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Research on Adaptive Guidance Technology of UAV Ship Landing System Based on Net Recovery

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Abstract

According to the characteristics of the target ship in motion in the net recovery process of UAV, this paper put forward the guidance law based on angle of sight by taking missile guidance law of proportional guidance law for reference, and introduced the backstepping guidance law to improve the adaptability of guidance law. Since the angle of sight guidance law is to make the UAV flight path angle and angle of sight be proportional to the rate of change, flight path angle can be tracked by controlling the angle of sight. That taking the guidance law into use can reduce the sensitivity of UAV motion on the ship parameters change, thereby to obtain more stable trajectory. The simulation shows the feasibility of this guidance law, and has strong robustness.

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Keywords: UAV; ship landing; net recovery; proportional guidance

1. Introduction

As an important part of modern naval air force, carrier-based unmanned aerial vehicles (UAVs) are mainly used for battlefield reconnaissance and surveillance, communications relay, electronic warfare and other tasks. UAVs can avoid casualties, more and more countries see those as the ideal weapon of war casualties in the future.

However, restrictions on landing platform and oscillation of offshore platform and influence of storms, especially carrier-based recovery technology make taking off and landing difficult for carrier-based UAVs. Currently, the main

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carrier-based UAVs' recycling technology consists of net recovery,Skyhook recycling hinder recovery, vertical landing technology, and the net recovery is applied in many carrier-based UAV [1~3].

Net recovery has been developed for many years. Seungho Yoon develops an adaptive guidance scheme based on tracking method to solve land-based net recovery, this scheme builds on the track-guided missile program for UAVs' net recovery [4-6], but this tracing scheme is mainly applied to the case of a fixed recycling network location, is not suitable for a mobile case. Domestic scholars optimizes guidance scheme [7~9].In fact, the carrier-based unmanned aerial vehicle's net recovery involves a moving target tracking problem, you can learn from guided missile program, with respect to a track-guided program, proportional navigation scheme is more suitable for such a moving target tracking problem.

In order to increase the adaptive capacity, backstepping is more and more used widely in the design of flight guidance and control system[10~15].In this paper, a longitudinal adaptive guidance program of UAVs' net recovery is developed from backstepping design idea.

Here introduce the paper, and put a nomenclatur if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

2. Mathematical Model

Mathematical model of UAV vertical movement can be described as formula (1), $H, X, V_d, \gamma, \theta, q, \alpha$ are height, location, ground speed, track tilt angle, pitch angle, pitch rate, angle of attack, g is acceleration of gravity, L, D are Lift and drag.

Movement on ship recycling network model can be described as:

$$\begin{aligned} \dot{H}_{ship} &= a_1 \sin(\omega_1 t) + a_2 \sin(\omega_2 t) \\ \dot{X}_{ship} &= V_{ship} \end{aligned} \tag{1}$$

$H_{ship}, X_{ship}, V_{ship}$ are height, location, ground speed of recycling network, $a_1, a_2, \omega_1, \omega_2$ are the amplitude and frequency of movement of the waves.

The net recovery process of carrier-based UAV is to guide the UAV fly at low speeds to center of recovery area network.

The sight is connected between the UAV and the ship, the distance is R, η is defined between UAV velocity vector and the sight angle, The angle between the line of sight and the horizontal line of sight angle is γ_s ,the sight angle directly determines the relative relationship between the UAV and recycling network ,which is to meet:

$$\gamma_s = a\tan\left(\frac{H - H_{ship}}{X - X_{ship}}\right) \tag{2}$$

Relative motion between the UAV and the ship is:

$$\begin{aligned} \dot{R} &= -V_d \cos(\gamma - \gamma_s) + V_{ship} \cos\gamma_s \\ R\dot{\gamma}_s &= -V_d \sin(\gamma - \gamma_s) - V_{ship} \sin\gamma_s \\ \eta &= \gamma - \gamma_s \end{aligned} \tag{3}$$

