29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

AUTOMATED CONTROL STRATEGY FOR HALE UAV FLAMEOUT LANDING AND ITS FLIGHT SIMULATION STUDY

Shi Wenqing*, Yuan Zhengzhong*, Zhang Lei*
*** AVIC Chengdu Aircraft Design & Research Institute, Chengdu, China**

Abstract

An automated control strategy was proposed in the article to solve the flameout landing problem encountered by High Altitude Long Endurance Unmanned Aerial Vehicle (HALE UAV) during its mission flight. Theoretical analyses of HALE UAV flight characteristics after engine failure were discussed at first to establish the control strategy design principles. Modelling and simulation of flameout flight dynamics, flight control and state transition were carried out to facilitate the detail design, optimization and verification of the control strategy. A number of designated and random simulation cases including those in complicated situations were tested. Statistical results showed that a satisfactory success rate was finally reached by using the proposed automated control strategy.

1 Flameout Landing Problem

Forced landing due to engine failure, i.e. flameout landing, is a problem that should be taken seriously by all kinds of aircraft. For manned aircraft, this kind of action is conducted by pilots that had been trained to be able to make right decisions and to take proper steps in such emergency.

For Unmanned Aerial Vehicle (UAV), the flameout landing becomes complicated. Up to present, the architecture of flight management and flight control law comprehensively used by UAVs cannot yet deal with the random happened emergency such as a flameout landing with a reliable and smart enough artificial intelligence which would be characterized by dynamic replanning and adaptive control. Generally, when engine failure happens, the human controller in the ground control station has to take over the most or even full authority of control of the flameout UAV and act properly according to the parameter readings on monitor screens. The success rate under this condition used to be unsatisfactory due to the reasons such as unfamiliar flameout flight characteristics, lacking of direct information, unintuitive man and machine interface, wireless link degradation possibility and psychological burden of the human controller.

Specifically, for High Altitude Long Endurance (HALE) UAV, the flight altitude and air speed during most of its mission time are close to the engine working limits, which increases the engine failure risk. Meanwhile, the high lift-to-drag ratio and low dynamic response of the HALE UAV require an elaborative management of its navigation (position and heading) and energy (altitude and speed) from beginning to end when flameout landing should be carried out. So there is a strong demand for an automated control strategy which enables the HALE UAV mission or flight control system to handle the engine failure situation with a forced landing included.

In the article, an automated control strategy would be proposed to provide a solution to the flameout landing problem with an improved success rate within the framework of current UAV’s flight management and control. That means it could be realized conveniently in currently developing HALE UAVs and in those already in service.

2 Flameout Flight Characteristics

2.1 Forces Applied

When engine flameout happened, the propulsive force would be lost. Meanwhile, additional aero forces and moments would emerge compared to normal flight, because that the near zero flow ratio through the inlet, engine and nozzle would change the outer flow patterns of the aircraft.

Spillage drag and afterbody drag should be considered as the first order factors, which would impact the key performance of flameout flight such as glide ratio and descent rate. Pitch and yaw moments should be accounted as well which would affect the flameout flying stabilities and control qualities. Furthermore, the efficiencies of control surfaces should be checked due to the possible flow separation tendency in the absence of engine flow injection.

The forces on the aircraft during straight glide and coordinated descent turn are as shown in Fig.1. Lift, drag and gravity forces dominate the flameout flight characteristics, while the airspeed, angle of attack and the bank angle determine these forces.

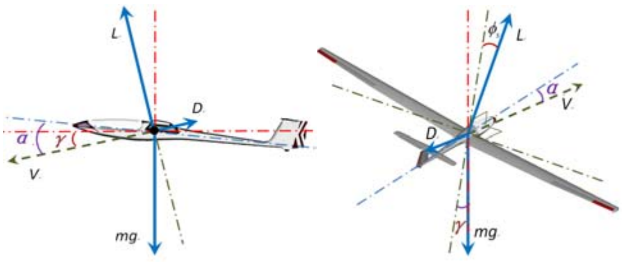

Fig.1 Forces Applied on UAV During Flameout Flight

2.2 Straight Glide

The motion equations for UAV's straight glide in static atmosphere are

$$m\frac{\mathrm{d}V}{\mathrm{d}t}=mg\sin\gamma-\frac{1}{2}\rho V^2SC_D \qquad (1)$$

$$mV\frac{\mathrm{d}\gamma}{\mathrm{d}t}=\frac{1}{2}\rho V^2SC_L-mg\cos\gamma \qquad (2)$$

where m is aircraft mass, g is acceleration of gravity, ρ is air density, V is air speed, S is reference area, C_L is lift coefficient, C_D is drag coefficient and γ is flight path angle.

