Hindawi Publishing Corporation
Abstract and Applied Analysis
Volume 2014, Article ID 983624, 10 pages
http://dx.doi.org/10.1155/2014/983624

Research Article
Safe Control for Spiral Recovery of Unmanned Aerial Vehicle

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Received 8 June 2014; Revised 25 June 2014; Accepted 2 July 2014; Published 26 August 2014

Academic Editor: H. R. Karimi

With unmanned aerial vehicles (UAVs) widely used in both military and civilian fields, many events affecting their safe flying have emerged. That UAV's entering into the spiral is such a typical safety issue. To solve this safety problem, a novel recovery control approach is proposed. First, the factors of spiral are analyzed. Then, based on control scheduling of state variables and nonlinear dynamic inversion control laws, the spiral recovery controller is designed to accomplish guidance and control of spiral recovery. Finally, the simulation results have illustrated that the proposed control method can ensure the UAV autonomous recovery from spiral effectively.

1. Introduction

Unmanned aerial vehicles (UAVs), with many unique advantages, have been widely operated in both military and civilian fields [1–5]. They can carry on all kinds of complex mission, such as aerial mapping [6], disaster monitoring [7], search and rescue [8], and reconnaissance and attacking [9]. With the UAVs widely used in the entire airspace and the increasing flight frequency, they have suffered from safety issues such as the crash, out of control, and collision with other planes [10, 11]. Particularly, two typical safety events happened on UAVs in recent years. One is that, in June 2012, a U.S. military UAV named as Global Hawk was stepping into the spiral during the routine training, eventually leading to spin and crash. The other is that, in 2011, a U.S. military UAV was intercepted and captured successfully by Iran, using the electronic jamming. So, how to effectively solve these safety problems and ensure UAVs fly safely and reliably has become an important problem to be addressed. The work in this paper is carried out just under such a background, but we mainly focus on one safety issue, that is, UAV's spiral.

Currently, the relevant researches on the spiral of aircraft are mainly in the field of manned aircraft. In foreign countries, since the 1950s of last century, the USA has carried on the research of spiral recovery for manned aircraft. The representative outcome was released by Langley Research Center, where a kind of idea for spiral recovery was proposed and discussed in theory. In the subsequent air shows, American pilots successfully used this method to recover from the stall and the spiral. In China, aimed at the flight characteristics of manned fighters, a series of methods for spiral judgment and recovery were developed and formed into flight specifications and institutions for different types of aircraft. For example, for J-6 fighter, the approach named as "flat, middle and push" is presented to the spiral recovery. In addition, other scholars have discussed the spiral technology for the aerobatics [12].

But at the same time, there is little research on the spiral recovery for the UAVs. For example, as is reported by a Russian website in 2008, a kind of professional technology is developed to avoid the UAV entering into the spiral. In China, individual scholar focuses on the problem of UAV's spiral recovery under the condition of rudder locked and designs a control law which seems to be effective for spiral recovery [13]. But this study is only suitable for the moment of spiral mode, and it does not consider the unstable spiral caused by the large attack angle. From the above analysis, it can be found that there are very few relevant literatures and researches on the UAV's spiral recovery, but for UAV the problem of the spiral is certainly a very important problem affecting UAV's flying safely.

As is known, the UAV is a very complex nonlinear system. Particularly, when UAV is flying in the state of spiral, the nonlinear characteristics will be particularly evident. In order to improve the performance of nonlinear systems, several researches have recently proposed some typical stability and vibration control methods, such as fault-tolerant control [14], sliding-mode control [15, 16], feedback control [17–19], sampled-data control [20], optimization control [21, 22], and energy-to-peak control [23, 24]. The effectiveness of these approaches has been verified, respectively, by different simulations or experiments, but they cannot be directly introduced to solve the control problem of UAV's spiral recovery. According to an expert from the US Air Force Research Laboratory, named Bruce T. Clough, autonomous safe control would be the most effective measures to improve the safety of the UAV [25]. Based on this idea, we try to propose the autonomous control method for the spiral recovery, ensuring the UAV recovery from the spiral effectively and making it fly safely.

In this paper, we contribute to the design of the controller to make the UAV recover from spiral autonomously. Firstly, we analyze the reasons why UAV may enter into the state of spiral. Secondly, the structure of the controller for spiral recovery is given and the control sequence of state variables is discussed. Then, based on the nonlinear dynamic inversion [26], the control law for spiral recovery is designed.

The rest of this paper is organized as follows. Section 2 is the cause formulation and analysis of UAV's spiral. In Section 3, we focus on the design process of the controller for spiral recovery. Simulation experiments are provided to illustrate the effectiveness of the approach presented in this paper in Section 4. Finally, the conclusion and the further work are depicted in Section 5.

2. The Cause Formulation and Analysis of UAV's Spiral

Spiral is an abnormal motion for an UAV. It is very likely to happen when an UAV is in the stalling state along with rotating around three axes. At that time, the UAV will descend sharply along the spiral trajectory with a small radius. Based on some relevant literature, the cause of UAV's spiral can be divided into three categories. They are wing self-rotation, direction divergence, and rolling divergence, respectively. Next, we will analyze these causes.

(1) Wing Self-Rotation. The coefficient of normal force, which is perpendicular to the wings of UAV, can be written as

$$C_z = C_y \cos\alpha + C_x \sin\alpha. \tag{1}$$

For the low-speed UAV, it has a larger lift coefficient, but a smaller drag coefficient. So, the lift coefficient can be used to analyze the change of rolling damping coefficient at a large angle of attack.

