafoil into account, Warning area (WA) is the area where the parafoil is not colliding with the obstacle but may crash later with wind disturbance and other uncertainty.

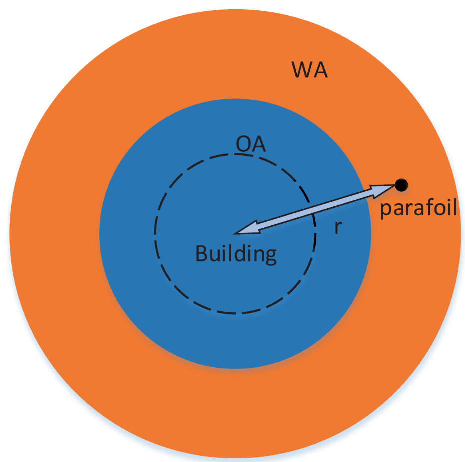


Fig. 3 Area description for parafoil obstacles avoidance

We define the collision cost function as

$$J_{collision} = \begin{cases} C, \text{if } P \in OA \\ \dfrac{k_{safe}}{r}, \text{if } P \in WA \\ 0, \text{otherwise} \end{cases} \tag{9}$$

where r is the distance between the parafoil's position and center of the obstacle, k_{safe} is the corresponding coefficient which can be selected manually.

Given the constraints of a real platform, the whole cost function is presented as

$$J = k_z * z_{error} + k_{ya} * \sum_{i=1}^{N} \ddot{\psi}_i + k_{obs} * \sum_{j=1}^{M} J^{(j)}{}_{collision} \tag{10}$$

where z_{error} is the error between predicted parafoil landing altitude and the real landing altitude, $\ddot{\psi}_i$ is the discretized acceleration of heading angle and $J^{(j)}{}_{collision}$ is the cost of collision with the jth obstacle. k_z , k_{ya} and k_{obs} are the coefficients, which can be selected manually.

In simple environments, where there are no obstacles or a few of obstacles, one cubic Bezier curve is adequate; but in obstacle-rich environments, two or more Bezier curves are required. Compared with a path with single cubic Bezier curve, a path with two Bezier curves, as show in Fig. 5, has four control points and a Middle Point (MP), which leads to three additional parameters – d_3 (distance between MP and Control Point3), d_4 (distance between T and Control Point4) and the position of MP. A feasible solution can be obtained by minimizing the cost function defined as

$$J = k_z * z_{error} + k_{ya} * \sum_{i=1}^{N} \ddot{\psi}_i + k_{obs} * \sum_{j=1}^{M} J^{(j)}{}_{collision} + k_m * d_{mid} + k_p * \| d_3 - d_2 \| \tag{11}$$

where d_{mid} is the distance between MP and target (T) and is introduced to the cost function to ensure that the derived middle point is close to the target. $\| d_3 - d_2 \|$ is utilized to ensure the minimal heading angle acceleration in MP. k_m and k_{obs} are the corresponding coefficients.

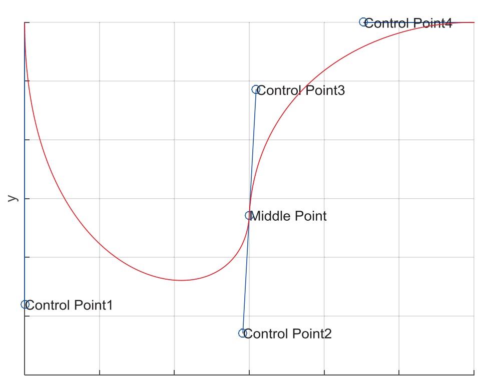


Fig. 5 Guidance path with two Bezier curves

Multi-layer planning method is introduced to find the proper number of curves and initial values of the parameters. Path with single cubic Bezier curve is capable of obstacle avoidance in simple environments, where there is no or few obstacles. But in obstacle rich environments, path with two Bezier curves is required. Given the realizability of nonlinear optimization, paths with three or more Bezier curves are not utilized.

C. Terminal landing strategy

A terminal path is obtained after solving the nonlinear optimization problem, as presented in Fig. 6. After entering terminal landing phase, a cubic Bezier curve will be utilized to try to obtain a feasible path in which the cost is below a specified value. If the criteria is not met, path with two Bezier curves will be selected and the initial values of the parameters can be modified to make the nonlinear optimizer converge.