3. Adaptive Guidance Scheme

3.1. Longitudinal guidance based on proportional navigation

In order to maintain a steady sight angle, trying to get a straight path, you need to try to eliminate the rate of change of the line of sight of any possible angle, angle changes when the front sight angle changes, and then track changes in the tilt angle varies with the sight angle:

$$\dot{\gamma} = K\dot{\gamma}_s \tag{4}$$

Based on proportional navigation guidance program, the purpose is to make the UAV trajectory inclination angle and rate of change of the rate of change proportional. According to proportional navigation law, the change of the trajectory angle is proportional to the change of the angle of inclination, sight angle tracking is guided by controlling the change of the tilt angle.

Figure. 1 shows the proportional navigation trajectory schematic. Fig. 1 ~ 6 represents the current position of ship and UAVs, dashed line indicates the current position of the aircraft and ship connection location. Tracking a given line of sight controls the angle and position relative height between the UAV and the ship.

In order to adapt to the uncertainty of flow interference and improve the robustness of guidance law, backstepping is used in longitudinal guidance structure. The entire guidance loop recursively constructed due to UAVs dynamic characteristics, virtual guidance commands of each sub-loop are generated by the basic dynamic inverse and proportional integral control law and to suppress nonlinear factors and uncertainties of UAV.

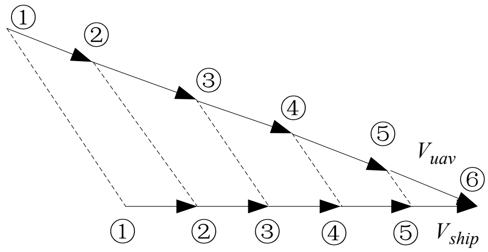

Fig. 1.Profile of Longitudinal Proportional Navigation

3.2. Longitudinal guidance structure based on backstepping

Backstepping is such a method that control input is recursive from the first equation of state, the mathematical model can be described as:

$$\begin{aligned} \dot{x}_1 &= f_1(x_1) + g_1(x_2) \\ \dot{x}_2 &= f_2(x_1, x_2) + g_2(x_3) \\ &\vdots \\ \dot{x}_n &= f_n(x_1, \cdots x_n) + u \end{aligned} \tag{5}$$

Here, x, u are the system state and input variables. Backstepping sees each x_{i+1} of subsystem as the virtual control command, and make the system to achieve stable state through appropriate feedback. Each sub-system can be described as:

$$\dot{x}_i = f_i(x_i) + g_i(u_i) \tag{6}$$

Here is designed to track the desired state law changes $\dot{x}_{des}$ .But the actual state of the system is often not equal to the virtual control command, which requires a feedback control so that the actual x_{i+1} tracks the virtual track control command, so that the entire control system is asymptotically stable. The nonlinear dynamic inversion can eliminate nonlinear factors to achieve to track control command, dynamic inversion is generally in the form of:

$$u_c = g^{-1}\left(\dot{x}_{des} - f(x)\right) \tag{7}$$

Usually the control law of the system can be designed according to equation (8).

The tilt angle trajectory guidance based on backstepping includes three sub-loops: the sight angle guidance loop, the tilt angle guidance loop and the pitch angle guidance loop. The sight angle guidance loop produces the desired tilt angle rate, the virtual guidance command of tilt angle loop is generated under the tilt angle guidance law, and the pitch angle guidance loop tracks virtual pitch angle command and generate inner loop pitch angular rate command. Pitch rate control loop tracks pitch rate command to achieve trajectory tracking control.

4. Guidance law based on backstepping

Based on backstepping, longitudinal tracking guidance includes three parts: the sight angle guidance, the tilt angle guidance and the pitch angle guidance, respectively, for these three guidance loop derive its guidance law.

4.1. Sight angle guidance law

Proportional navigation guidance law allows the rate of change of the tilt angle is proportional to the rate of change of the sight angle, namely:

$$\dot{\gamma}_{des} = K_{PN} \cdot \dot{\gamma}_s \tag{8}$$

K_{PN} Is a proportionality factor.