When an UAV is flying at a large angle of attack, if the rolling motion happens, for the sinking wings, the angle of attack will increase, while the lift coefficient will decrease. On the contrary, for the rising wings, the angle of attack will decrease, while lift coefficient will increase. At that time, damping in roll will change the symbol, and the damping effect will help the rolling, leading to self-rotation of the wings.

(2) Direction Divergence. When an UAV is in the stall condition, the nose will deflect automatically. That is because the UAV has lost the static stability. When the UAV emerges the direction divergence, different lifts values between two wings caused by the sideslip may make the UAV both deflect and roll. The pitching inertia moment generated during above process may make the angle of attack further increase.

(3) Rolling Divergence. Rolling divergence usually occurs when the UAV is flying at a negative angle of attack. At this time, if the UAV's lateral static stability $m_x^\beta > 0$, it will have the lateral static stability. Otherwise, if the absolute value of negative angle of attack exceeds that of the stall, that is, $m_x^\beta > 0$, UAV will lose the lateral static stability. At this time, it will be very likely to cause the rolling divergence.

3. Controller Design for Spiral Recovery

In this section, we will design the controller design for spiral recovery. This controller should be switched automatically when an UAV enters into the spiral. Meanwhile, it can carry on the recovery control of spiral autonomously according to the actual dynamic of spiral. The design of controller should take into account the following two parts: control sequence and control law.

3.1. Control Sequence of State Variables. When an UAV is flying in the stall, there will be coupling interaction and location constraints existing among each control surface, and then the effect of control surfaces may reduce [27, 28]. Consequently, it is difficult to control each state variable of UAV system simultaneously during the process of spiral recovery. According to the practical experience of spiral recovery used for manned fighters, the effective approach is to prevent the UAV from rotation firstly. If the angle of attack is controlled with a large angular rate of rotation, it will be insufficient for manipulation torque generated by pushing the stick forward to overcome the upward inertia torque. At that time, the angle of attack cannot reduce down. Even the rotation will become more quickly due to the effect of rolling and partial torque generated by pushing the stick forward. Meanwhile, the control of the attitude angle mainly depends on the ailerons. However, the efficiency of manipulating ailerons is lower at a high angle of attack. Therefore, the prerequisite for controlling the attitude angles is UAV at a small angle of attack.

In summary, one must grasp the control sequence of state variables accurately during the process of spiral recovery and give the outputs corresponding to control these relevant variables. By this way, it can prevent the spiral from becoming more divergent and make the most effect out of controlling surfaces. So, the control sequence of spiral recovery can be concluded in Table 1.

Table 1: Control sequence of spiral recovery.

The sequence	The applied strategies
1	When the UAV is in the spiral, switch to control module of the spiral and give an output of angular rate to execute the control of slowing angular rate of rotation
2	When UAV's deflection and rolling slow down, give an output of the attack angle to execute the control of reducing the attack angle rapidly
3	When the attack angle is below the critical angle of attack, give an output of attitude angle and then control the rotating attitude angle
4	When UAV stops deflection and rolling, achieve the desired attitude angle and carry on the control of diving and speeding up;
5	When the velocity increases to some degree, carry on the control program of exiting diving

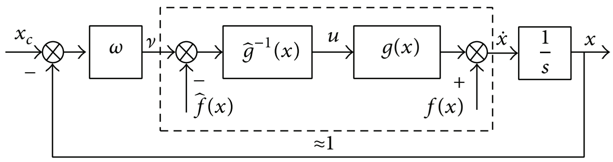


Figure 1: The structure of dynamic inversion compensation for affine nonlinear system.

3.2. Control Law for Spiral Recovery Based on Nonlinear Dynamic Inversion. If UAV is in the spiral, the nonlinear characteristics will become particularly evident. Therefore, based on linear small-disturbance motion model, control laws of three channels cannot be independently designed. It is well known that, for flight vehicle design, the most widely used method is nonlinear dynamic inversion control [29]. The fundamental principle of this method is that nonlinear inversion and nonlinear function are used to eliminate the nonlinearity of the controlled objective, thus forming global linearization. In order to illustrate this principle better, take the following affine nonlinear system as an example:

$$\dot{x} = f(x) + g(x)u. \tag{2}$$

If $g(x)$ is invertible, then let $u = \hat{g}^{-1}(x)(\nu - \hat{f}(x))$, where pseudocontrol input ν can be selected as $\nu = \omega(x_c - x)$. Because it is impossible to obtain the accurate invertible model of the system, $-\hat{f}(x)$, $\hat{g}^{-1}(x)$ are used to express approximate compensation and inversion of this system. The structure of dynamic inversion control system is shown in Figure 1.

The dynamic inversion control approach can automatically adapt to the large change of flight conditions and configuration at the fixed gain. So, it will be more effective to control the UAV in the state of maneuvering flight. In this section, we will combine singular perturbation theory with nonlinear dynamic inversion to design control law of UAV's spiral recovery.

As is analyzed above, the UAV's nonlinearity is very evident when it is in the spiral. Consequently, the six-degree-of-freedom motion model [30] should be introduced here, which is shown as follows:

$$\begin{aligned}
\dot{p} &= (c_1 r + c_2 p)\, q + c_3 \overline{L} + c_4 N, \\
\dot{q} &= c_5 pr - c_6 \left(p^2 - r^2\right) + c_7 M, \\
\dot{r} &= (c_8 p - c_2 r)\, q + c_4 \overline{L} + c_9 N, \\
\dot{\alpha} &= q - \tan\beta \left(p\cos\alpha + r\sin\alpha\right) + \frac{(-L + Mg\cos\gamma\cos\mu) - T\sin\alpha}{MV\cos\beta}, \\
\dot{\beta} &= p\sin\alpha - r\cos\alpha - \frac{T\sin\beta\cos\alpha - (Mg\cos\gamma\sin\mu + Y\cos\beta)}{MV}, \\
\dot{\mu} &= \sec\beta \left(p\cos\alpha + r\sin\alpha\right) - \frac{g\cos\gamma\cos\mu\tan\beta}{V} \\
&\quad + \frac{\left[\sin\alpha\left(\tan\gamma\sin\mu + \tan\beta\right)\right] - \cos\alpha\tan\gamma\cos\mu\sin\beta}{MV/T} \\
&\quad + \frac{L\left(\tan\gamma\sin\mu + \tan\beta\right) + Y\tan\gamma\cos\mu\cos\beta}{MV\cos\gamma}, \\
\dot{V} &= \frac{-D + Y\sin\beta - Mg\sin\gamma + T\cos\beta\cos\alpha}{M}, \\
\dot{\chi} &= \left(\left(T\sin\mu\sin\alpha + \cos\mu\sin\beta\cos\alpha\right) + \left(L\sin\mu + Y\cos\mu\cos\beta\right)\right)\left(MV\cos\gamma\right)^{-1}, \\
\dot{\gamma} &= \left(\left(L\cos\mu - Mg\cos\gamma - Y\sin\mu\cos\beta\right) + T\left(\sin\mu\sin\beta\cos\alpha + \cos\mu\sin\alpha\right)\right)\left(MV\right)^{-1}, \\
\dot{x} &= V\cos\gamma\cos\chi, \qquad \dot{y} = V\cos\gamma\sin\chi, \qquad \dot{h} = -V\sin\gamma.
\end{aligned} \tag{3}$$

According to (3), it can be clearly seen that this motion consists of 12 state variables. Among these variables, p, q, and r are the rate of roll angle, pitch rate, and yaw rate, respectively; α, β, and μ are the angle of attack, sideslip, and roll, respectively; V, χ, and γ are velocity, the angle of yaw, and trajectory inclination, respectively; X, Y, and Z are

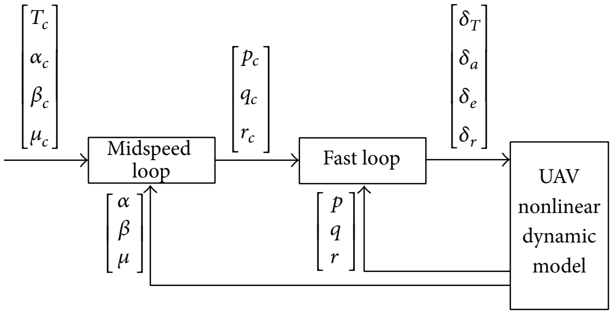


Figure 2: The structure of control laws based on the nonlinear dynamic inversion.

the projection of UAV's centroid on the ground coordinate system. Define a vector which consists of these above state variables as follows:

$$\mathbf{x} = [p \quad q \quad r \quad \alpha \quad \beta \quad \mu \quad V \quad \chi \quad \gamma \quad X \quad Y \quad Z]^T. \tag{4}$$

Based on the movement rule of UAV and singular perturbation theory, the state variables can be divided into three parts, which are fast-speed variables $[p \quad q \quad r]^T$, the middle-speed variables $[\alpha \quad \beta \quad \mu]^T$, and the slow-speed variables $[V \quad \chi \quad \gamma]^T$ or $[X \quad Y \quad Z]^T$. By this way, nonlinear equation (3) can be divided into three different time-scale subsystems. Based on the state feedback control, the structures of these three first-order linear decoupling control structures can be obtained. At this time, these three different speed circuits can be designed independently. For the design of UAV's spiral recovery, we are mainly concerned about the fast-speed and midspeed variables. The structure of nonlinear dynamic inversion control law designed is shown in Figure 2. Next, we will illustrate the design of these two loops.

(1) The Control Law of Fast-Speed Loop. The fast-speed loop is used to control these variables p, q, r. According to the given inputs of angular, p_c, q_c, r_c, the deviation of control surface can be solved. The equation of fast-speed loop can be written as the following form:

$$\mathbf{x}_1 = f_1(\overline{\mathbf{x}}) + g_1(\overline{\mathbf{x}})\,\mathbf{u}, \tag{5}$$

where $\mathbf{x}_1 = [p \quad q \quad r]^T$, $\overline{\mathbf{x}} = [V \quad \gamma \quad \alpha \quad \beta \quad \mu \quad p \quad q \quad r]^T$ is a vector that consisted of eight state variables, and $\mathbf{u} = [\delta_a \quad \delta_e \quad \delta_r]^T$ is the output of inner loop, and it is also the input control of UAV objective. The first item $f_1(\overline{\mathbf{x}})$ in the right of (5) represents nonlinear coupling torque, and the second item $g_1(\overline{\mathbf{x}})$ of that represents manipulating torque generated by control surfaces. These two items can be, respectively, shown as follows:

$$f_1(\overline{\mathbf{x}}) = \begin{bmatrix} f_p(\overline{\mathbf{x}}) \\ f_q(\overline{\mathbf{x}}) \\ f_r(\overline{\mathbf{x}}) \end{bmatrix} = \begin{bmatrix} C_{p_0} + C_{p\beta} + C_{pp}p + C_{pr}r + I_{p_1}pq + I_{p_2}qr \\ C_{q_0} + C_{q\alpha} + C_{qq}q + I_{q_1}pr + I_{q_2}\left(r^2 - p^2\right) \\ C_{r_0} + C_{r\beta}\beta + C_{rp}p + C_{rr}r + I_{r_1}pq + I_{r_2}qr \end{bmatrix},$$

$$g_1(\overline{\mathbf{x}}) = \begin{bmatrix} C_{p\delta_a} & C_{p\delta_e} & C_{p\delta_r} \\ 0 & C_{q\delta_e} & 0 \\ C_{r\delta_a} & C_{r\delta_e} & C_{r\delta_r} \end{bmatrix}. \tag{6}$$