When the UAV achieves a steady glide (equilibrium glide), we have its glide ratio

$$\frac{\mathrm{d}X}{-\mathrm{d}H}=-\cot\gamma=\frac{C_L}{C_D} \qquad (3)$$

where X is the range covered over the ground and H is the altitude.

Usually γ is small enough ($\cos\gamma\approx 1$) that we have the rate of descent

$$\frac{-\mathrm{d}H}{\mathrm{d}t}=-V\sin\gamma=\sqrt{\frac{mg}{2\rho S}}\frac{C_D}{C_L^{3/2}} \qquad (4)$$

So for a given altitude the maximum range covered over the ground will be got when C_L/C_D is at its maximum, while the maximum time stayed in the air will be got when $C_L^{3/2}/C_D$ is at its maximum. For a specific configuration of the UAV, the angle of attack (α) is different for the two maximums. That means the longest-rang Velocity of Calibrated Air Speed (VCAS) is different from the one for longest-time, as shown in Fig.2.

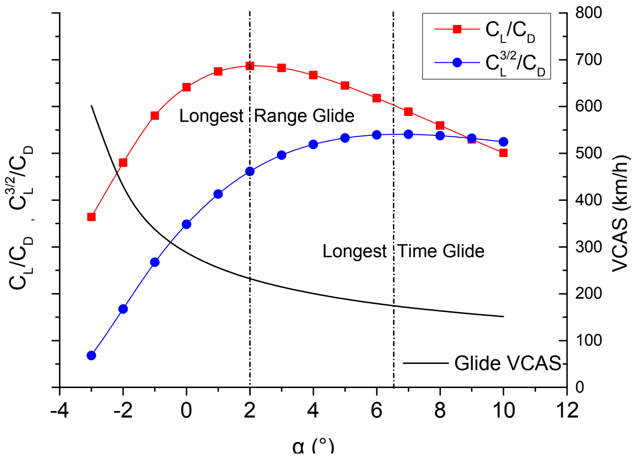

Fig.2 Different α and VCAS for Longest Range Glide and Longest Time Glide

Besides angle of attack, configuration change impact the C_L/C_D and $C_L^{3/2}/C_D$. Meanwhile, the VCAS for longest-rang glide or longest-time glide would be different from configuration to configuration. The UAV need to change its VCAS when configuration had changed, in order to maximize the glide performance or save its energy. In practice, the maximum performance is limited by some reasons, so a suboptimum VCAS will be used.

2.3 Descent Turn

The motion equations for UAV's descent turn in static atmosphere are

$$m\frac{\mathrm{d}V}{\mathrm{d}t} = mg\sin\gamma - \frac{1}{2}\rho V^2 S C_D \quad (5)$$

$$mV\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{1}{2}\rho V^2 S C_L \cos\phi_s - mg\cos\gamma \quad (6)$$

$$mV\cos\gamma\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{1}{2}\rho V^2 S C_L \sin\phi_s \quad (7)$$

When the UAV achieves a steady descent turn, we have the heading change rate

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = (\frac{\rho g S}{2m})^{1/2}(C_L{}^2\cos^2\phi_s + C_D{}^2)^{1/4}\tan\phi_s \quad (8)$$

and the heading change per altitude loss

$$\frac{\mathrm{d}\psi}{\mathrm{d}H} = \frac{\rho S}{2m}\frac{\mathrm{C}_L{}^2\cos^2\phi_s + C_D{}^2}{C_D}\tan\phi_s \quad (9)$$

with speed constrain

$$\frac{1}{2}\rho V^2 S\sqrt{C_L{}^2\cos^2\phi_s + C_D{}^2} = mg \quad (10)$$

While for some UAV or UAV's configuration, there may be a pole for Eq.9, in most cases the relation is monotonic for useable VCAS and ϕ_s range. That means for certain speed, the larger the ϕ_s, the quicker the turn and the less altitude loss for a given heading change, as shown in Fig.3.

