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Design for Guidance Method of UAV Autonomous Landing on Mobile Platform Based on Prediction of Intersection Points

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Abstract. The development of the technology for UAVs (Unmanned Aerial Vehicle) autonomous landing on mobile platform is introduced in this article. And the existing problems of UAVs autonomous landing on mobile platforms are also analysed. In order to solve these problems, a guidance method of UAV autonomous landing on mobile platform based on prediction of intersection points is proposed in this paper. In this method, the intersection point of the trajectory of UAV and the trajectory of the mobile platform is predicted based on the speed plan for UAV and the motion state of mobile platform. Then, the UAV will be guided to the intersection point by proportional guidance law. And at each time of the landing of the UAV, the location of the intersection point will be corrected in real time. In order to verify this method, a mathematical simulation experiment was designed. The result of this experiment shows that UAVs are able to land more accurately on the mobile platform with less overload using this method.

1. Introduction

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In Modern Warfare, the UAV is playing an increasingly important role in both land and naval battlefields. The landing stage of UAV is the last stage of the whole flight process, which determines the success of UAV recovery. At present, the way of UAV recovery includes landing gear recovery, net-catch-landing recovery and parachute recovery[1]. Landing gear recovery is suitable for landing platforms with relatively long runways, such as aircraft carriers or other large surface ships[2]; parachute recovery often makes it difficult to control the falling points of UAVs[3]. The net-catch-landing recovery method is more suitable for mobile platforms which have the need to recover UAVs but have no relatively long landing runway, such as small surface ships and land vehicles[4].

Small surface ships and ground vehicles have relatively great maneuverability, which is difficult for UAVs to land on it automatically. Because, if the platform has too much maneuverability, the UAV which need to land on it has to generate greater normal acceleration to intersect the platform. However, limited by many factors, such as aerodynamic shape, flight speed or structural strength of airframe, the normal acceleration the UAVs generating is limited. If the normal acceleration needed by UAV during landing is less than the maximum normal acceleration it can produce, it may lead to UAV recovery failure[5].

However, If the platform is not mobile, it will increase the possibility of platform being under attack, which reduces the viability of platforms and UAVs on the battlefield. Therefore, it is necessary to design a guidance method which can make the UAV landing successfully even when the platform maneuver amplitude is large[6].



2. The realization principle of guidance method

In order to solve the problem of UAV autonomous landing on mobile platforms with relatively great maneuverability, a guidance method for UAV autonomous landing based on prediction of intersection point is presented in this paper. In this method, the time-to-go of UAVs landing is calculated by dichotomy, and the data base of this calculation is the velocity variation law of UAV in landing phase set in advance and the motion state of mobile platform calculated by GPS data. Based on the time-to-go, the location of the intersection point of the trajectory of UAV and the trajectory of the moving platform can be predicted. Then, the UAV will be guided by the proportional guidance method to the intersection point. Because of the influence of wind, air temperature, engine parameters and other factors, it is impossible for UAV to fly completely according to the preset velocity variation law in the landing process[7]. Therefore, in each control cycle of the flight process, the velocity variation law of UAV will be modified according to the UAV's flight speed at this control cycle measured by GPS and the UAV's acceleration at this control cycle measured by INS. Due to the velocity variation law of UAV being modified, the time-to-go of the UAV's landing process and the location of the intersection point are also modified at each control cycle. At a time the location of the intersection point modified, the UAV will be guided to the modified intersection point until it successfully lands on the mobile platform. The implementation of the method is as follows.

2.1. Guidance method for UAVs autonomous landing

The implementation of the method is based on the following three hypotheses:

Firstly, the recovery method of UAV is net-catch-landing recovery, that is, as long as the UAV can intersect the mobile platform, it is considered that the UAV lands on the mobile platform successfully, and the attitude angle of UAV landing is not required;

Secondly, the motion form of mobile platform is uniform acceleration motion.

Last, it is considered that the GPS data and the INS data obtained by UAV are accurate, that is, the GPS positioning and velocity measurement errors and the acceleration measurement errors of inertial devices are neglected.

The relative motion of UAV and platform is discussed only in the vertical plane in this paper. First, spatial coordinate system of UAV and mobile platform has to be established. Take the position of UAV to enter the landing phase as the origin of coordinates. Take the plumb line at the origin of the coordinate system as the Y axis, and the positive direction of it is pointing upward. The X axis and the Y axis are in the same vertical plane, and the X axis is perpendicular to the Y axis. The positive direction of the X axis is pointing to the direction of the mobile platform. The schematic diagram of the coordinate system is shown in Figure 1.