Let the expected angular acceleration rate of fast-speed loop meet the ideal closed-loop dynamic response, which is as follows:

$$\dot{p}_d = \left(k_{Pp} + \frac{k_{Ip}}{s} + k_{Dp}s\right)(p_c - p),$$

$$\dot{q}_d = \left(k_{Pq} + \frac{k_{Iq}}{s} + k_{Dq}s\right)(q_c - q),$$

$$\dot{r}_d = \left(k_{Pr} + \frac{k_{Ir}}{s} + k_{Dr}s\right)(r_c - r), \tag{7}$$

where $[p_d, q_d, r_d]^T$ represents the expected angular acceleration and $[p_c, q_c, r_c]^T$ represents the command signal of angular acceleration generated by the low-speed loop. The variables K_{P*}, K_{I*}, and K_{D*} are PID feedback gain of fast-speed loop, and their values are 20~30 rad/s. According to the dynamic inversion principle, the control input $\mathbf{u}$ can be obtained as

$$\overline{\mathbf{u}} = \begin{bmatrix} \delta_a \\ \delta_e \\ \delta_r \end{bmatrix} = g_1^{-1}(\overline{\mathbf{x}}) \left[\begin{bmatrix} \dot{p}_d \\ \dot{q}_d \\ \dot{r}_d \end{bmatrix} - \begin{bmatrix} f_p(\overline{\mathbf{x}}) \\ f_q(\overline{\mathbf{x}}) \\ f_r(\overline{\mathbf{x}}) \end{bmatrix} \right]. \tag{8}$$

Equations (7) and (8) are combined to form an integrated fast-speed loop, achieving the control law design of fast-speed loop for UAV. The control structure corresponding to the fast-speed loop is shown in Figure 3.

(2) The Control Law of Middle-Speed Loop. The middle-speed loop is used to control these variables α, β, and μ. According to nonlinear dynamic inversion theory, the inputs p_c, q_c, r_c can be solved. If deflection of control surfaces is ignored, this loop can be written as the following affine form:

$$\begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\mu} \end{bmatrix} = \begin{bmatrix} f_\alpha(\mathbf{x}_2) \\ f_\beta(\mathbf{x}_2) \\ f_\mu(\mathbf{x}_2) \end{bmatrix} + g_2(\mathbf{x}_2) \cdot \begin{bmatrix} p \\ q \\ r \end{bmatrix}, \tag{9}$$

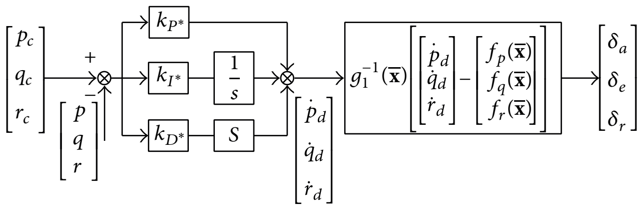


Figure 3: The control structure corresponding to the fast-speed loop.

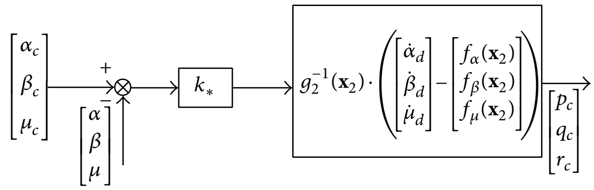


Figure 4: The control structure corresponding to the middle-speed loop.

where $\mathbf{x}_2 = [V, \gamma, \alpha, \beta, \mu]^T$ and each element of $[f_\alpha(\mathbf{x}_2), f_\beta(\mathbf{x}_2), f_\mu(\mathbf{x}_2)]^T$ is shown as follows:

$$\begin{aligned} f_\alpha(\mathbf{x}_2) &= \frac{g}{V}\cos\gamma\frac{\cos\mu}{\cos\beta} - \frac{\sin\alpha}{MV\cos\beta}T, \\ f_\beta(\mathbf{x}_2) &= \frac{g}{V}\cos\gamma\sin\mu - \frac{\cos\alpha\sin\beta}{MV}T, \\ f_\mu(\mathbf{x}_2) &= \frac{g}{V}\cos\gamma\tan\beta\cos\mu + \frac{(\tan\gamma\sin\mu + \tan\beta)\sin\alpha}{MV}T. \end{aligned} \tag{10}$$

Let the closed-loop dynamic response of expected inputs of angular rate $\dot{\alpha}, \dot{\beta}, \dot{\mu}$ of fast-speed loop be with the following form:

$$\begin{bmatrix} \dot{\alpha}_d \\ \dot{\beta}_d \\ \dot{\mu}_d \end{bmatrix} = \begin{bmatrix} k_\alpha & 0 & 0 \\ 0 & k_\beta & 0 \\ 0 & 0 & k_\mu \end{bmatrix} \begin{bmatrix} \alpha_c - \alpha \\ \beta_c - \beta \\ \mu_c - \mu \end{bmatrix}, \tag{11}$$

where k_α, k_β, k_μ are the bandwidth of middle-speed loop, which is selected in 2~4 rad/s.

Based on the idea of dynamic inversion, the output of control command can be obtained as follows:

$$\begin{bmatrix} p_c \\ q_c \\ r_c \end{bmatrix} = g_2^{-1}(\mathbf{x}_2) \cdot \left(\begin{bmatrix} \dot{\alpha}_d \\ \dot{\beta}_d \\ \dot{\mu}_d \end{bmatrix} - \begin{bmatrix} f_\alpha(\mathbf{x}_2) \\ f_\beta(\mathbf{x}_2) \\ f_\mu(\mathbf{x}_2) \end{bmatrix} \right). \tag{12}$$

Equations (11) and (12) are combined to form the integrated middle-speed loop, and at last control law design of UAV's middle-speed loop is achieved. The control structure corresponding to the middle-speed loop is shown in Figure 4.

