Development of a flying test bench using small UAVs

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This paper describes a development of lifting body type UAV and its test flight. The span of the developed UAV is 42 cm and its weight is 350 g. It was equipped with a flight computer, sensors and a GPS antenna, and an autonomous flight can be performed. After wind tunnel experiments, its dynamics was modeled and a stabilizing controller was designed by H-infinity control method. The navigation and guidance system was designed using PID controller, which enables waypoint tracking. Numerical simulations and flight tests were carried out and the designed flight system was validated.

Nomenclatures

α	=	Angle of attack
p	=	Roll rate
q	=	Pitch rate
r	=	Yaw rate
ϕ	=	Roll angle
θ	=	Pitch angle
α_g	=	Longitudinal gust component
β_g	=	Lateral gust component
δ_a	=	Aileron deflection
δ_e	=	Elevator deflection
n_p	=	Noise of roll rate sensor
n_r	=	Noise of yaw rate sensor
λ	=	Root in a equation

I. Introduction

The Re-Entry Vehicle of next generation has been developed in several countries. In the developments, the many challenging problems must be solved, for example, heat protection, path planning, flight control, and so on. Generally, these problems are overcome with many experiments and simulations, and huge cost becomes necessary. Recently, Unmanned Aerial Vehicle (UAV) technology has been developed and some aircraft are in use. The small size UAV was developed in our laboratory and has demonstrated an autonomous flight. This UAV was equipped with a rate gyro, an accelerometer, a geomagnetism sensor, a GPS, an altitude sensor, a wireless modem and a microcomputer. Because the equipped avionics have same functions as those of larger aircraft, the developed UAV can be used as a test bench of an advanced flight control method. Additionally, aerodynamic characteristics can be estimated in a flight. The smaller test model becomes, the lower cost becomes. Therefore, a small Re-Entry Vehicle model with an ability of autonomous flight was developed and flight tests were performed. First, mission profiles are mentioned. Then, the design and aerodynamics are described. After the modeling of the dynamics, a flight controller is designed. Finally, numerical simulations and flight testing are shown.

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II. Mission of gliding UAV

A Re-Entry Vehicle enters from the orbit of the earth, and its flight is divided into several phases. In each phase, control purposes are different. In this research, final phase is focused on. The landing at the desired baseis aimed at. In this phase, precise attitude control is necessary. The flight testing of this phase were carried out using meter-sized test model.[1,2] The aircraft used in these research have a lifting body shape. Because the lifting body aircraft do not have tails, and are designed for mainly heat protection, stabilities must be enhanced by the controller. In order to estimate feasibility of aerodynamics and controller performances, flight testing is necessary.

In this research, a small UAV of lifting body shape was developed and investigated. The controller at the landing phase was validated and a feasible study of the lifting body Re-Entry vehicle was performed.

III. Design of lifting body aircraft

There are many requirements for lifting body Re-Entry Vehicle. The non-classical shape results in aerodynamic characteristics without enough stability. This challenging design requires high performance controller and validation with flight testing. In this research, low cost flight testing of landing phase of Re-Entry Vehicle was proposed. Therefore, flight model has a typical shape of a lifting body aircraft. Figure 1 shows the constructed lifting body aircraft. The span is 39cm, the length is 42cm, and the gross weight is 350g. It has a pair of elevons and a vertical tail. The body has avionics bay, where a flight computer, sensors, a battery, an actuator and a wireless modem are installed. The body was made of styrene foam. This flight model has aerodynamic characteristics derived from lifting body shape. The UAV has equipments of guidance, navigation and control. Therefore, it can be used for the research about flight system and aerodynamic design.

