ENERGY MANAGEMENT METHOD FOR AN UNPOWERED LANDING

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(Communicated by Bin Li)

Abstract. The unpowered landing of unmanned aerial vehicle (UAV) is a critical stage, which affects the safety of flight. To solve the problem of the unpowered landing of UAV, an energy management scheme is proposed. After the cruise is over, the aircraft shuts down the engine and begins to land. When the aircraft is in the high altitude, the dynamic pressure is too large, and it is difficult to open the speed brake. When the aircraft is in the low altitude, it is close to the runway. The method of S-turn may make the aircraft veer off the runway and may be unable to land. So two different schemes of high altitude and low altitude are designed to control energy. In the high altitude, when the energy is too high, it takes the S-turn scheme to consume excess energy. At the same time, the availability and reasonability of the S-turn scheme is demonstrated. In the low altitude, the open angle of speed brake is controlled to adjust the energy consumption. Finally, the simulation results are given to illustrate the availability of energy management.

1. Introduction. With the development of aviation technology, control technology and navigation technology, UAV has been widely used in military, civilian and scientific research fields [1, 2, 3, 4, 5, 6]. The flight process of a UAV generally includes taking-off, air cruise and landing. The landing stage is a complicated and risky stage during the flight process, and it is also a key stage which determines whether the UAV can safely complete a mission. There are many studies on the automatic landing where the engine of the aircraft is working normally [7, 8, 9, 10, 11]. Compared with the normal aircraft, the unpowered landing of the aircraft has great advantages. With the unpowered landing method, the aircraft does not need to carry too much fuel when taking off, thus the burden of fuel reduces. Moreover, when the aircraft engine fails, the unpowered landing can ensure the aircraft to land safely, which is very important in practice. However, compared to the normal landing with a working engine, the unpowered landing has three major challenges: (1) The total voyage of the aircraft should be within a reasonable interval and should not be too far away; (2) The thrust cannot be used to control the speed; (3)
Since the total energy of the aircraft will just decrease, the ability of pulling up and going around is reduced.

When the aircraft is unpowered, it is necessary to plan the flight path in order to enable the aircraft to return to the runway. Literature [12] handles the unpowered trajectory planning and landing process by simulating the pilot’s thinking process. Literatures [13, 14, 15, 16] propose an unpowered landing plan for aircraft based on machine vision and image processing. Literatures [17, 18, 19, 20] design the landing trajectory by various optimization algorithms, such as [21, 22, 23]. In addition, the altitude of the UAV is required to be controlled such that the aircraft can land on the runway, and the speed need to be controlled, ensuring that the touchdown velocity is not excessively large or small to avoid damaging the landing gear or the tail. Therefore, during the landing process, the energy of the aircraft needs to be controlled. Literatures [24, 25, 26, 27] propose various schemes for controlling energy in the energy management phase of the aircraft. The unpowered landing of space shuttle is described in [28], which uses the S-turn scheme to consume energy. Literature [29] describes the landing scheme of the reusable launch vehicle (RLV), where the heading alignment cylinder adjustment scheme is used to consume energy through the movement of the heading alignment cylinder. However, these methods are only for high-altitude energy management, while the low altitude case is not mentioned. In fact, without energy management at low altitude, the safety of the terminal landing of aircraft is seriously affected. Therefore, in this paper, the energy management for unpowered landing of aircraft is considered, where the S-turn scheme and the speed brake control scheme are used in the high altitude and the low altitude respectively. An unpowered landing process begins after the engine is shut down at the end of the cruise phase of the UAV. To achieve the unpowered landing of UAV, in the high altitude, we design different flying voyages according to the different energies to ensure that the energy is in a reasonable and controllable range when the aircraft reaches the low altitude. In the low altitude, the precise control of the standard energy is achieved by opening and closing the speed brake.