4. Simulation Analysis and Verification

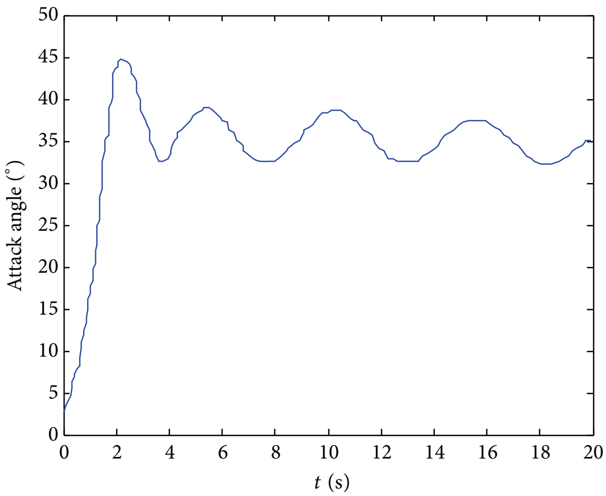
To verify the effectiveness of the proposed method, three different comparative simulation scenarios are carried on. All the computations and experiments are operated on a computer with Core i3 CPU, 3.30 GHz, and Windows XP operating systems. These experiments are depicted as follows. Section 4.1 depicts how to make the UAV enter into the spiral. From Section 4.2 to Section 4.4, the effects of spiral recovery under three different conditions are compared.

4.1. Entering into the Spiral. First, we should try to make an UAU enter into the spiral. Here, the UAV used in the simulation is the fixed-wing with the angle critical of attack 30°. At beginning, the UAV is supposed that it is flying in level, with height 2000 m and velocity 42 m/s. we cut off the control module of spiral recovery, and assume UAV is controlled by the autopilot. Carry on the operation of BHU, and the UAV will come into the spiral after a short time. The change of attitude angle and angular rate are shown in Figures 5(a), 5(b), and 5(c). As is shown in Figures 5(a), 5(b), and 5(c), the attack angle is changing periodically and is greater than the critical attack angle. Three-dimensional trajectory of UAV flight is shown in Figure 5(d). According to Figure 5, it can be seen that UAV is entering in the spiral after the maneuvering operation.

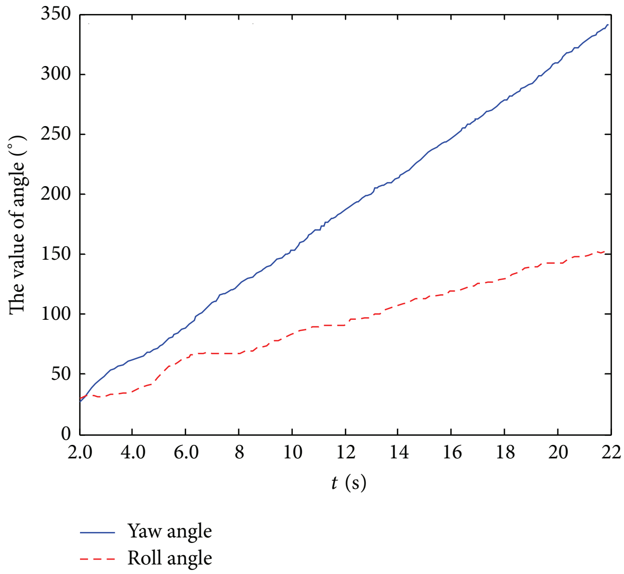
4.2. Autonomous Control of Spiral Recovery. In this section, the work is to verify whether the proposed method can make the UAV recovery from spiral autonomously. Assume that UAV's initial state and the operation of its coming into spiral are the same as those in Section 4.1. Once the UAV enters into the state of spiral, the control module of spiral recovery can be switched automatically. Under the action of spiral recovery controller, the change curves of UAV's attitude angle and angular rate are shown in Figures 6(a)–6(c).

From these figures, it can be seen that when the UAV has entered into the spiral, the control module of spiral recovery will be switched automatically. Then, given $p_c = 0, q_c = 1$, and $r_c = 0$, control the angular velocity of rotation. At $t = 8.7$ s, UAV will cognize that the rotation rate is slower, and then, given $\alpha_c = 5, \beta_c = 0$, and $\mu_c = 50$, control the attack angle and attitude angle. At $t = 14$ s, UAV will cognize the attack angle is lower, and then, given $\alpha_c = 4, \beta_c = 0, \mu_c = 0$. At $t = 19.8$ s, UAV will stop rolling and achieve the desired attitude angle, ultimately recovering from the spiral effectively. The three-dimensional flight trajectory of spiral recovery is shown in Figure 6(d). According to this figure, it can be clearly seen that the UAVs have succeeded to recover from the spiral. That means autonomous control of spiral recovery is effective.