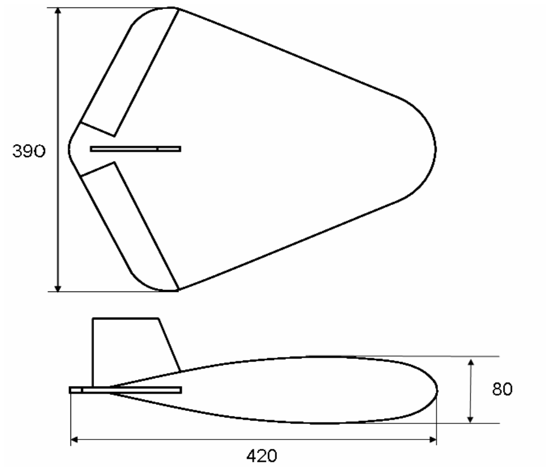

Figure 1. Designed aircraft model

IV. Modeling

Firstly, wind tunnel testing was carried out. Figure 2 shows wind tunnel experiments. The aircraft model was mounted on the load cell, and aerodynamics forces were measured. Here, the wind velocity was 4m/s. Using the measured aerodynamic data, the conditions of trim point and the aerodynamics derivatives were calculated. Figure 3 shows lift and drag coefficients. No decrease of the lift coefficient with the increase of angle of attack is observed even when an angle of attack is larger than 40deg. Its reason is that the aspect ratio is small.

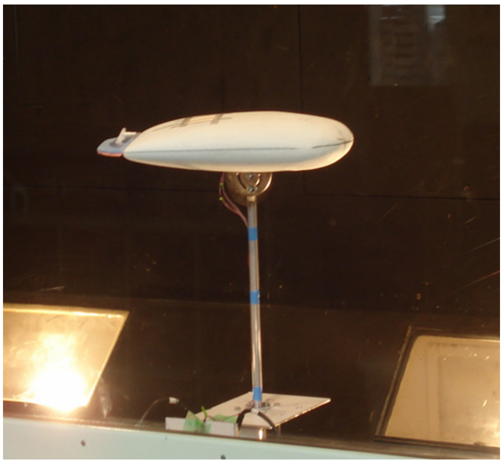

Figure 2. Wind tunnel experiments

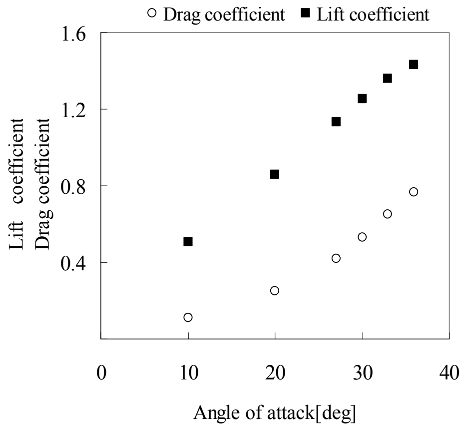

Figure 3. Lift coefficient and drag coefficient

From the aerodynamic derivatives, linearized 6-DOF dynamic equations were formulated.
Longitudinal motion:

$$\dot{x}_{lon} = A_{lon} x_{lon} + B_{lon} w_{lon} + B_{lon} \delta_e$$
$$y_{lon} = C_{lon} x_{lon} + D_{lon} w_{lon}$$
$$x_{lon} = [\alpha \quad q \quad \theta]^T \quad , \quad w_{lon} = [\alpha_g \quad w_\Delta]^T$$

Lateral-Directional motion:

$$\dot{x}_{lat} = A_{lat} x_{lat} + B_{lat} w_{lat} + B_{lat} \delta_a$$
$$y_{llat} = C_{lat} x_{lat} + D_{lat} w_{lat}$$
$$x_{lat} = [\beta \quad p \quad r \quad \phi]^T \quad , \quad w_{lat} = [\beta_g \quad n_p \quad n_r \quad w_\Delta]^T$$

Here, w_{lon} and w_{lat} are disturbances. The trimmed forward velocity is 6.4m/s and the trimmed angle of attack is 0.47rad. This trim condition depended on the gross weight. The aerodynamic derivatives relative to angular velocities were estimated analytically.[3] The characteristics of the dynamics were investigated using the eigenvalues. The eigenvalues of the longitudinal dynamics are as follows:

$$\lambda_{sp} = -1.30 \pm 4.49i\,, \qquad \lambda_{ph} = -0.66$$

They consist of a pair of complex values for stable short period mode and a negative real value for phugoid mode. The eigenvalues of the lateral-directional dynamics are as follows:

$$\lambda_{roll} = -4.03, \qquad \lambda_{Dutch\ roll} = -0.92 \pm 7.83i, \qquad \lambda_{spiral} = 0.73$$

They consist of a pair of complex values for stable Dutch roll mode, a negative real value for stable roll mode and a positive value for unstable spiral mode. The instability in lateral-directional dynamics of Re-Entry Vehicle has been reported in Ref. 4. Similar instability appears in the present UAV of lifting body type. Additionally, in a flight at a high angle of attack, the controllability of the control surfaces is degraded and sometimes they reverse. This makes controller design difficult. Controller design of the unstable lifting body UAV produces a useful knowledge which can be applied to developments of a Re-Entry Vehicle.