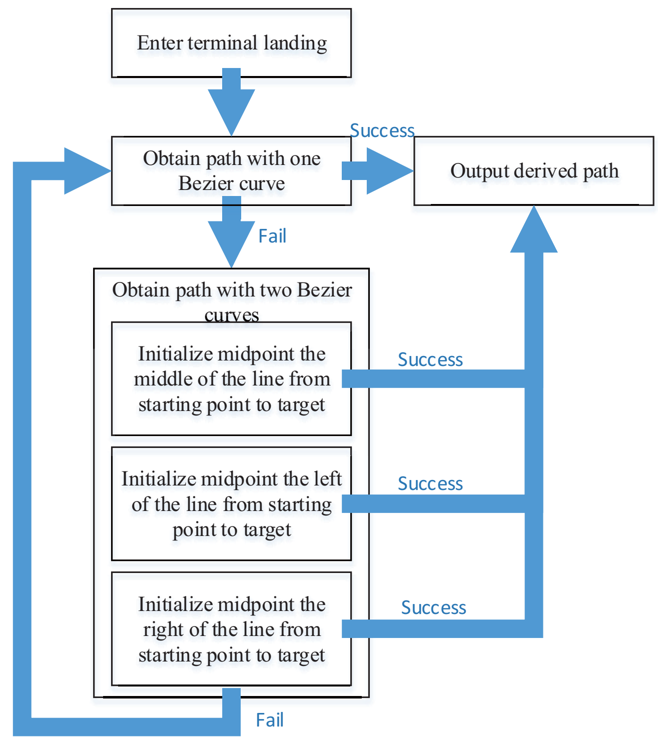


Fig. 6 Terminal landing strategy

VI. Simulation Results

The performance of proposed terminal landing planning method is demonstrated through three simulation tests: (1) path with single cubic Bezier curve is capable to conquer the obstacles avoidance problem in simple environment; (2) initial values of the parameters of the cost function can be selected manually and will determine the geometric characteristics of the path; (3) in obstacle rich environment, a feasible path will be given by the terminal landing strategy, which will produce a path with two Bezier curves by selecting the initial parameters values and changing the initial position of midpoint for optimization process to make the nonlinear optimizer converge to a specified cost value.

A. simple environment

In this test, the initial altitude is 150 m when parafoil enters the terminal landing phase. The vertical velocity of parafoil system is assigned to 1.76m/s according to the real flight test. We assign the starting point (-300m, 0m) and terminal point

(0m, 0m). The centers of two obstacles are chosen (-250m, -60m) and (-80m, -150m) respectively and the radius chosen 20m. A feasible path, as shown in Fig. 7, is obtained with $C = 20$, $k_{safe} = 20$, $k_z = 1$, $k_{obs} = 0.02$ and $k_{ya} = 0.01$.

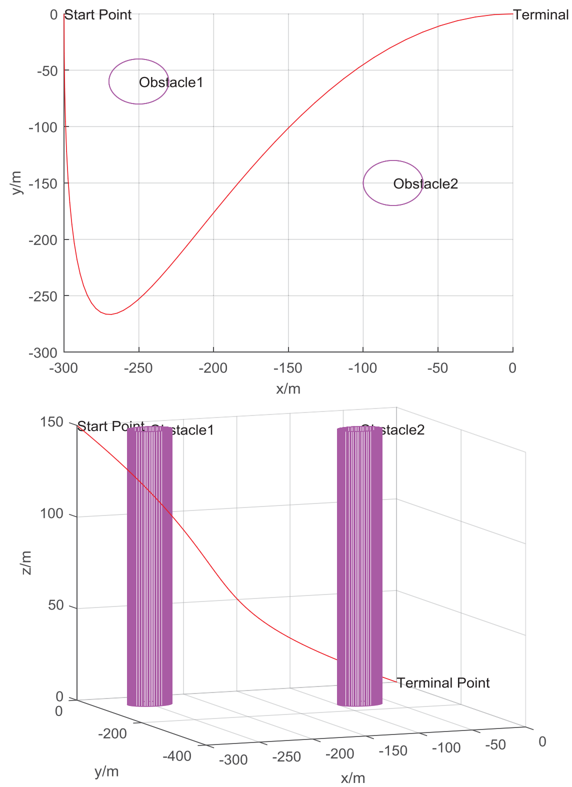
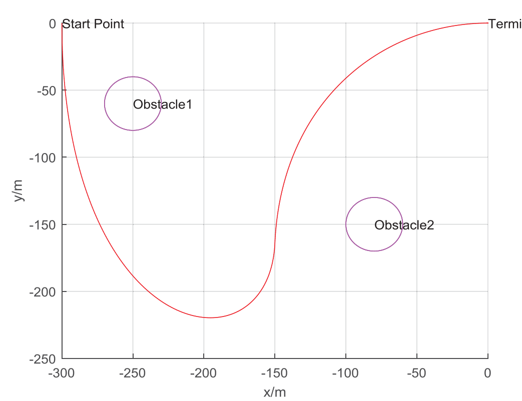


Fig. 7 Simulation result

B. *discuss of the parameters selection*

The coefficients can be modified to gain a smoother path, as shown in Fig. 8, by assigning the coefficient value $k_{ya} = 1$. We can also fine-tune other coefficients to achieve less altitude error, larger distance between the path and the obstacles, etc.



