ALFLEX Guidance, Navigation and Control

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ABSTRACT

This paper introduces the Guidance, Navigation and Control System developed for the Automatic Landing Flight Experiment, ALFLEX. The system was developed to demonstrate technology readiness for the re-entry space vehicle's automatic landing. Lessons learned in the development are also discussed.

Key Words: HOPE, ALFLEX, Automatic landing, Flight test, Navigation, Guidance and Control

1. Introduction

A guidance, navigation and control (GNC) system was developed for the ALFLEX vehicle to land safely on a 1000-m runway. The vehicle is a 37% subscale model of a conceptual vehicle in the Japanese ongoing H-II orbiting plane (HOPE) program, where the model was one of the candidates in the 1992 conceptual design. In order to achieve the goal of the experiment while minimizing the cost and time for development, the ALFLEX program included the following principles for the GNC system design.

(1) Scaled model experiment
The GNC system as well as the experiment was designed to be dynamically similar to HOPE for the flight experiment to be a demonstration of HOPE landing technology readiness. Concerning wind and gust disturbance conditions, they also follow the rule of similarity. The wind and gust disturbance conditions were defined so that the HOPE can land safely against those of US military specifications, which are widely used.

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(2) Off-the-shelf hardware
In order to reduce the cost and time of development, the GNC system uses prefabricated hardware, and it is designed based on the performances of these components. The only exception is differential GPS, i.e. navigation uses the components under the non-critical conditions for the experiment safety.

(3) No redundant GNC system
Although the HOPE vehicle will have a highly reliable redundant system, the ALFLEX vehicle has a non-redundant system of single channel components. The choice of this structure satisfies the experiment objective and is reasonable based on the limited number of experiments, the non-hazardous nature of the experiment area, and the fact that each component has high reliability, comparable to general components in commercial use.

(4) Limited development tests
The design employs data of the minimum essential tests, such as wind tunnel tests and simple ground tests, otherwise it uses catalogue performance data of components. The GNC system design is robust enough to tolerate these errors obtained in limited tests. The ALFLEX perform a special preliminary flight test, called the "5 degrees of freedom" hanging flight test in order to reduce the risk of the first flight, but the data is not prerequisite for the GNC design.

Following these principles, the preliminary design started in April 1993, and the development of components and flight control program started November of the same year. In May 1995, the GNC system development was completed, and then assembly and system tests were begun. All the final tuning and fixing of GNC system were completed in March 1996 to be ready for the landing flight trial in Australia. This paper introduces all aspects of the ALFLEX GNC system. The next section discusses the similarity rule.

2. Similarity in dynamic experiment

Smaller experiment vehicle size is associated with lower cost and time of development and experiment. Since the landing flight velocity is subsonic, size and velocity change does not greatly influence the flow characteristics. Therefore, the goal of demonstrating landing technology for the re-entry space vehicle can be achieved in scale model experiments. In a scaled model experiment, gravitational acceleration is common between the model and actual vehicles; the acceleration scale is 1. Furthermore, air density is common, so the vehicles' density scale also becomes 1 because the aerodynamic force is mainly generated by pressure. From the two invariables, a scale of the experiment model length introduces other physical quantities' scale. Table 1 shows scales of typical physical quantities, where L is the length scale. Since the scales of velocity and time become the square root of L, similarity numbers of aerodynamics, such as Reynolds number and Mach number, are different between the model and the actual vehicle. Mach numbers are both small (HOPE is around 0.5 and ALFLEX is around 0.3) and both Reynolds numbers are more than the critical Reynolds number. Therefore, the flows' characteristics are not so different from each other. Concerning mass properties, total mass is designed to satisfy the similarity rule, but moments of inertia are not intentionally designed to satisfy the rule. If the model vehicle's density is equal to the actual vehicle, it naturally satisfies the similarity rule in moments of inertia. Because of this, no significant difference is anticipated.