V. Stabilizing controller design

The design goal is to accomplish flight testing in landing phase. The flight envelope of a Re-Entry Vehicle is large. In this research, a design point of gliding at a medium angle of attack is used. Here, the velocity is 6.5m/s and the angle of attack is 27deg. This trim point depends on the gross weight of the aircraft. Therefore, mission equipments change the weight and trim condition. This paper treats a flight model without mission equipments.

The controllers were designed for the longitudinal dynamics and lateral-directional dynamics separately. In both the controllers, robust stabilities subject to aerodynamic uncertainties are necessary. In order to guarantee the enough robust stability, H-infinity controller was used[5]. The design requirements for the longitudinal dynamics controller are as follows:

1. Robust stabilities subject to multiplicative uncertainties at output side are ensured.
2. Responses are suppressed for longitudinal gust.
3. Deflection angles of elevons are suppressed.

These requirements are formulated in a generalized plant (Figure 4). The H-infinity controller was obtained which minimized H-infinity norm from disturbance to controlled output.

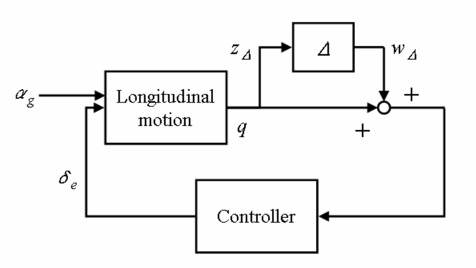

Figure 4. Block diagram for longitudinal dynamics

The design requirements for the lateral-directional dynamics controller are as follows:

1. Robust stabilities subject to multiplicative uncertainties at input side are ensured.
2. Responses are suppressed for lateral-directional gust.
3. Deflection angles of elevons are suppressed.
4. Sensor noise is taken into account.

These requirements are formulated in a generalized plant (Figure 5). The H-infinity controller was obtained which minimized H-infinity norm from disturbance to controlled output. These controllers attain a stable flight with existence of aerodynamics uncertainties, gust inputs and sensor noises.

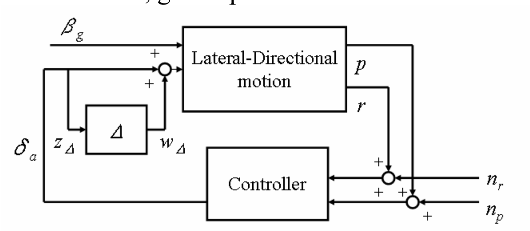

Figure 5. Block diagram of lateral-directional dynamics

VI. Guidance and navigation system design

The inner loops are constructed from the airframe dynamics and the designed controllers. It attains stable flights. By inputting appropriate commands to the inner loops, an autonomous landing is attained. For the longitudinal dynamics, a flight path angle is input as a command from outer loop. In this research, a single flight path angle of -25deg, which is a value at trim condition, is used. For the lateral directional dynamics, a bank command is input. Bank command is determined by the heading error using PID controller. Figure 6 shows the outer loop of lateral directional dynamics. This guidance and navigation system attains a waypoint tracking.

From the position measured using GPS and next waypoint, an error of heading angle was determined. The error of heading angle was input to PID controller, and bank command is generated. Bank command is input to the inner loop as an additional value of aileron angle. Because the airframe dynamics was stabilized by the controller, bound aileron input results in steady turn. The gain of PID controller was tuned with trial-error manner.