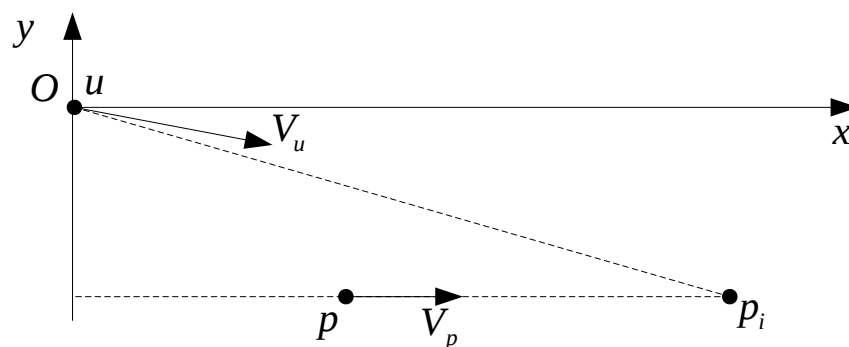


Figure 1. The schematic diagram of the coordinate system.

In Figure 1, point u represents the position of the UAV, point p represents the position of the mobile platform, point p_i represents the position of the predicted intersection point, vector V_u represents the speed of the UAV, vector V_p represents the speed of the mobile platform.

The dynamic model of UAV moving in the vertical plane is shown in Formula 1^[8].

$$\begin{cases} \frac{dV_u}{dt} = \frac{F_T \cos \alpha - F_D}{m_u} - g \sin \theta_u \\ \frac{d\theta_u}{dt} = \frac{F_T \sin \alpha + F_L}{m_u V_u} - \frac{g \cos \theta_u}{V_u} \\ \frac{dx_u}{dt} = V_u \cos \theta_u \\ \frac{dy_u}{dt} = V_u \sin \theta_u \end{cases} \quad (1)$$

In Formula 1, g represents the acceleration of gravity, x_u and y_u respectively represents the position of UAV in the coordinate system, m_u represents the mass of the UAV, θ_u represents the trajectory inclination angle of the UAV, F_T represents the thrust of UAV's engine, F_D and F_L respectively represents the drag force and the lift force that air acts on the UAV, α represents the angle of attack of the UAV and it is the variable which controls the UAV.

The α can be calculated through the normal acceleration required of during the UAV landing. Set N_r as the normal acceleration required of during the UAV landing, and set N_a as the normal acceleration that the UAV generates during the landing process. The expression of N_a is shown in Formula 2.

$$N_a = \frac{F_T \sin \alpha + F_L}{m_u} - g \cos \theta_u \quad (2)$$

In Formula 2, F_L can be expressed as a function related to α , the expression of F_L is shown in Formula 3[9].

$$F_L = \frac{1}{2} \rho V_u^2 S C_L(\alpha) \quad (3)$$

In Formula 3, ρ represents air density, S represents the reference area of the UVA, $C_L(\alpha)$ represents Lift coefficient related to α . Therefore, N_a can be expressed as a function related to α . The condition for effective and successful control of UAV is that the normal acceleration required of during the UAV landing is equal to the normal acceleration that the UAV actually generates during the landing process. The condition can be expressed as which the Formula 4 shows.

$$N_r = N_a = \frac{F_T \sin \alpha + \frac{1}{2} \rho V_u^2 S C_L(\alpha)}{m_u} - g \cos \theta_u \quad (4)$$

From the above analysis, it can be found that the essence of the UAV landing process control is to design the variation law of normal acceleration required of during the UAV landing, which is the innovation of this article. in this paper, the guidance law of UAV landing phase is proportional navigation method. In the theory of proportional navigation method, N_r can be expressed as:

$$N_r = V_u K \dot{q} \quad (5)$$

In Formula 5, K represents the proportional coefficient of proportional guidance method for UAV landing, $\dot{q}$ represents the rate of change of sight angle between the UAV and the target. Notably, in this article, the target is not the mobile platform, but to the predicted intersection point of the trajectory of UAV and the trajectory of the mobile platform. The predicted intersection point can be calculated by the following procedure.

Set the initial location of the mobile platform is (x_{p0}, y_{p0}) , the initial velocity of the mobile platform is (V_{xp0}, V_{yp0}) , the acceleration of the mobile platform is (a_x, a_y) . The motion state of the mobile platform can be expressed as the Formula 6.

$$\begin{cases} V_{xp}(t) = V_{xp0} + a_x \cdot t \\ V_{yp}(t) = V_{yp0} + a_y \cdot t \\ x_p(t) = x_{p0} + \int_0^t V_{xp}(t) dt \\ y_p(t) = y_{p0} + \int_0^t V_{yp}(t) dt \end{cases} \quad (6)$$

Set the velocity variation law of UAV is $\hat{V}_u(t)$. Therefore, the flight distance of UAV during landing can be expressed as the Formula 7.