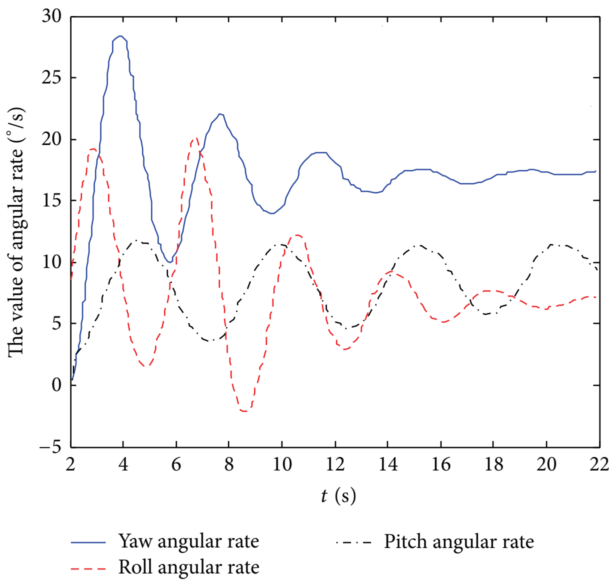
4.3. The Method Named as "Flat, Middle and Push". As is shown in Introduction, an effective way to spiral recovery in manned-fighter field is named as "flat, middle and push." Therefore, in order to further verify the effectiveness of proposed method, this method is introduced to the spiral recovery of the UAV.



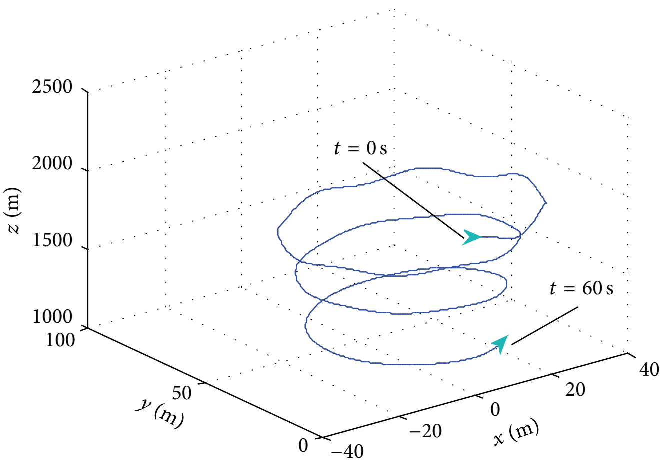
(a) The response curve of attack angle



(b) The response curve of roll angle and yaw angle



(c) The response curve of attitude angular rate



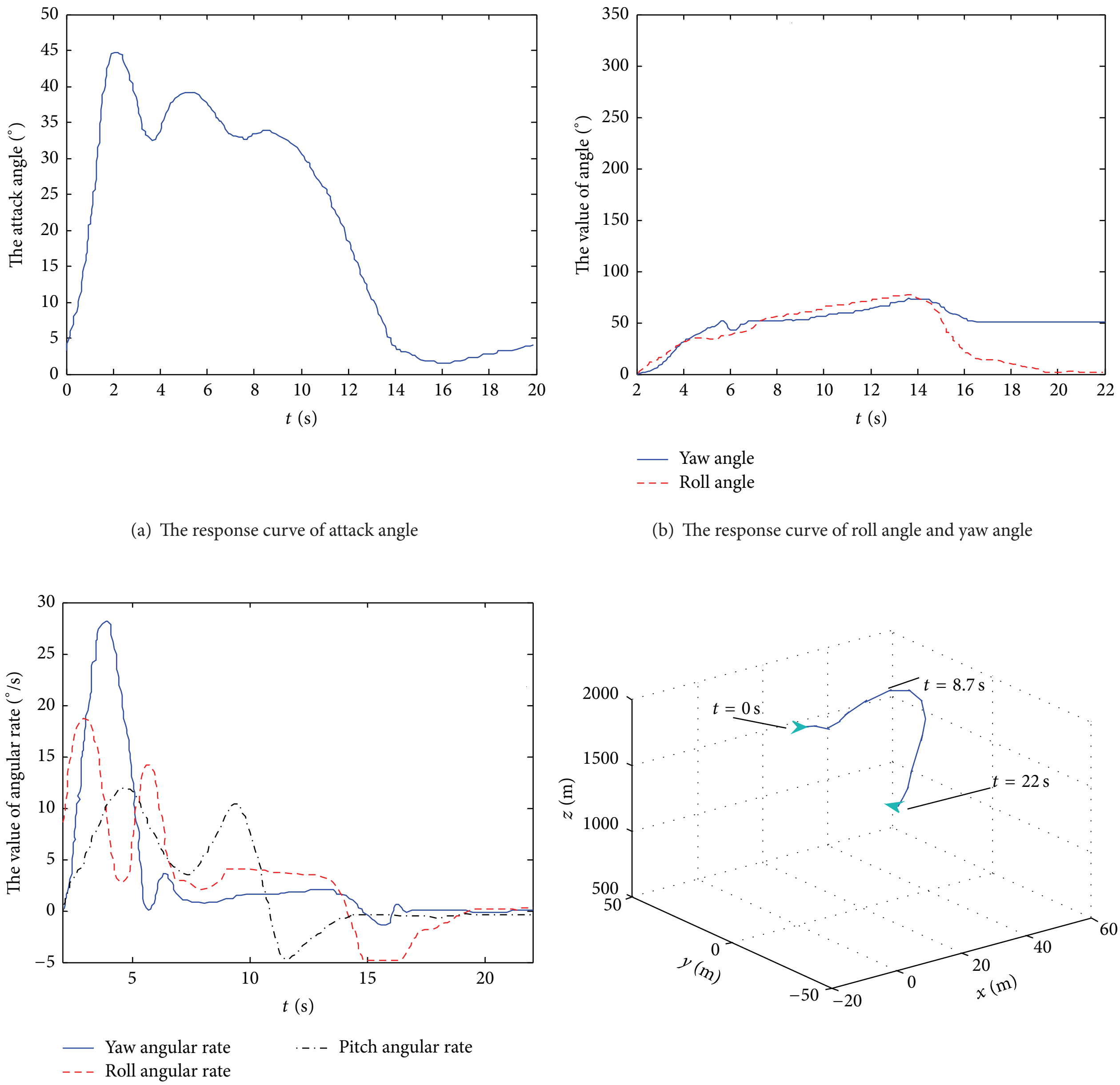
(d) Flight trajectory of UAV's entering into the spiral

Figure 5: The dynamic process of UAV's entering into the spiral.