In summary, the contributions of the paper are as follows. Firstly, for the S-turn scheme, the calculation method of the predicted range and track angle in each stage is analyzed and designed in detail. Especially, the calculation method of the predicted range designed changes continuously, and the expected track angle command converges monotonously to zero. Obviously, the reasonable design of each phase of S-turn scheme in high altitude can ensure flight safety. Secondly, in the low altitude, a method is presented to find the glide path with uniform speed by controlling the speed brake, where the self-stability of the glide path equilibrium velocity is used in the low altitude to increase the robustness of the adjustment of the speed brake. Then, a safe landing path is planned when the speed brake is half-opened to ensure that the UAV has the ability to complete the safe return landing mission by adjusting the speed brake to manage energy.

The rest of this paper is organized as follows: Section 2 describes the S-turn scheme to control the flight range of aircraft to achieve energy management. Section 3 describes the control scheme for the speed brake to control energy. Section 4 performs simulation analysis on the proposed method. A summary of unpowered energy management is given in Section 5.

2. Energy management of S-turn scheme. In this section, we first discuss the correlation between the aircraft’s energy and the range, which can lay a theoretical
basis for the S-turn energy control scheme. Here, the range refers to the projection
distance of the flight path to the ground. Then it is illustrated in detail on how
to specifically perform the flight process at each stage during the S-turn scheme.
Finally, the availability and reliability of the S-turn scheme are demonstrated by
analyzing the continuity of the predicted range and the convergence of the track angle.

2.1. Relationship between energy and range. The mechanical energy per unit
weight of the aircraft is
\[
\frac{E}{G} = h + \frac{V^2}{2g} = h + \frac{\dot{q}}{\rho g},
\]
where \( E \) is the mechanical energy of the aircraft; \( G \) is the gravity of the aircraft; \( h \)
is the height of the aircraft in the airport coordinate system; \( V \) is the velocity of
the aircraft; \( g \) is the acceleration of gravity; \( \dot{q} \) is the dynamic pressure; \( \rho \) is the air
density.

Theorem 2.1. If \( g \) is a constant, then the mechanical energy of the aircraft is neg-
atively correlated with the range with \(-\frac{D}{G \cos \gamma}\) as the negative correlation coefficient.

Proof. According to (1), the energy per unit weight of the aircraft varies with the
expected range,
\[
\frac{d(E/G)}{ds} = \frac{d(E/G)}{dt} \frac{dt}{ds} = \frac{d((h + \frac{V^2}{2g}))}{dt} \frac{dt}{ds}. \tag{2}
\]
Note that
\[
\frac{dh}{ds} = \tan \gamma, \tag{3}
\]
\[
\frac{dV}{dt} = -\frac{D}{m} - g \cdot \sin \gamma, \tag{4}
\]
\[
\frac{ds}{dt} = V \cdot \cos \gamma, \tag{5}
\]
where \( s \) is the range; \( D \) is the resistance of the aircraft; \( \gamma \) is the glide angle; \( m \) is
the mass of the aircraft. Substituting (3), (4), (5) into (2), we have
\[
\frac{d(E/G)}{ds} = \tan \gamma - \frac{V}{g} \cdot \frac{D}{m} + g \cdot \sin \gamma \cdot \frac{1}{V \cdot \cos \gamma} = -\frac{D}{G \cdot \cos \gamma}.
\]
Then it is shown that the energy consumption of the aircraft is related to the
resistance \( D \) and the glide angle \( \gamma \). Hence, the conclusion of this theorem follows
readily.

It can be seen from Theorem 2.1 that the relationship between the unit energy
of the aircraft and the range is \( E = f(S) \), which is monotone decreasing. According
to the safe returning voyage in the normal state, the function relationship of energy
with range can be designed. This function reflects the correspondence between the
energy and the range in the nominal state, which provides guidance to design the
S-turn scheme. Since the energy of the aircraft at each position is available in
real time, by comparing with the energy channel specified in the nominal state, a
judgment condition is provided for the logical switching of aircraft flight.
2.2. **The stages in S-turn.** The design idea of S-turn scheme to control energy can be concluded as follows. Ensuring that there exists a S-turn in the return voyage in the nominal state by designing a reasonable glide path, then a nominal energy-range function curve is formulated. For the problem of excessive energy in the return voyage of the aircraft, it can be solved by increasing the S-turn range to consume more energy. For the stage returning to the runway, if the energy of the aircraft is insufficient due to resistance and so on, the energy management stage is started to reduce voyage so as to reduce energy consumption. The S-turn scheme is specified below.