Table 1 Scale ratio for physical quantities

Items	Ratio
Length	L
Time	$\sqrt{L}$
Velocity	$\sqrt{L}$
Acceleration	1
Force	L^3
Pressure	L
Mass	L^3
Moment of Inertia	L^5
Vehicle's density	1
Air density	1

3. Wind design condition

The way in which wind conditions are designed is important for automatic landing system design, because wind and gust disturbances influence landing performance most. In the ALFLEX GNC design, wind conditions are defined to satisfy the similarity rule, based on the requirement that the HOPE vehicle be able to safely land under general standard wind conditions defined for transport aircraft. They basically follow wind conditions defined in two specifications: MIL-F-9490D (the US military specification for automatic flight control systems) and MIL-F-8785C (military specification for flying qualities of manual control airplane). One exception is wind conditions above the boundary layer, where maximum head and tail winds determine the glide slope flight condition. To prevent the steeper glide path angle that would be introduced for the experiment model under similar wind conditions, some relaxation for the wind condition specification is necessary in order to introduce the same glide path angle. Concerning wind condition in the boundary layer, it follows MIL-F-9490D automatic landing system design condition. Wind models are defined in the following. Further study, such as design margin analysis and consideration of vector shear wind, was conducted in order to enhance performance.

Design wind model

The design goal is that HOPE GNC should satisfy the MIL-F-9490D, that is to say, ALFLEX design wind conditions are defined from the MIL-F-9490D low altitude wind model with similar transform.

(a) steady wind

Maximum wind intensities are defined for each direction at 6.1 m/s (20 ft) altitude, such that 12.86 m/s (25 kt) is for head wind, 7.716 m/s (15 kt) for cross wind, and 5.144 m/s (10 kt) for tail wind. Head, cross and tail winds are those in negative X- and Y-, and in positive X-axis directions, respectively, where the XYZ system is a runway coordinate. The wind profile for each altitude is given by the following equation:

$$u = \sqrt{L}U_{6.1}(0.46\log\left(\frac{H}{L}\right) + 0.64) \qquad (1)$$

where H is altitude above the ground, L is the ALFLEX's scale of length (0.37).

$U_{6.1}$ is 12.86m/s (25kt) for head wind, 7.716m/s (15kt) for cross wind, and 5.144m/s (10kt) for tail wind. H/L corresponds to altitude and velocity for the HOPE real vehicle. According to the specification of MIL-F-9490D, equation (1) should be used only below 152 m (500 ft), because the upper layers have various wind profiles. Because of a reason discussed in the reference trajectory design and for its smooth transition, equation (1) is used at every altitude ($1 \leq H \leq 1500$). For arbitrary direction, the head or tail and cross wind combination is defined by the following equation.

$$U_{6.1} = U_{cross} + \frac{1}{2}(U_{head} - U_{tail})\cos\varphi + \frac{1}{2}(U_{head} + U_{tail} - 2U_{cross})\cos^2\varphi \qquad (2)$$

where φ denotes wind direction. Figure 1 shows the wind profile versus altitude for the maximum head wind, and Fig. 2 shows wind profile versus direction in three different design conditions.

(2) Continuous gust

The gust disturbance condition also follows MIL-F-9490D. It is defined by the runway coordinate, and its power spectra are defined by assuming independent random processes.

$$\phi(\omega) = \sigma_i^2 \frac{2L_i}{\pi} \frac{1}{(1+\Omega^2 L_i^2)}, i = x, y, z \qquad (3)$$

Here, Ω : wave number in radians (rad/m), L_i : scale length of random gust, σ_i : variance of random gust. Figures 3 and 4 show these parameters for each altitude. Parameters are naturally extended to upper altitude by assuming that gusts are homogeneous above 610 m (2000ft), as MIL-F-8785C defined.

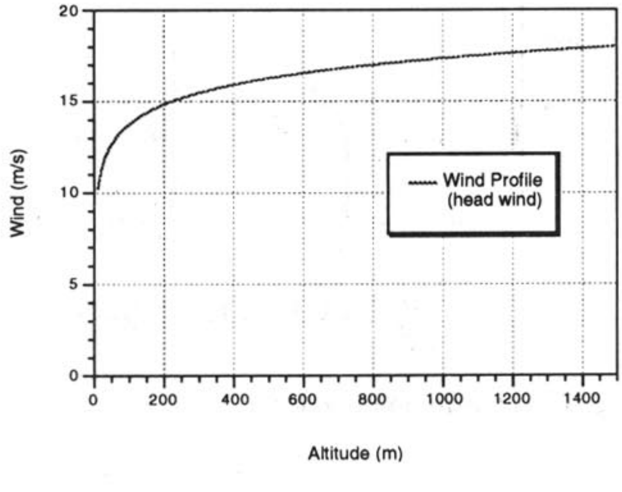


Fig. 1 Maximum steady wind vs altitude.