Assuming UAVs and ships move with a constant velocity, take a derivative with the rate of change of the sight angle in formula (4):

$$R\ddot{\gamma}_s + (2\dot{R} + K_{PN}V_d \cos(\gamma - \gamma_s))\dot{\gamma}_s = 0 \tag{9}$$

To keep the sight angle stable, it must satisfy the inequality:

$$2\dot{R} + K_{PN}V_d \cos(\gamma - \gamma_s) > 0 \tag{10}$$

That is:

$$K_{PN} > -\frac{2\dot{R}}{V_d \cos(\gamma - \gamma_s)} \tag{11}$$

$$K_{PN} > 2 \cdot \left(1 - \frac{V_{ship}}{V_d} \cdot \frac{\cos\gamma_s}{\cos(\gamma - \gamma_s)}\right) \tag{12}$$

When the scale factor K_{PN} satisfies the equation (13), you can get a stable sight angle, and the greater K_{PN} , the response of the tilt angle faster. Rate of change of the sight angle can be proportionally integral controlled:

$$\dot{\gamma}_s = \left(K_{\gamma s} + \frac{K_{I\gamma s}}{s}\right) \cdot (\gamma_{sc} - \gamma_s) \tag{13}$$

$K_{\gamma s}$ is proportional coefficient of the sight angle control, $K_{I\gamma s}$ is integral coefficient, γ_{sc} is the sight angle command. Therefore, the sight guidance law is:

$$\dot{\gamma}_{des} = K_{PN}\left(K_{\gamma s} + \frac{K_{I\gamma s}}{s}\right) \cdot (\gamma_{sc} - \gamma_s) \tag{14}$$

4.2. Tilt angle guidance law

Tilt angle guidance loop generates virtual pitch angle pitch angle command of the pitch guidance loop. Rate of change of the tilt angle meet:

$$\dot{\gamma} = \frac{\overline{q} S C_L}{m V_d} - \frac{g}{V_d}\cos\gamma \tag{15}$$

m is the quality of UAV, $\overline{q}$ is the dynamic pressure, S is the reference area, C_L is the lift coefficient. The lift coefficient C_L consists of two parts: C_{L0} (when the angle of attack is zero) and $C_L(\alpha)$ ((when the angle of attack is not zero), Due to the speed and angle of attack range of shipboard UAV is small, the lift coefficient has a linear relationship with the angle of attack:

The rate of change of the tilt angle can be described as a function of the angle of attack, track tilt angle, dynamic pressure, and ground speed:

$$\dot{\gamma} = \frac{\overline{q} S C_L^{\alpha}}{m V_d}\alpha + \frac{\overline{q} S C_{L0}}{m V_d} - \frac{g}{V_d}\cos\gamma \tag{16}$$

Then:

$$\dot{\gamma} = f_{\gamma}(\gamma) + g_{\gamma}(\alpha) \tag{17}$$

Then:

$$\alpha_c = \frac{m V_d}{\overline{q} S C_L^{\alpha}}\left(\dot{\gamma}_{des} + \frac{g}{V_d}\cos\gamma - \frac{\overline{q} S C_{L0}}{m V_d}\right) \tag{18}$$

The inverse function of the tilt angle is defined as a function of the angle of attack:

$$G_{\alpha 2\gamma}^{-1} \overset{\Delta}{=} g_{\gamma}^{-1}\dot{\gamma}_{des} + \frac{mg}{\overline{q} S C_L^{\alpha}}\cos\gamma - \frac{C_{L0}}{C_L^{\alpha}} \tag{19}$$

$\overline{q}$ can be described as the indicated airspeed V_i:

$$\overline{q} = 0.5 \cdot \rho_0 \cdot V_i^2 \tag{20}$$

ρ_0 is the atmospheric density at sea level.