According to the control strategy and different missions, the S-turn returning process is divided into the following four stages: S-turn phase, acquisition phase, heading alignment cylinder (HAC) phase and pre-approach phase. The ground path planning of the turning scheme is depicted in Fig. 1, where the coordinate system is shown. The black rectangle indicates the position of the runway, the point $P$ is the projection point at 4500m above sea level, and the circle with the center $O$ is called the heading alignment circle (HAC)\(^1\), which is tangent to the direction of the runway at point $P$. The logic switching at each stage of the terminal energy management when the aircraft returns to the runway is shown in Fig. 2.

2.3. **The predicted range.** Based on the above S-turn flight plan, the predicted range $RP$ is of great importance. The predicted range and the real-time energy of the aircraft are used to determine whether the aircraft should adopt S-turn phase, when it should enter the acquisition phase and the pre-approach phase. Moreover, a feedback control for the altitude is adopted in the longitudinal control law of the aircraft, since the calculation methods of the predicted range and the altitude are coupled. Therefore, we must ensure that the change of predicted range is continuous during the entire process of S-turn energy management, otherwise the longitudinal control quality of the aircraft will get worse. Meanwhile, starting from the acquisition phase, the desired track angle of the aircraft is used to control the lateral-directional flight control. The expected track angle must be reasonable, especially from the late acquisition phase (flying along the tangent direction of the heading alignment circle), the track angle of the aircraft should monotonically converge to zero to ensure the rationality of the aircraft turning. The calculation methods for the predicted range and track angle at each stage are given as follows.

As shown in Fig. 3, when the aircraft is in the S-turn phase and the acquisition phase, the predicted voyage $RP$ is

$$RP = \tilde{s}_t + s_h + \tilde{x}_h + x_h,$$

where $\tilde{s}_t$ is the flight distance on the turning arc when the aircraft rolls to capture the HAC, which is given below,

$$\tilde{s}_t = r_s \cdot |\angle st|.$$

Here, $r_s$ represents the required turning radius when the aircraft rolls with the maximum allowable roll angle in the current speed, that is,

$$r_s = \frac{V^2(t) \cdot \cos \gamma}{\tan \phi \cdot g}.$$

\(^1\)In this paper, left HAC is used as an illustration. In fact, there are symmetrical positive and negative HAC. They can make S-turn flights.
Here, $\phi$ is the actual roll angle of the aircraft, $\angle st$ is the required rotation angle when the aircraft’s velocity changes from the current direction to the direction heading to the HAC’s tangent point, that is, 

$$
\angle st = \left[ \arctan \left( \frac{y \pm r_{HAC}}{x - x_h} \right) \right] \pm \arctan \left( \frac{r_{HAC}}{r_a} \right) - \chi.
$$

Here, the “±” sign depends on which HAC is used for alignment. The left HAC corresponds to “+” while the right HAC corresponds to “−”. $r_a = \sqrt{r_c^2 - r_{HAC}^2}$, and $r_c$ is the distance between the aircraft and the center of the HAC. $s_h$ is the projection distance when the aircraft travels along the tangential direction of the HAC, that is, 

$$
S_h = \sqrt{(r_a - r_s \cdot \sin |\angle st|)^2 + (r_s - r_s \cdot \cos |\angle st|)^2}.
$$

Note that $s_h$ is an approximation of the theoretical value, which is not perpendicular to the radius of the acquisition circle. In actual, the aircraft should fly according
Figure 2. Flow chart of terminal energy management at various phases.

The distance from the aircraft to the center of the HAC circle is less than the specific constant value. The calculation methods of $\tilde{x}_h$ and $x_h$ are identical at each stage, which will be stated uniformly in the following.