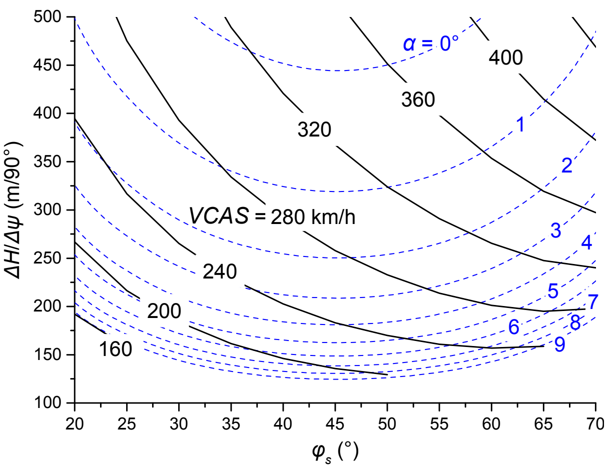

Fig.3 Descent Turn Characteristics

This kind of characteristic gives us a chance to achieve a demanded heading for a given altitude loss by change the angle of bank, which will be quite useful for energy management.

3 Automated Control Strategy

3.1 Top Level Considerations

To archive a successful flameout landing, the UAV has to be piloted to the right positions with right heading and right speed. So the top level of the automated control strategy is a navigation plan with a step-by-step energy management, according to which the lower level flight control targets generate and states transit.

According to the flight characteristics described above, the principle of HALE UAV flameout landing should be as follows

- Before the energy is confirmed enough to reach the next key point, glide as long distance as possible and turn with minimum altitude loss.
- Join the circular pattern at the key points, make descent turn with constant radius to ensure the periodical passing of the key point.
- Check the energy when reaching the energy check altitude of the key point, bleed energy using descent turn maneuver to predetermined roll out altitude, speed and heading.
- Use speed brake and landing gear as final energy bleeding measure in landing approach, in order to touch the runway with acceptable touch down point, speed and rate of descent.

3.2 Navigation Management

The flight routes for flame out landing should be preplanned based on the airfield conditions to enable the UAV to choose the best one according to its relative position to the runway.

Each route includes a Far field Key point (FK) and a Near field Key point (NK) set before the Final Approach Fix (FAF) to provide room for rough and fine adjustment of the energy and to get a window for final approach, as shown in Fig.4. The landscape, wind field, air traffic control and the flight performance of the UAV should be considered when preplanning the flameout landing flight routes for takeoff, landing and alternate airfields. There are predetermined properties for each key point

$$P = \{Lat, Lon, R, \varepsilon, H_r, \psi_r, H_c\} \qquad (11)$$

where Lat and Lon are key point latitude and longitude. R and ε are the radius and direction (clockwise or counterclockwise) of the circular pattern. H_r and ψ_r are the roll out altitude and heading at which the aircraft should roll out. H_c is the energy check altitude that a descent turn would start. These properties are basic information for navigation and energy management.

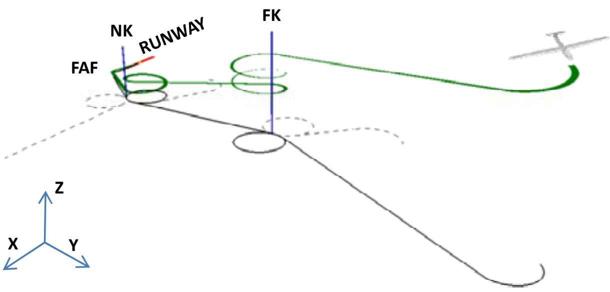

Fig.4 Typical Flameout Landing Flight Routes

When engine failure is confirmed, an immediate homing turn should be carried out in order to save the energy. The target key point for aiming at is selected among those key points (preplanned FKs, NKs and FAF) based on the speed, altitude, relative position and heading difference to each of them. The priority sequence is FKs, NKs and then FAF. That means if FKs could not be reached by calculation, the UAV would attempt to aim at the NKs and then FAF. For FKs or NKs that all could be reached, a further selection is carried out according to their excess altitudes

$$H_E = f(H, \Delta Lat, \Delta Lon, \Delta\psi_i, \Delta\psi_o) - H_r \qquad (12)$$

where H is current altitude. ΔLat , ΔLon are the latitude and longitude difference between current position and target key point. $\Delta\psi_i$ is the difference between current heading and the heading of straight track from current position to target key point. $\Delta\psi_o$ is the difference between the heading of straight track from current position to target key point and the roll out heading of the target key point. Fig.5 gives a graphical illustration. The key point with the largest H_E will be selected as the aiming target.