$$\hat{R}_u(t) = \int_0^t \hat{V}_u(t) dt \quad (7)$$

In order to calculate the location of the intersection point, the time-to-go of UAV intersecting the mobile platform must be calculated. Set that t_{go} represents the time-to-go of UAV intersecting the mobile platform. At t time, t_{go} can be obtained by solving equations shown in Formula 8.

$$\hat{R}_u(t + t_{go}) = (x_p^2(t + t_{go}) + y_p^2(t + t_{go}))^{1/2} \quad (8)$$

Therefore, At t time, the location of the intersection point can be calculated by the following formula.

$$\begin{cases} x_{pi} = x_p(t + t_{go}) \\ y_{pi} = y_p(t + t_{go}) \end{cases} \quad (9)$$

Set q as the sight angle between the UAV and the intersection point and it can be expressed as the Formula 10.

$$q = \arctan \frac{y_u - y_{pi}}{x_u - x_{pi}} \quad (10)$$

The rate of change of sight angle between the UAV and the intersection point can be calculated by doing differential calculus for formula 10. Set the rate of change of sight angle in the k control cycle as $\dot{q}_k$, the time span of each control cycle is T , so $\dot{q}_k$ can be calculated as the Formula 11.

$$\dot{q}_k = \frac{q_k - q_{k-1}}{T} \quad (11)$$

Introduce Formula 11 into Formula 5, the expression of the normal acceleration required in the k control cycle can be obtained.

2.2. Correction method of velocity variation law

Mentioned at the beginning of this section, it is impossible for UAV to fly completely according to the preset velocity variation law in the landing process and the velocity variation law has to be modified in each control cycle.

Set the velocity of the UAV measured by GPS in the k control cycle is V_{um}^k , the tangential acceleration of the UAV measured by GPS in the k control cycle is a_{um}^k . According to the preset velocity variation law, the preset velocity of the UAV in the k control cycle is $\hat{V}_u^k$. The preset tangential acceleration of the UAV is expressed as $\hat{a}_u^k$ and it can be obtained by doing differential calculus for $\hat{V}_u(t)$. In the k control cycle, the deviation between the actual velocity and tangential acceleration of the UAV and their preset values can be expressed as ΔV_u^k and Δa_u^k . Their expression is shown as Formula 12.

$$\begin{cases} \Delta V_u^k = V_{um}^k - \hat{V}_u^k \\ \Delta a_u^k = a_{um}^k - \hat{a}_u^k \end{cases} \quad (12)$$

The velocity variation law of the UAV can be modified based on ΔV_k and Δa_k . The modified correction rule is shown as Formula 13.

$$\begin{cases} \hat{V}_u(t) = \hat{V}_u(t) + \Delta V_u^k & (\text{if } \Delta a_u^k = 0) \\ \hat{V}_u(t) = \hat{V}_u(t) + \Delta V_u^k + \Delta a_u^k \cdot t & (\text{if } \Delta a_u^k \neq 0) \end{cases} \quad (13)$$

Introduce the modified velocity variation law into Formula 7, and calculate the time-to-go and the location of the intersection point based on this.

3. Numerical simulation

In order to verify the rationality of the guidance method proposed in this article, numerical simulation experiment is designed. The numerical simulation parameters are shown in Table 1 and Table 2.

Table 1. Parameters of the UAV.

Parameters	Values
Initial velocity	200m/s
Initial trajectory inclination angle	0 °
Initial location	(0 m, 0 m)
Mass	18 kg
Thrust	30 N
Reference area	0.0087 m ²
Lift coefficient	$C_L(\alpha) = 1.28 * \alpha$
Drag coefficient	$C_D(\alpha) = 0.186 * \alpha$

Table 2. Parameters of the mobile platform.

Parameters	Values
Initial location	(1500 m, -300 m)
Initial velocity	(10 m/s, 0 m/s)
Initial acceleration	(10 m/s ² , 0 m/s ²)

The air density ρ is 1.225 kg/m³. Set the proportional coefficient K is 3. Set the thrust deviation value is $\pm 10\%$ and the drag deviation value is $\pm 20\%$. The numerical simulation results are shown in the following figures.

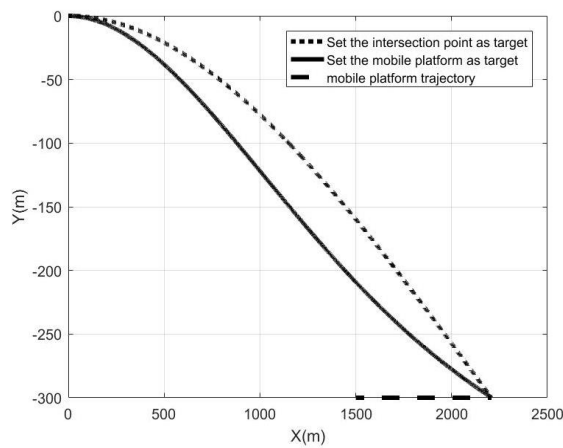


Figure 2. The trajectory of different guidance method.