When $r_c \leq 1.1 \cdot r_{HAC}$ and the aircraft have not entered the pre-approach phase, as shown in figure 4, the predicted range of the HAC phase is

$$RP = r_a + \tilde{x}_h + x_h,$$

$$\tilde{x}_h = r_{HAC} \cdot \left[\arctan\left(\frac{y \pm r_{HAC}}{x - x_h} \pm \arctan\left(\frac{r_{HAC}}{r_a}\right)\right)\right].$$

The deviation between the calculated value and the truth value is very small. And when the aircraft turns to capture the HAC, the radius changes greatly as the velocity decreases. The actual flight path of the aircraft is smaller than the predicted range. The deviation here is large, and the energy consumption can be only controlled in a reasonable range, which will be controlled precisely until getting into the control process of the retarder. It is also a more reasonable choice to reserve more energy to enter the low attitude landing phase. Therefore, the way of calculating is reasonable and effective.
$x_h$ denotes the actual distance from the heading alignment circle to the runway and it is an initially given constant. When the aircraft enters the HAC, wherever it is in the HAC phase or the pre-approach phase, the predicted range is

$$RP = \tilde{x}_h + x_h.$$  

(9)

Here, $\tilde{x}_h$ means the arc length between point P and the projection point from the line connecting the HAC’s center and the aircraft to the arc, which is used...
to approximately represent the voyage distance along the arc. In summary, the method for calculating the predicted range of the HAC phase and the pre-approach phase is that outside the HAC, is used (8) and inside the HAC, is used (9).

The predicted range in each phase of the aircraft S-turn scheme is as described above. In the S-turn phase and the early stage of acquisition phase (adjust the heading direction to the tangential direction of the heading alignment circle), the predicted range of these two processes are uncertain, because the S-turn flying range and the track angle are completely determined by the energy relationship; in the early stage of the acquisition phase, using the aileron to control the maximum roll in the paper, in order to quickly capturing the heading alignment circle to be tangent to the circle. The turning arc length required for this process is affected by the S-turn phase. However, in the late stage of the acquisition phase (flying along the tangent direction of the heading alignment circle), the HAC phase and the pre-approach phase, in order to ensure the reliability and stability of the S-turn scheme, the track angle and lateral deviation must be monotonically convergent.

**Theorem 2.2.** After the aircraft enters the late stage of the acquisition phase, the aircraft’s track angle $\chi$ converges to zero monotonically. The whole predicted range changes continuously.

*Proof.* When the aircraft enters the late stage of the acquisition phase, from (6) and (7), it can be seen that the predicted range of the captured section becomes $RP = r_a + \bar{x}_h + x_h$, the prediction method of which can transit to the HAC phase continuously. Considering (6), (8) and (9), the entire predicted range algorithm is continuous.

As shown in Fig. 5, before the aircraft enters the pre-approach phase, when the aircraft flies along the tangential direction of HAC, and the distance from the aircraft to the center of HAC satisfies that $r_c \geq 1.1 \cdot r_{HAC}$, it holds that

$$\chi_{cmd} = \angle \text{cir} + \angle \text{tan}. \quad (10)$$

Here $\chi_{cmd}$ denotes the calculated expected aircraft track angle. Then the aircraft flies towards the tangential direction of HAC. When the distance between the aircraft and the center of HAC satisfies that $r_c < 1.1 \cdot r_{HAC}$, we have

$$\chi_{cmd} = \angle \text{cir} + \arcsin(r_{HAC}/R). \quad (11)$$

When the aircraft is at the intersection point of the acquisition phase and the HAC phase, the calculation results of $\chi_{cmd}$ are equal by using (10) and (11). Therefore, $\chi_{cmd}$ changes continuously from the acquisition phase to the HAC phase. From (11), the aircraft will be flying towards the HAC interior.

The predicted range $RP \leq x_h + r_\theta$ is used to judge whether the current phase is the HAC phase or the pre-approach phase. That is, in HAC, $Oa$ is the dividing line; outside HAC, the spiral $ab$ is the dividing line, which is shown in Fig. 6. Then the calculation method of $\chi_{cmd}$ in the pre-approach phase is illustrated below.

First, define $\alpha$ as the angle between the medial axis and the line connecting from the airplane to the end point $d$ of the runway. Suppose the aircraft enters the pre-approach phase along the spiral $ab$ from point $c$, as shown in Fig. 6, here $\chi = \gamma_1$.