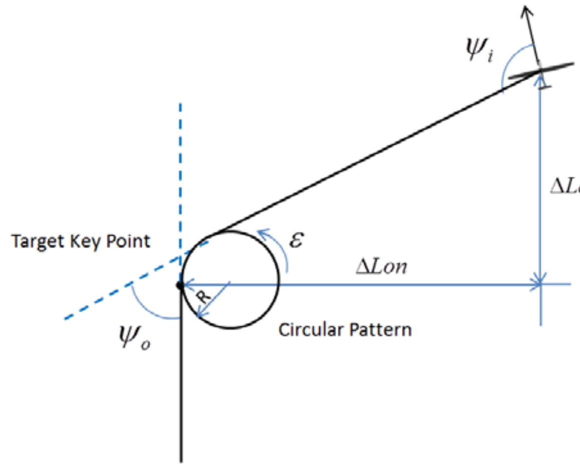

Fig.5 Aiming Turn and Circular Pattern

Aiming at FK from the beginning initiates an entire procedure of flame out landing. Aiming at NK or even FAF from the beginning initiates a partial procedure. In these cases, there is limited chance for energy adjustment before final approach, which means it is harder than an entire procedure.

When homing turn has been finished, straight glide along the route to join the circular pattern of target key point is carried out. Because there is no propulsive force, the gliding altitude and speed could not be simultaneously controlled. Keep the speed at VCAS for longest range glide, and then the altitude at the join point is somewhat random based on the wind or other reasons. So an adjustment has to be carried out at the target key point.

FK is prepared for rough adjustment where the UAV fly out from there should be at predetermined roll out altitude and heading to NK. NK is prepared for fine adjustment with its roll out heading to FAF. Finally, the UAV roll out from FAF would be within an altitude and heading window. Then a final approach will be followed.

3.3 Energy Management

Energy management means to bleed its excess energy when the altitude and speed of the flame out UAV is confirmed too high to land on the runway. There are two kinds of method to bleed energy, one is descent turn and the other is configuration change.

As described in section 2.3, we could use different bank angle ϕ_s to bleed different energy (i.e. to lose different altitude) for a given heading change in a descent turn. Descent turns for energy management are carried out at FK and NK when energy check altitude has been reached. The anticipated energy bleeding rate during descent turn is represented by heading change per altitude loss

$$\frac{\mathrm{d}\psi}{\mathrm{d}H} = \frac{\psi_{Hc} - \psi_{Hr}}{H_c - H_r} \tag{13}$$

where ψ_{Hc} is the aircraft heading at energy check altitude. ψ_{Hr} is the anticipated heading at roll out altitude.

We control $\mathrm{d}\psi / \mathrm{d}H$ by changing ϕ_s from energy check altitude so that the altitude difference and heading difference will be both diminished when the UAV descent to roll out altitude of the key point.

The energy management descent turn at key point follows the constant radius descent turn for pattern circling. For a given VCAS, the lower the altitude, the smaller the bank angle will be used, as shown in Fig.6.

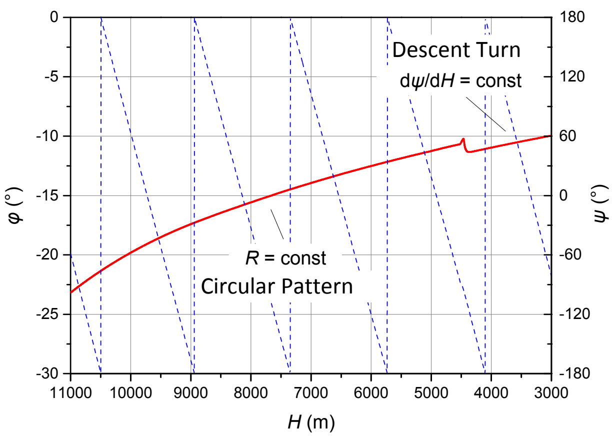

Fig.6 Bank Angle during Circular Pattern and Descent Turn at Key Point

Speed brake and landing gear are used as typical configuration change. Those should be carefully applied as the final energy releasing measures after NK. The UAV glides straight during final approach besides a partial circular pattern at FAF. As described in section 2.2, the glide slope depends on the lift-drag ratio. The UAV should be controlled inside the upper limit and lower limit, by speed brake applied and landing gear down accord to its relative position to upper limit H_{upper} and lower limit H_{lower} along the glide slope

$$f(x, H_{upper} - H, H - H_{lower}) \tag{14}$$

where x is the distance to the runway touch zone.