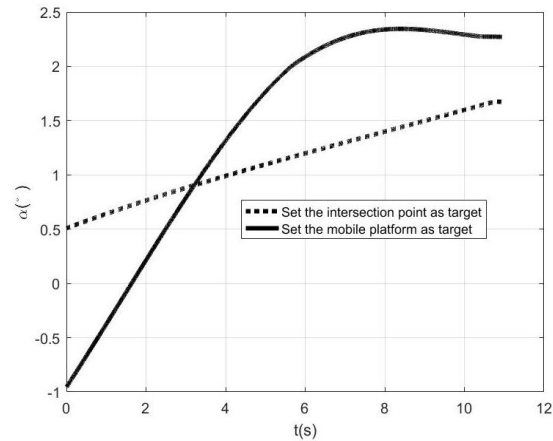


Figure 3. The angle of attack of different guidance method.

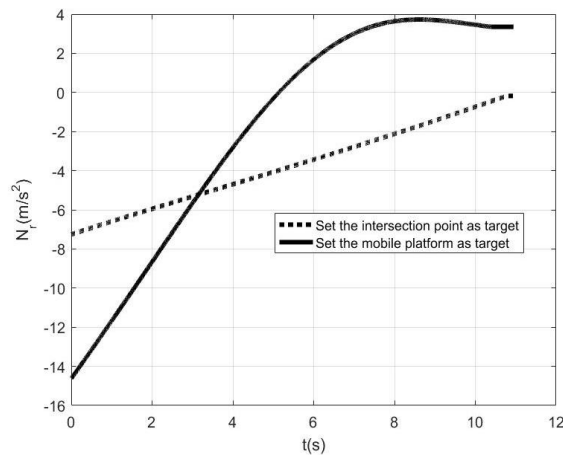


Figure 4. The required normal acceleration of different guidance method.

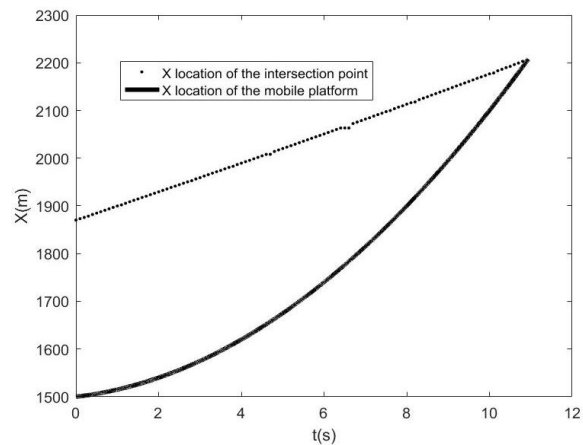


Figure 5. The change of locations of the intersection point and the mobile platform.

As can be seen from Figure 2, the flight trajectory of the UAV is more straight than that of the direct tracking mobile platform when it makes autonomous landing using the guidance method proposed in this article. As shown in Figure 3 and Figure 4, the required angle of attack and the required normal acceleration of the UAV landing with the guidance method presented in this article are both smaller than those of the direct tracking mobile platform. Referring to the results shown in Figure 5, this reason that the required normal acceleration of the UAV landing with the guidance method presented in this article are smaller than those of the direct tracking mobile platform can be explained. Due to the change range of the location of the predicted intersection point is much smaller than that of the mobile platform, the guidance method proposed in this paper is essentially to make UAV track a very small maneuvering target rather than the mobile platform which has greater maneuvering range. Obviously, according to the characteristics of proportional navigation, the normal acceleration required to track a small maneuvering target is less than that required to track a large maneuvering target.

4. Conclusion

Numerical simulation shows that the UAV can land precisely on the mobile platform when it lands with the guidance method based on predicting intersection point proposed in this article. Moreover, the required normal acceleration of this method is less than the traditional guidance method based on mobile platform as tracking target. The autonomous landing guidance method proposed in this article

can ensure that the UAV can successfully land with a small normal acceleration while the mobile platform maintains a high maneuverability, which is of great importance in improving the survivability of UAV and mobile platform in the battlefield. The next step is to improve the algorithm of the guidance method so that it can realize the UAV autonomously landing on the platform with more complex maneuvering forms. It can lay a theoretical foundation for the UAV autonomously landing on the mobile platform in air.

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