When UAV is in the spiral, imitate the ground operator to carry on recovery control of the spiral, using the method "flat, middle and push." The process of this method is shown as follows. First, make the rudder flat. Second, put the control handle to the middle position and then push the control handle to the end in the direction of the spiral. Third, when the vehicle stops rotating, put the control handle to the middle position.

The change curves of UAV's attitude angle and angular rate are shown from Figure 7(a) to Figure 7(c), and the three-dimensional trajectory of spiral recovery is shown in Figure 7(d). From these figures, it can be seen that although this method can realize recovery control of the spiral, the control method is weak, and it takes a long time to recover from the spiral. Thus, it may lead to large loss of the height, making it possible for UAV to crash.

4.4. Recover from the Spiral without considering the Control Sequence. In the previous section, the proposed method is verified. However, if we do not consider the control sequence of the controller, what will the effect of spiral recovery be? Regardless of the control sequence, give desired outputs directly, and then, with nonlinear dynamic inversion



(a) The response curve of attack angle

(b) The response curve of roll angle and yaw angle

(c) The response curve of attitude angular rate

(d) Flight trajectory of UAV's spiral recovery

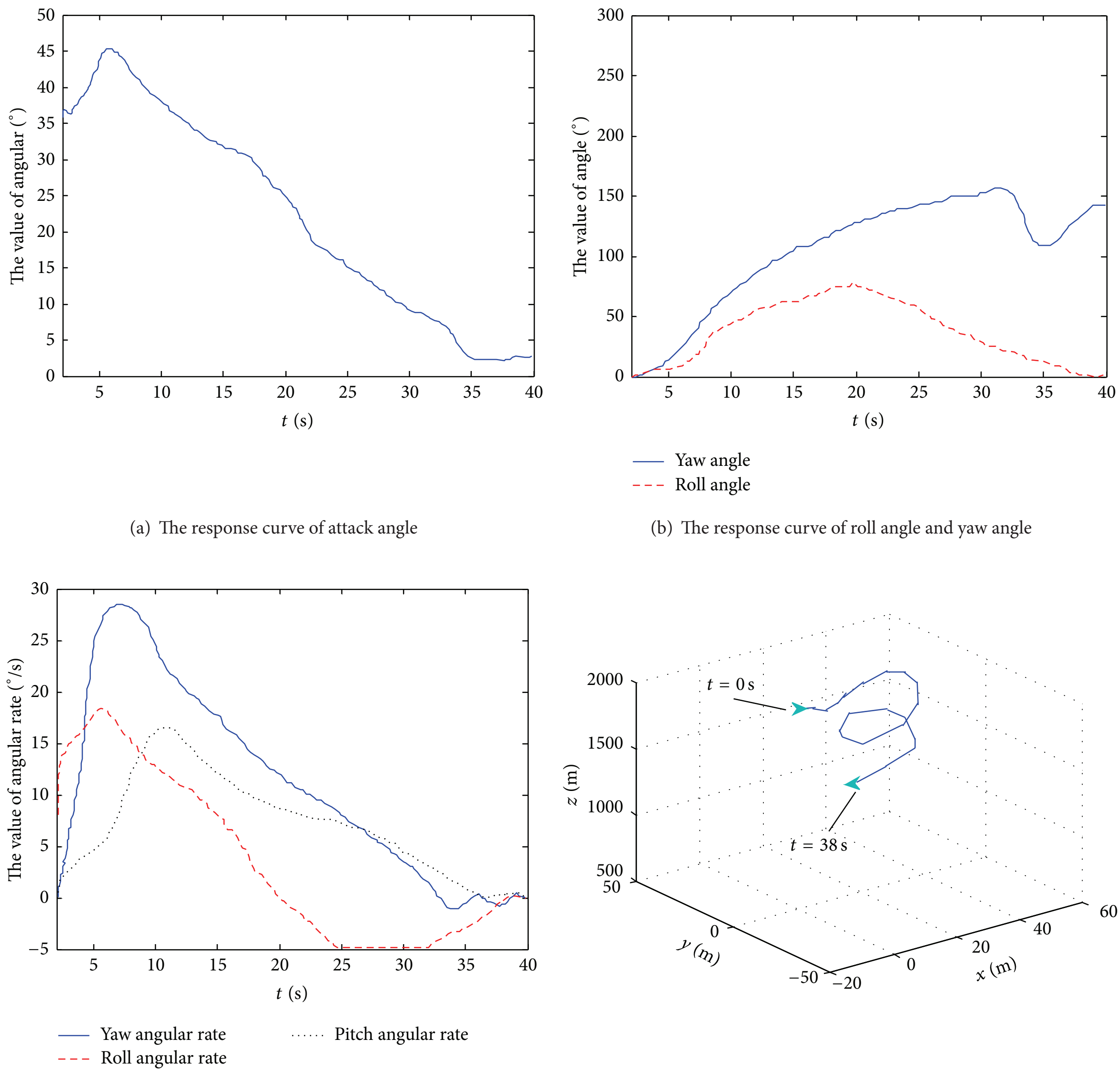
Figure 6: The dynamic process of UAV's spiral recovery.

control laws, the change curves of UAV's attitude angle and angular rate are shown in Figures 8(a), 8(b), and 8(c). Three-dimensional trajectory of spiral recovery is shown in Figure 8(d). From these figures, it can be clearly seen that the change of the angle of attack and the angular rates of attitude are more complex than those in Figures 6 and 7. These figures have shown that if spiral recovery control is carried on regardless of control sequence, the control effect will weaken, thus making the spiral more complex to some degree.