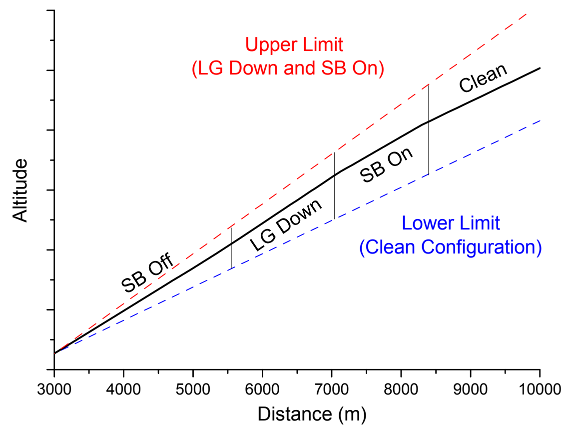

Fig.7 Energy Management with Configuration Change during Straight Glide

4 Modeling

Modeling and simulation were used in detail design and optimization of the strategy.

4.1 Flight Dynamics

Flameout flight dynamics modeling is based on thrust and drag accounting methodology the same as normal flight. As described in section 2.1, additional forces and moments due to flameout should be accounted. Those could be measured specifically in high altitude cell and wind tunnel, simulating the engine's wind milling condition after engine failure. The aeroelastic correction for lift and drag are taken into account by fluid-structure interaction calculation, especially during descent turn, owing to the high aspect ratio layout of the HALE UAV. There is a more important procedure, normal flight test results before real flameout landing should be accumulated for aero forces and moments identification.

The motion equation used for dynamic modeling is 6th order point mass forces (coordinated flight). The applied forces are in a system that is defined by X-axis in the direction of vehicle velocity relative to air, Z-axis is upwards and Y-axis completes the right-handed frame. These forces are functions of lift L, drag D, thrust T, mass m, flight path angle γ, angle of attack α and bank angle ϕ_s, driving the UAV's motion in 3D space.

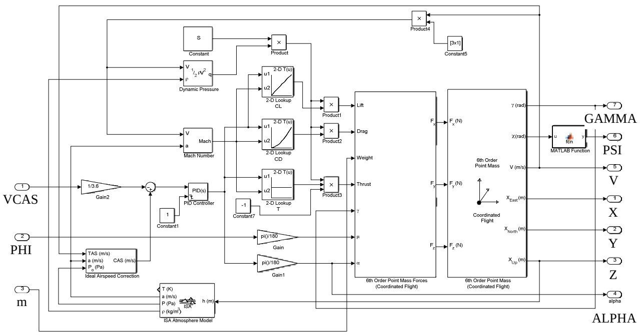

Fig.8 Flight Dynamic Model

4.2 Flight Control

Speed control inner loop is different to normal flight. Because there is no propulsive force, we have to use the angle of attack α to control the speed VCAS. The navigation outer loop is enhanced to perform the desired flight route maneuvers, including homing turn, straight glide, pattern circling, descent turn and configuration change. A top level state management process runs as control strategy executer, interacting with the control loops.

The control laws used in inner and outer loop are those commonly used in nowadays UAVs. VCAS is controlled by α using PID controller. ϕ_s is the main control variable for navigation. L1 control is used for straight glide to keep the aircraft on track. PD control of ϕ_s is used for pattern circling and descent turn. So the control strategy could be realized conveniently in current developing HALE UAVs and in those already in service. Matlab[TM] Simulink is used as the control modeling tool, as shown in Fig.9.

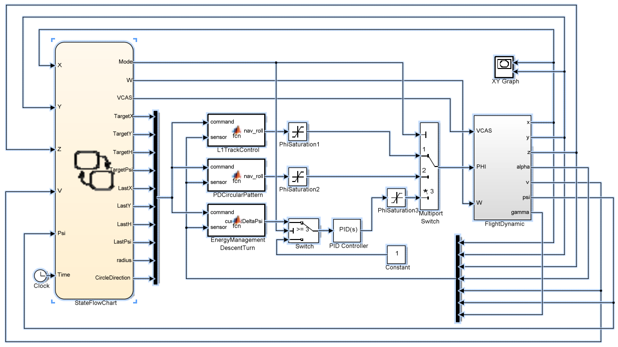

Fig.9 Flight Control Model

4.3 State Transition

State management is responsible for the transition of flight state and aircraft state. The top level state includes five parallel states, Flight Mode, Navi Target, Engine State, Landing Gear and Speed Brake. In each of them, exclusive substrates exist. We use Matlab[TM] Stateflow as the upper level mode logic and task scheduling tool via its state machines and flow charts, as shown in Fig.10. State Flow interacts with the continuous dynamics and control model specified above.