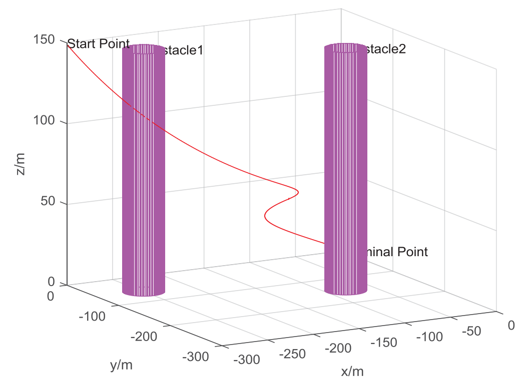


Fig. 8 Simulation result

C. *obstacle-rich environment*

In an obstacle rich environment, path with single Bezier curve is not able to be derived by optimizing the cost function. Fig. 9 gives the test with three obstacles and a path with two Bezier curves is obtained. The center of the third obstacle is chosen (-120m, -50m) and the radius chosen 25m.

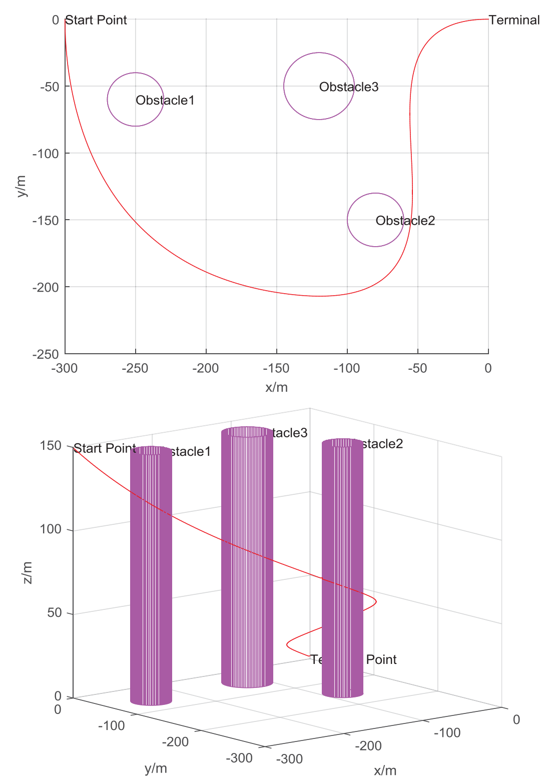


Fig. 9 Simulation result

Our previous work focuses on parafoil system modeling and controller design [17] and the derived path is also integrated into our simulation model in SIMULINK. The simulation model is modified to present non-powered parafoil characteristics by assigning inputs of thrust and symmetric brake to zeros. The result is shown in Fig. 10, which shows the dynamic constraints are satisfied and the path is feasible for practical utilization.

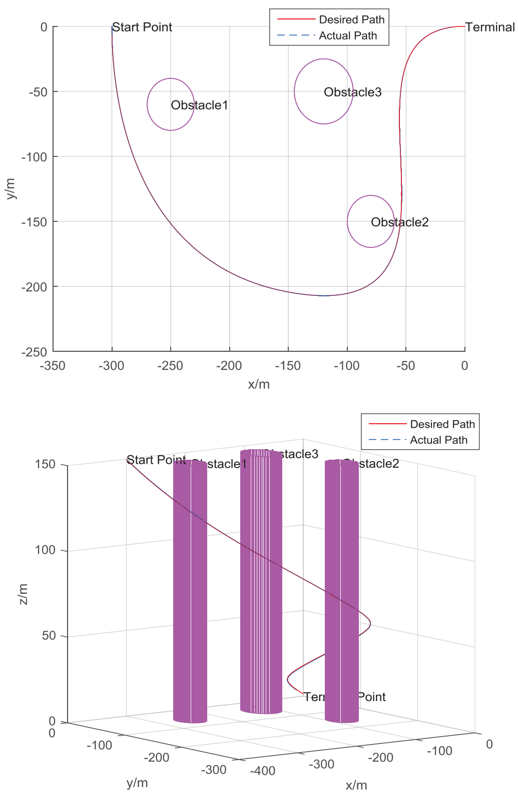


Fig. 10 Actual result of trajectory following in SIMULINK

VII. CONCLUSION AND FUTURE WORK

This paper presents a completed method of parafoil landing with terminal landing using Bezier curves to solve obstacles avoidance problems for parafoil system. Definitions of Bezier curve are given, which converts the trajectory generation problem into an optimization problem. We then present the cost functions while taking the limitation of real parafoil system and feasibility of the curves into account. Then the terminal landing strategy is utilized to deal with different environments. The simulation results shown its effectiveness of the method, which can be applied in obstacle rich environment while taking max heading angle acceleration and landing altitude error into account. As an important future work, cost function definition would be revised to add the influence of wind disturbance and some other physical limitations and practical test would be carried out to verify the method.

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