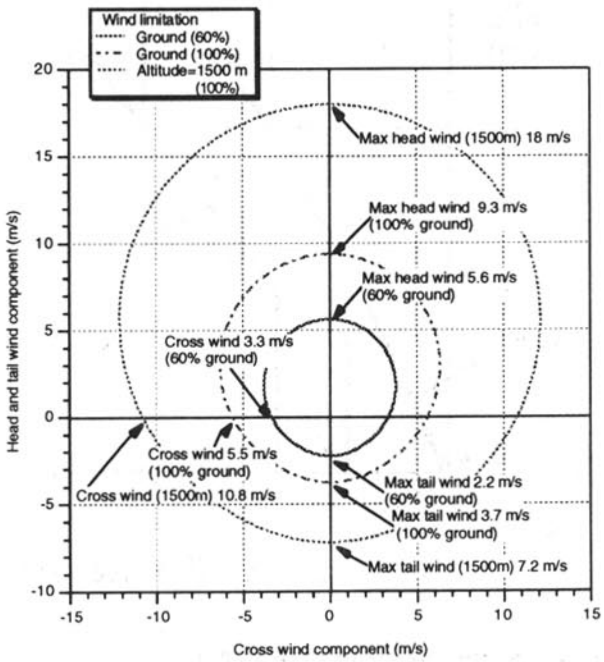


Fig.2 Maximum design wind velocity vs direction.

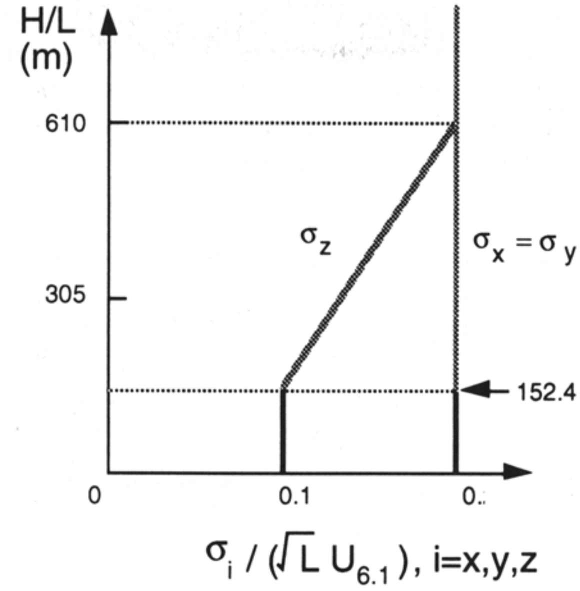


Fig. 3 Intensity of turbulence σi.

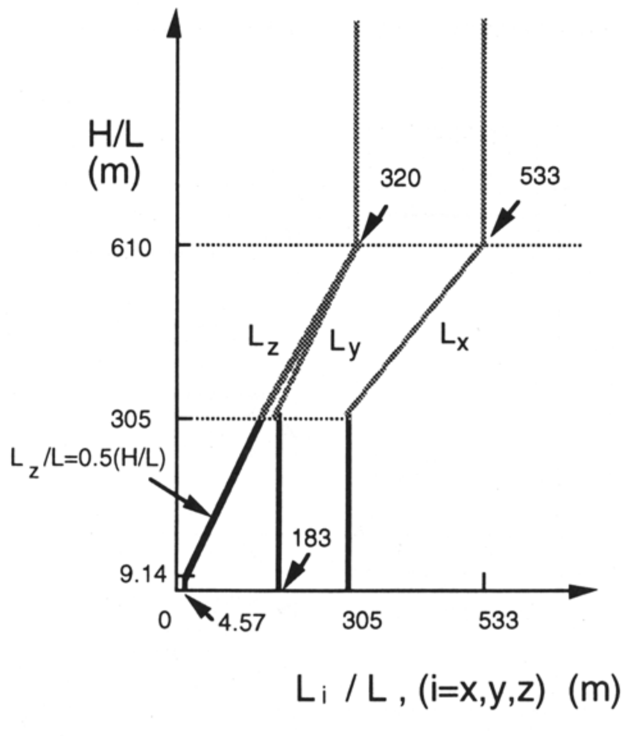


Fig. 4 Scale length of turbulence. *L*i
(*L:* Scale ratio =0.37)

4. Reference trajectory design

A Principle of reference trajectory design is that it defines the following three basic flight conditions and connects them smoothly.

(1) Horizontal hanging flight of 5 degrees of freedom with constant equivalent air speed (EAS) at an altitude of 1500 m.
(2) Equilibrium gliding flight of straight approach with constant EAS, or constant dynamic pressure.
(3) Shallow glide slope flight of -1.5 degree path angle with deceleration to an appropriate EAS.