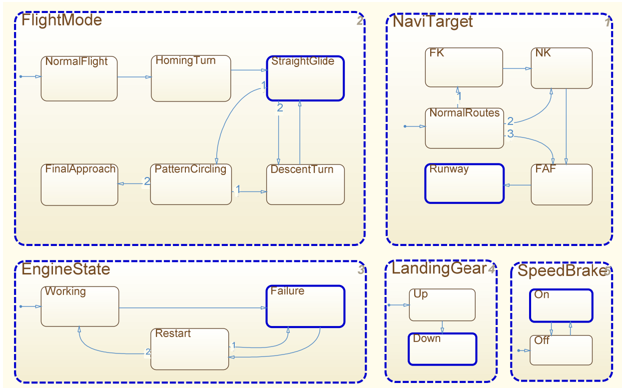

Fig.10 Top Level State Flow Chart

There are six substates in Flight Mode, including Normal Flight, Homing Turn, Straight Glide, Pattern Circling, Descent Turn and Final Approach. When simulation starts, default transition is to Normal Flight. An entire flameout landing includes all of the states and will repeat the Straight Glide, Pattern Circling, Descent Turn at FK and NK based on the energy management described in section 3.3. Meanwhile, the target for navigation will transit from Normal Routes to FK, NK, FAF and then Runway based on the navigation management described in section 3.2. Flight Mode and Navi Target are interactive, providing information and command to dynamics and flight control model.

Engine State includes Working, Failure and Restart. A successful engine restart from failure would transit the engine state to working, which will end the flame out landing with a normal home return flight. Landing Gear state includes Up and Down. Speed Brake state includes On and Off. Both of them are driven by configuration change for energy management.

4 Simulation and Results

Then flight simulations with state transition, flight control and flight dynamics model included were carried out to facilitate the detail design, optimization and verification of the control strategy.

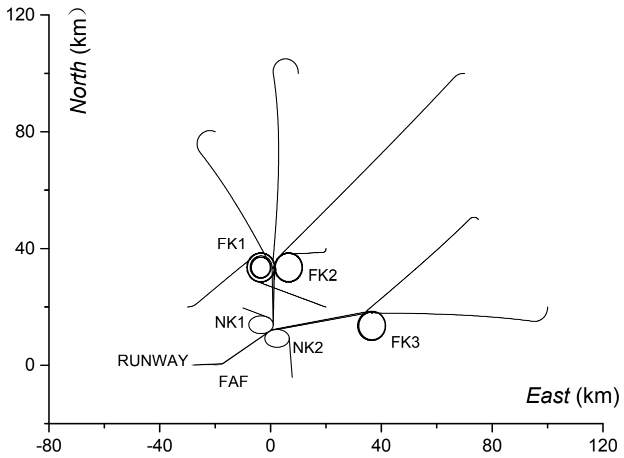

Fig.11 Single Case Simulation

Flight characteristics and configuration change were confirmed by specific mission segment simulation. Target key point selection, control logic matching and state transition conditions optimization were achieved by the whole process simulation, as shown in Fig.11. Based on the design of experiments, a number of designated and random simulation tests were carried out, including those in complicated situations such as heavy weights, low altitude and changing winds. Statistical results showed that a satisfactory success rate was finally reached by using the proposed automated control strategy.

5 Conclusions

The automated control strategy design is based on the flight characteristics of HALE UAV's flameout straight glide and descent turn. A set of optional flight routes and a step-by-step energy plan form the top level management process. Flight dynamics, flight control and state transition are modeled and simulated. Statistical results of simulation showed that the success rate of the strategy was satisfactory.

References

[1] John D. Anderson, Jr. Aircraft Performance and Design. WCB/McGraw-Hill.1999.

[2] Eng Pillar C.S.. Path planning, guidance and control for a UAV forced landing. *Doctoral Thesis.* Queensland University of Technology. 2011.

[3] Pastor E, Royo P, Santamaria E, et al. In-Flight Contingency Management for Unmanned Aerial Vehicles. *Journal of Aerospace Computing, Information, and Communication*, Vol. 9, No. 4, pp144-160, 2012.

[4] Atkins E M, Portillo I A, Strube M J. Emergency flight planning applied to total loss of thrust. *Journal of Aircraft*, Vol.43, No.4, pp 1205-1216, 2006.

Contact Author Email Address

Wayne.Q.shi@gmail.com

Copyright Statement