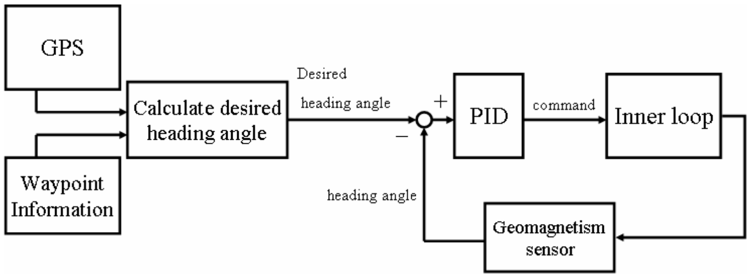

Figure 6. Guidance system

VII. Simulations and results

In order to validate the designed controller, numerical simulations for gust input were carried out. Figure 7 shows the input longitudinal gust component in an angle of attack, and Figure 8 shows the simulated longitudinal responses. Because robust stabilities are enhanced, the controller decreases the pitching motion q caused by the gust.

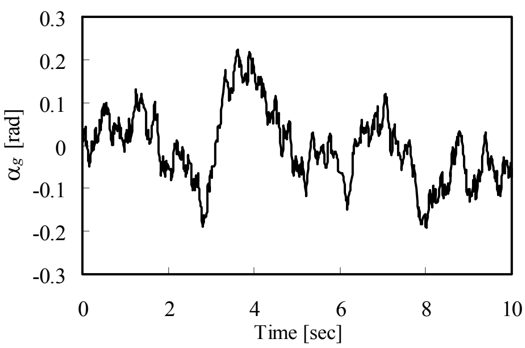

Figure 7. Input gust component

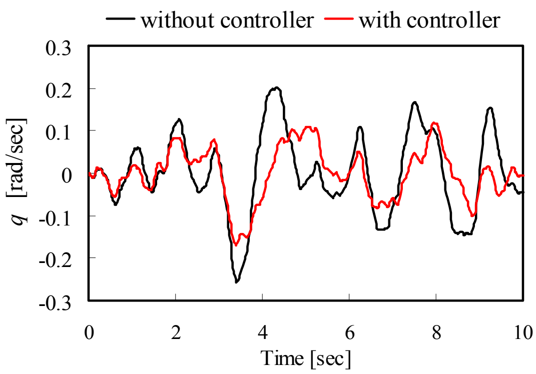

Figure 8. Response of pitch rate to gust-input

VIII. Flight testing

Numerical simulations can not take account of actual disturbances and uncertainties. Therefore, flight testing is necessary to evaluate performances of the flight system. The flight model was constructed from a flight computer, and several equipments. Table 1 shows equipments of flight model. The designed flight system was implemented in the microcomputer after discretization with 20Hz. This flight model had an ability to attain waypoint tracking at the trim condition that is a velocity of 6.5m /s, an angle of attack of 27deg, and a glide path angle of -25deg.

The constructed flight model is launched from the launch system using a balloon. Figure 9 shows the launch system. It was constructed from a balloon with helium, equipments to separate the flight model, and a cable of DYNEEMA[6]. First, heading tracking experiments ware carried out. The Lifting body UAV was launched at the attitude of 35m, and the heading was maintained to point to west. In this experiment, there existed west wind of 4m/s. After launched, UAV was pulled up, and a steady glide was attained. Figure 10 shows recorded errors of heading angle every one second. The heading was stabilized nearly at the desired heading direction. However, because the flight time was too short, perfect heading guidance can not be attained.

Table1. Equipments on flight model

Flight computer (MAVC1)
Accelerometer (onboard)
Rate gyro (onboard)
GPS
Barometric altimeter
Geomagnetism sensor
R/C Receiver
Wireless modem
Servo motor
Lithium-Polymer battery