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3$\theta$ is a constant which is adjusted according to the actual situation. If $\theta$ is too large, the adjustment of the track angle is affected in the heading calibration section. If $\theta$ is too small, the capacity to adjust the lateral deviation in the pre-approach section is limited.
then we have

$$\alpha_1 = \arctan \left( \frac{r_{HAC} \cdot (1 - \cos \gamma_1) + r_{HAC} \cdot (\theta - |\gamma_1|) \cdot \sin |\gamma_1|}{x_h + r_{HAC} \cdot \sin |\gamma_1| + r_{HAC} \cdot (\theta - |\gamma_1|) \cdot \cos \gamma_1} \right).$$

Here $\alpha_1$ is the angle between the medial axis and the line connecting from the point $c$ to the end point $d$ of the runway, and $r_{HAC} \cdot (\theta - |\gamma_1|)$ is the length of the tangent line $ce$. If $cd$ is a specified dividing line, then set the desired track angle $\chi_{cmd} = \gamma_1$ when $|\alpha| > |\alpha_1|$. Obviously, for every point on the spiral $ac$, one has $\chi > \gamma_1$. Therefore, the transition of the desired track angle $\chi_{cmd}$ is reasonable.

When the aircraft reaches the line $Oa$ inside the HAC, from (11), the track angle $\chi_{cmd} = \chi_{Oa}$ is invariant on anywhere of the line $Oa$. $\chi_{Oa}$ is a constant value. Thus,
ad can be set as the outermost dividing line of the pre-approach phase, and the corresponding \( \alpha_{ad} \) can be calculated. Let \( \chi_{cmd} = \chi_{Oa} \) when the aircraft flies past the line \( Oa \) and \( |\alpha| > |\alpha_{ad}| \). By setting multiple standard switching points on the spiral (like the point \( a \) and \( c \)), the track angle can be gradually adjusted according to different \( \alpha \). With this, the terminal track angle can be changed to be aligned with the medial line of the runway. Therefore, the desired value of the track angle converges to zero and the abnormal jump will not appear.

Hence, with the ingenious cohesion between each phase of the S-turn scheme, the algorithm of the predicted range is continuous and reliable. Moreover, the algorithm of the desired track angle is monotonically convergent and it gradually turns towards the direction of the medial line. Thus, the validity and the reliability of the proposed S-turn strategy is verified.

3. The scheme of the speed brake. In this section, the scheme of the energy control using the speed brake is demonstrated. First of all, it was demonstrated that the aircraft can land at the uniform speed glide path by the control of the speed brake. Then, the control command of the speed brake is given to ensure that the aircraft has the appropriate energy during the landing phase.

The aircraft is subjected to lift \( L \), drag \( D \) and gravity \( G \) during the flight. And the direction of the force is shown in Fig. 7. The wind axis coordinate system is shown in the figure.

\[ \text{Figure 7. The force direction of the aircraft} \]

In the \( x_w \) direction, the resultant force of the aircraft is \( G \cdot \sin \gamma - D \). In the \( y_w \) direction, the resultant force of the aircraft is \( L - G \cdot \cos \gamma \). When the aircraft glides by the following glide angle \( \gamma_0 \), it is necessary to ensure that the resultant force in the \( y_w \) direction is 0, that is, the expected lift of the aircraft is \( L_e = G \cdot \cos \gamma_0 \). According to the expected lift of the aircraft, the state of the aircraft is obtained. Then, the resistance of each height is calculated in the case where the speed brake is closed and opened. Denote the resistance as \( D_c \) when the speed brake is closed and as \( D_o \) when the speed brake is opened. If the expected resistance \( D_e = G \sin \gamma \) is between \( D_c \) and \( D_o \), it means that there is a glide path to make the speed of the aircraft unchanged.