Table 2: The time of recovery from spiral.

Simulation number	II	III	IV
Recovery time	19.8 s	38.1 s	36.7 s

To verify the control effect of the three simulations above, the time of spiral recovery of the three comparative simulations above is shown in Table 2. According to the above table, it can be clearly seen that the proposed method in



(a) The response curve of attack angle

(b) The response curve of roll angle and yaw angle

(c) The response curve of attitude angular rate

(d) Flight trajectory of UAV's spiral recovery

FIGURE 7: The dynamic process of UAV's spiral recovery.

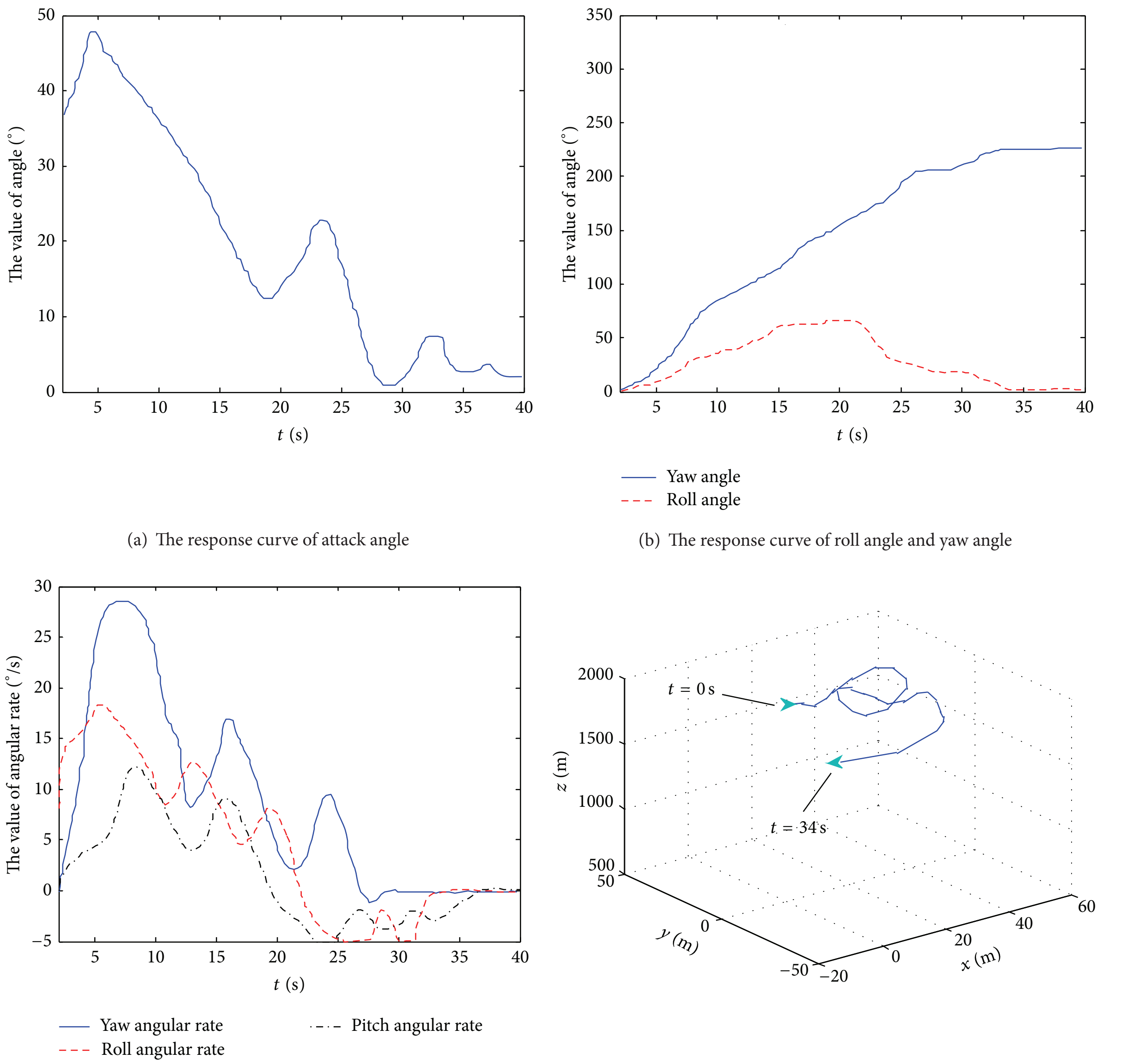
this paper to recover from the spiral is the shortest one. This means this method can make the UAV recover from the spiral autonomously. Finally, the effectiveness of the proposed control method has been verified.

5. Conclusions

In this paper, an autonomous control method for UAV's spiral recovery is proposed, which is based on nonlinear dynamical inversion. The simulation results have verified that the proposed control method can make the UAV recover from the spiral effectively. Compared with the other two methods, mentioned in the paper, the time of recovery from the spiral is the shortest for this method. Our further study will focus on the robustness of this control method and carry on the practical flight experiment on a small UAV of our research team to verify its usage value.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.



(a) The response curve of attack angle

(b) The response curve of roll angle and yaw angle

(c) The response curve of attitude angular rate

(d) Flight trajectory of UAV's spiral recovery

Figure 8: The dynamic process of UAV's spiral recovery.

Acknowledgments

This research is supported by the National Science Foundation of China (NSFC) under Grant no. 61105012 and the National Aviation Science Foundation of China (NASFC) under Grant no. 20135896027.

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