Therefore, the inverse function of the tilt angle is a function of the angle of attack $(\gamma 2\alpha)^{-1}$, it is also a function of the tilt angle, the angle of attack, indicated airspeed, ground speed, and the expected rate of change of the tilt angle. It can quickly respond to the effects of wind disturbance because ground speed and airspeed is guided into this guidance law. Without considering the impact of lateral influence, the pitch angle command θ_c, AOA α_c should meet:

$$\theta_c = \alpha_c + \gamma \tag{21}$$

4.3. Pitch angle guidance law

Pitch angle guidance loop tracks virtual pitch angle command θ_c provided by tilt angle guidance loop. Without considering the impact of lateral influence, pitch angle θ and pitch rate q should meet:

$$\dot{\theta} = q \tag{22}$$

The dynamic inverse of the pitch angle guidance loop can be formed as:

$$q_c = \dot{\theta}_{des} \tag{23}$$

Expected rate of change of pitch angle $\dot{\theta}_{des}$ is controlled by the ratio of the pitch angle:

$$\dot{\theta}_{des} = K_\theta(\theta_c - \theta) \tag{24}$$

Therefore, the pitch angle guidance law is:

$$q_c = K_\theta(\theta_c - \theta) \tag{25}$$

A longitudinal guidance law UAV consults current ground speed, indicated airspeed, tilt angle, pitch angle and calculates ground speed directly in this law, you can increase the adaptive capacity of guidance against wind interference, making guidance laws can quickly adapt to changes in ground speed caused by airspeed.

For small low-speed carrier-based unmanned aerial vehicles, the range of the speed and angle of attack is generally small, and therefore within the scope of its flight envelope, the lift coefficient and lift coefficient derivative of the angle of attack can be seen as a constant value. When there is wind interference, indicated airspeed larger changes, thereby causes the changes of the ground speed, which can quickly react to guidance command. When there is wind, indicated airspeed decreases, the speed increases, the angle of attack command increases, than the rate of pitch angle command increases, UAVs quickly pull to prevent a declination of height; contrary, pitch rate command reduce to prevent the height rise.

5. 4 Simulation

In order to verify the effectiveness of adaptive net recovery, take a carrier-based unmanned aerial vehicles for example, the design its net recycling laws is designed according to equation (24), and simulation is done.

Assuming the initial height of UAVs is 250m, the flight speed is 33m/s, a steady declination in the tilt angle is -4°, the maximum wind speed is 6m/s; the ship is at a speed of 7m/s, course is steady, with a moderate sea conditions. For uncertainty of the initial position, UAV quality, atmospheric disturbances and positioning error of a simulation test, Figure 2-4 shows the UAV flight results of the net recovery process.

As can be seen from Figures. 2 to 4, in a steady-state flight, the UAV and the sight angle of the ship is maintained at -4 °, the tilt angle is relatively constant and the trajectory is close to a straight line. In the 100m, the UAV is affected by wind interference, rapid changes in airspeed happens, thereby causes the ground speed, and then changes in sight angle. When the ground velocity and the sight angle changes, guidance loop respond quickly by changing the angle of attack command to change the UAV attitude, keeping the relative relationship between the UAV and recycling network.

Sight angle measurement deviation between the UAV and the ship will affect the relative position of the UAV and the ship, due to the sight angle guidance scheme based on proportional navigation, the impact on the position of the recycling network is less. Figure. 4(b) shows the distribution outlets within a given range of uncertainty, carrier-based UAV can fly into the recycling network, the largest deviation of recycling network is 0.15m. According to the simulation results, the guidance law can guide the UAV to fly into the recycling network, with robust and adaptive capacity, within a given range of uncertainty.