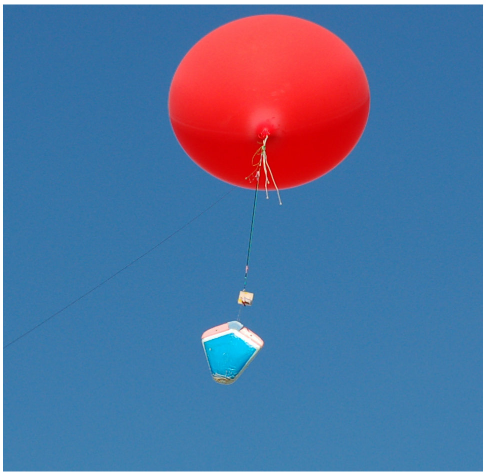

Figure 9. Launch system

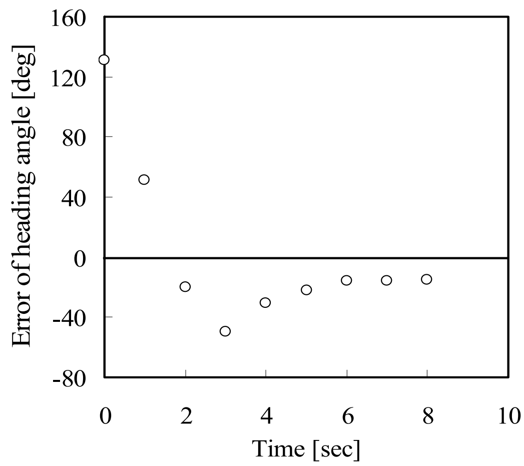

Figure 10. Error of heading angle

Next, waypoint tracking experiment was performed. The Lifting body UAV was launched at the altitude of 80m, and it was controlled to reach desired waypoints. In this experiment, there existed a west wind of 6m/s. Figure 11 shows recoded errors of heading angle every one second. After launched, UAV was pulled up, and a steady glide was attained. Figure 12 shows measured position data every one second. Because the wind velocity is almost same as the trimmed forward velocity, the gliding UAV could not reach the waypoint. However, the airplane attitude was stabilized and its divergence did not occur under strong gust disturbances.

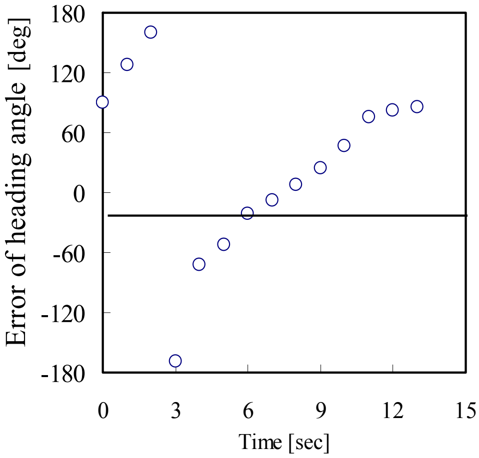

Figure 11. Error of heading angle

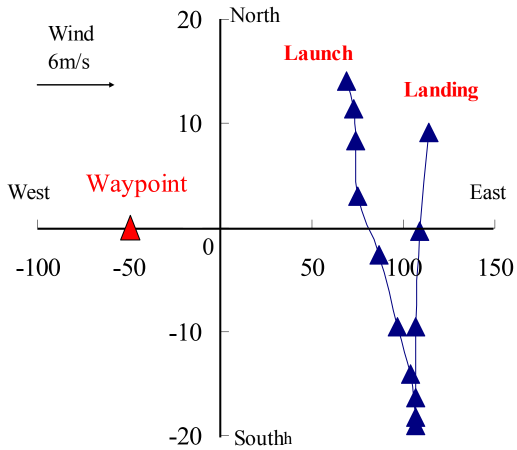

Figure 12. Flight record

IX. Conclusion

The lifting body type UAV was developed. This UAV aimed at a test bench in landing phase of Re-Entry Vehicle. From the wind tunnel experiments, aerodynamic derivatives were calculated and dynamics model was constructed. Using H infinity control theory, the stabilizing controller, which guarantees robust stabilities, was designed. And the guidance and navigation system was constructed from PID controller. These flight systems attain waypoint tracking. The flight system was implemented in the flight model, and the flight tests were carried out. After it was launched from the balloon, it attained a stable flight.

Avionics, aerodynamic design and flight system design can be investigated using a simple and low cost flight model. Especially, it is a great advantage to perform a flight test using inherently unstable aircraft at a high angle of attack. From this research, the ability as a test bench was shown. The work to attain more precise path planning and path tracking, and flight tests from high altitude are going on.

Acknowledgments

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