**Theorem 3.1.** There is a glide path where the glide speed can keep unchanged at a desired speed by the control of speed brake.
Table 1. The resistance of closed speed brake and opened speed brake

| h(m) | ρ(kg/m³) | α(°) | D_c(N) | D_o(N) |
|------|----------|------|--------|--------|
| 4500 | 0.7768   | 4.86 | 5541   | 7565   |
| 4000 | 0.8191   | 4.74 | 5643   | 7782   |
| 3500 | 0.8632   | 4.46 | 5769   | 8028   |
| 3000 | 0.9091   | 4.36 | 5913   | 8296   |
| 2500 | 0.9569   | 4.12 | 6071   | 8558   |
| 2000 | 1.0065   | 3.76 | 11760  | 14290  |
| 1500 | 1.0580   | 3.60 | 12290  | 14950  |
| 1000 | 1.1116   | 3.44 | 12840  | 15630  |

Proof. When the aircraft glides with the glide angle \( \gamma_0 \), the expected lift of the aircraft is \( L_e = G \cos \gamma_0 \), and the formula for the lift is

\[
L = \frac{1}{2} \rho V^2 S_r c_y.
\]  
(12)

Here, \( S_r \) is the reference area of the aircraft, \( c_y \) is the lift coefficient. The formula for the resistance is

\[
D = \frac{1}{2} \rho V^2 S_r c_x.
\]  
(13)

Here, \( c_x \) is the resistance coefficient.

Assume that the expected velocity is \( V_e = 500 km/h \), the glide angle is \( \gamma_e = -15^\circ \) and \( \gamma_e = -19^\circ \) when the gear is down. The expected lift is \( L_e = G \cos \gamma_e \). In the low altitude, the function of the lift coefficient \( c_y \) is

\[
c_y = f(\alpha, Ma, h).
\]  
(14)

Here, \( Ma \) is the mach of the aircraft, and \( \alpha \) is the angle of attack.

According to (12) and (14), the angle of attack range is \([3.44^\circ, 4.86^\circ]\) under the condition of the expected lift. Also, the resistant coefficient \( c_x \) is

\[
c_x = f(\alpha, Ma, h, SB).
\]

where \( SB \) is the open angle of the speed brake. According to the angle of attack, the range of resistance coefficient \( c_x \) is \([1.9218, 3.7882]\). According to (13), when the speed brake is closed, the maximum resistance \( D_c^{\text{max}} \) and the minimum resistance \( D_c^{\text{min}} \) within a height range can be known; when the speed brake is open, the maximum resistance \( D_o^{\text{max}} \) and the minimum resistance \( D_o^{\text{min}} \) within a height range also can be known. If the speed of the aircraft at the glide path keeps unchanged, the expected resistance \( D_e \subseteq [D_c, D_o] \). Therefore, in a fixed glide path, it is possible to infer from the expected speed whether there is a glide path that maintains a constant speed by control speed brake.

According to (12) and (13), the resistance of closed speed brake and opened speed brake is shown as the table 1. When flying at an altitude greater than 2500m, The expected resistance \( D_e = G \sin |\gamma_e| = 7340N \), \( D_c \) is between \( D_e \) and \( D_o \). The vehicle is able to glide down at a constant speed of \( V = 500 km/h \). When the landing gear is down, even thought the aircraft flying on a steep glide path, The expected resistance \( D_e = G \sin |\gamma_e| = 9234N \), \( D_e < D_o \), the aircraft has too much resistance to maintain a constant speed, and landing at a uniform high speed is not a good option. So a safe landing path is planned when the speed brake is half-opened.
For the steep glide path that is not falling at a constant speed when the landing gear is down, the open angle of the speed brake should be judged based on the energy. In order to reflect the energy characteristics, the control command of speed brake is obtained by calculating the relationship between the current actual unit weight energy $EN$ and the current expected unit weight energy $EN_u$ by predicting the interpolation of the voyage. The open angle of speed brake command $SB_{cmd}$ is

$$SB_{cmd} = \left[ \frac{1}{2} + k \times (EN - EN_u) \right] \times 50.$$ 

$sat(x)$ is a saturated function,

$$sat(x) = \begin{cases} 
0, & x \leq 0, \\
 x, & 0 < x \leq 50, \\
 50, & x > 50.
\end{cases}$$

$$sat(SB_{cmd}) = \begin{cases} 
0, & SB_{cmd} \leq 0, \\
 SB_{cmd}, & 0 < SB_{cmd} \leq 50, \\
 50, & SB_{cmd} > 50.
\end{cases}$$

Here, $EN_u = \frac{1}{2} \times \frac{v^2}{g} + h$, $k$ is a constant gain. In this paper, the maximum open angle of the speed brake is $50^\circ$.