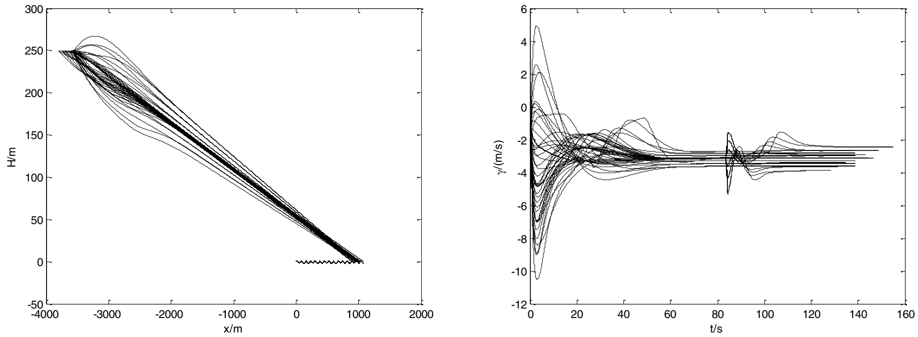

Fig. 2. (a)Altitude Histories of UAV and Ship; (b) Terminal Altitude Profiles of UAV and Ship

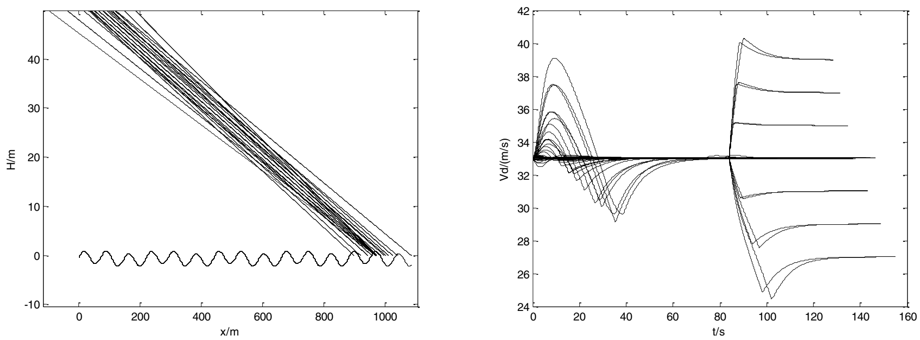

Fig. 3 .(a) Sight-of-Line Angles of UAV to Ship; (b) Path History of UAV

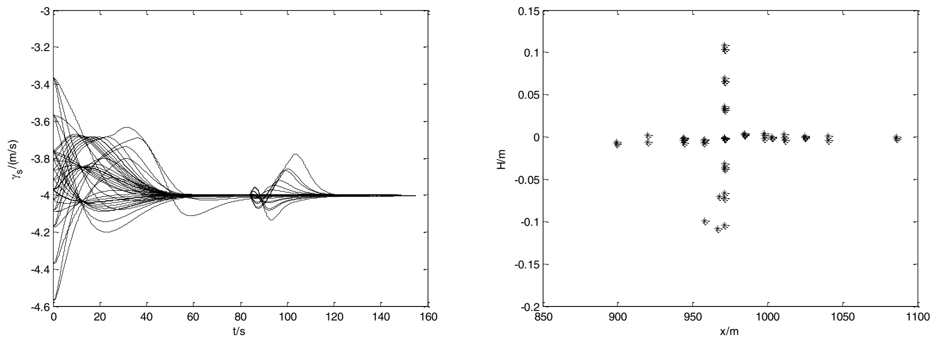

Fig. 4. (a) Ground Speed History of UAV; (b) Terminal Altitude

6. Conclusion

In this paper, a scheme based on adaptive guidance of proportional navigation is presented due to the characteristics unmanned aerial vehicle's net recovery. The longitudinal guidance loop consists of sight angle guidance loop, tilt angle guidance loop and pitch angle guidance loop with backstepping and use proportional integral guidance law and dynamic inverse guidance law to produce virtual guidance command. Taking a sample UAV for example, a net recovery guidance law is designed and a nonlinear simulation with given uncertainty factors is done. Results show Backstepping guidance law can guide the UAV safely to the net recovery and meet the requirements.

However, the net recovery process, especially the end of the recovery network, is greatly affected by the interference, and the UAV trajectory control is a long process, so the impact of wind on this stage performance larger, follow-up work is required to further improve the adaptive capacity of guidance for recycling terminal region.

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