Remark 1. In this paper, we establish a basic analytical framework based on an energy management scheme for the unpowered landing of unmanned aerial vehicle. There are still some important issues need to be considered in the future, such as, the robust stability [30, 31], voyage coordination [32, 33], and so on.

4. Simulations. In this section, simulation results for the S-turn scheme and the speed brake scheme are presented. We choose 4500m as the boundary height of high and low altitude. When the aircraft is above 4500m in height, S-turn scheme is used for energy management. When the aircraft is below 4500m in height, the speed brake scheme is used for energy management.

4.1. The results of S-turn scheme. For the S-turn scheme, we increase the initial velocity by $+100\text{m/s}$ to make the energy higher than the nominal energy channel. The energy curve of the aircraft is shown in Fig. 8, and the actual flight trajectory of the aircraft is shown in Fig. 9. Similarly, we reduce the initial velocity by $-100\text{m/s}$ to make the energy below the standard energy channel. The energy curve of the aircraft is shown in Fig. 10. The actual flight trajectory of the aircraft is shown in Fig. 11.

In the Fig. 8 and Fig. 10, $EnAcq$ is the unit standard energy line, $EnST$ is the highest unit energy line, and $EnUnit$ is the actual unit energy line during flight. At the initial point $A$, the actual energy of the aircraft exceeds the highest energy line, so the aircraft enters the S-turn phase and the turning time is longer than that of the normal state, and the energy begins to decrease rapidly. When the aircraft flies to the point $B$, the energy of aircraft is under the nominal energy line, so the aircraft ends the S-turn part and enters the acquisition part. The flight trajectory of the aircraft in the high energy state is shown in Fig. 9. When the initial energy of the aircraft is low, aircraft travels along a straight line through the energy management phase to reduce energy consumption, at the point $C$, the actual energy of the aircraft enters nominal energy channel. The flight trajectory
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4. The results of speed brake scheme. In order to verify the energy management capability of the speed brake, we consider two situations:

1. The speed brake is closed in the whole process, and it has no effect on the resistance. The most gentle glide path is obtained to ensure a safe landing in the high altitude section.

2. The speed brake is fully open in the whole process, and the steepest glide path is found that ensures a safe landing in the high altitude section.

Now, in the case of the same initial energy, the low-altitude glide path is $-15^\circ / -19^\circ$, and the touchdown velocity is between 280$km/h$ and 300$km/h$ to meet the landing requirements. The simulation is performed and the final result is shown in Table 2.
It can be seen from Table 2 that the control effect of the speed brake is obvious. In the case of the same initial energy, the range of the glide path of the high-altitude aircraft can be changed from $-9^\circ$ to $-29^\circ$ by adjusting the speed brake.

In the nominal case, we need the speed brake to open about $25^\circ$ to ensure a larger controllable range. The simulation curves of the speed brake is shown in Fig. 12, 13, 14.

Here, $EnUnit$ is the actual energy, $EnCmd$ is the expected energy and $SB$ is the open angle of the speed brake. As can be seen from the figures, the aircraft can control the energy through the opening and closing of the speed brake to guarantee
that the energy is consistent with the nominal energy line finally. Therefore, from the above simulation results, it can be verified that the control effect of the speed brake is obvious.

5. **Conclusions.** This paper presents S-turn scheme and speed brake control scheme for energy management. It is confirmed that these two schemes can manage the energy effectively in the unpowered landing process. The methods are simple, reliable and have a good control effect. In the high altitude, due to the dynamic pressure
limits, the speed brake can not be opened. Therefore, the S-turn scheme is adopted to achieve energy management by increasing or reducing the voyage. According to the function relation between the predicted range and energy, the aircraft automatically plans its high-altitude voyage. In the low altitude, the aircraft is close to the runway, it should fly along the axis of the runway, so the speed brake scheme is adopted, and the speed brake can control energy more accurately. We have designed a method to find the glide path that guarantees the uniform flight speed of the aircraft. After that, the energy of the aircraft is controlled in the steep glide path according to the nominal energy to ensure the safe landing.

Acknowledgments. We would like to thank you for handling our paper. Any suggestion and comment are welcome.

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