Transition from (1) to (2), or from the release to equilibrium flight is unique for the experiment. The design goal is to minimize the altitude loss safely. Flight conditions (2) and (3) and its transition are common to the real HOPE, and the design goal is to maximize the landing performance. A single reference trajectory is defined independently from the wind condition.

(a) 5 degrees of freedom hanging flight
High velocity is desirable in order to make the transition from hanging flight to equilibrium gliding flight smooth. Furthermore, higher dynamic pressure is desirable because it makes the control surface deflection small. The mother helicopter KV-107 has a velocity limitation of 46.3 m/s (90 kt) under the condition of hanging an external. After checking safety, the nominal velocity of 5 degrees of freedom is defined as 46.3 m/s. For a trial quit procedure, however, it needs a 70 kt turn, and it is designed for 60 kt hanging flight. Concerning the transition flight after the release, analysis that minimizes the altitude loss under acceleration and its rate limitations shows that the minimum altitude loss is less than 500 m. This indicates that there is ample time for equilibrium gliding flight after release at an altitude of 1500 m.

(b) Equilibrium gliding flight
Conditions of guidance performance against steady winds determine an equilibrium gliding flight envelope in a velocity and glide path angle diagram, a so-called V-gamma diagram. The parameters for this discussion are the maximum head and tail winds, the

vehicle's L/D property, and speedbrake performance. Another condition is introduced to satisfy the lower velocity limitation on the shallow glide path after flare maneuver with an appropriate normal acceleration. Parameters of this condition are the amount of normal acceleration for preflare and the same with the previous conditions. Figure 5 shows the permissible envelope prepared for a 796-kg ALFLEX vehicle. Low velocity and low glide slope angle are selected as an equilibrium gliding flight condition in the permissible envelope. The point selection is in order to lessen the flight condition change from the equilibrium gliding flight to touch down, which is useful to reduce the guidance error. If the maximum head wind was transformed with the similarity rule from what is expected with 1% possibility from the statistical data, the ALFLEX design glide path would become approximately –35 degrees, where HOPE would be approximately –25 degrees. This is because the air density change is not similar and deceleration of the model is smaller than the real vehicle in constant dynamic pressure flight; the experiment model's drag coefficient is larger than the real vehicle's because the landing gear is not retracted and it has a large hole on the back, and other reasons. For the glide path angles to coincide, the maximum head wind condition is relaxed by 33% (from 26 m/s to 17.4 m/s) at 1000 m altitude. The maximum tail wind condition is defined 40% of the maximum head wind. These steady wind condition introduced the equilibrium gliding flight condition of 84 m/s EAS and –30 degrees glide path angle.

(c) Touch down

Various factors must be taken into account when determining the touch down velocity. A lower velocity is desirable to reduce the runway length, and tires have upper velocity bound. The lower bound of touch down velocity is determined by the dynamic pressure needed to maintain aerodynamic control. Pitch attitude angle has an upper bound of 23 degrees so as not to hit the tail and it also sets the lower bound for the touch down velocity. Finally, the nominal touch down velocity of 51.5 m/s EAS is determined. This velocity is in the so-called front side of the V-gamma diagram and it has ample margin to the lower bound. Normal acceleration in the pre-flare is set to 1.5 G. The larger the normal acceleration, the greater the sensitivity of altitude to an error in the timing of initiating preflare maneuver, and the attack angle margin becomes smaller. On the other hand, the smaller the normal acceleration, the shallow glide flight endurance time becomes smaller and may not satisfy the minimum velocity condition before the final flare. The shallow glide slope phase's objective is to reduce the error in the preflare maneuver, so its length can be reduced if the error is small. The ALFLEX shallow glide slope phase is quite small, that is approximately 1 second.

Figure 6 shows the ALFLEX's designed reference trajectory. Prior to the shallow glide slope, the FCC calculates the reference trajectory along with runway coordinate X, and the trajectory after the final flare, and touch down is the nominal path obtained from a numerical simulation of the nominal condition.

5. Design goal of GNC system

The GNC system must be designed to ensure a safe landing on a given runway. The vehicle's states at touchdown are most important to avoid damage to the landing gear and tumbling down of the vehicle. Table 2 shows a breakdown of the GNC system landing requirements, which are introduced from the basic requirements; such as a sink rate of less than 3.1 m/s and landing on a runway 1000 m long and 45 m wide.

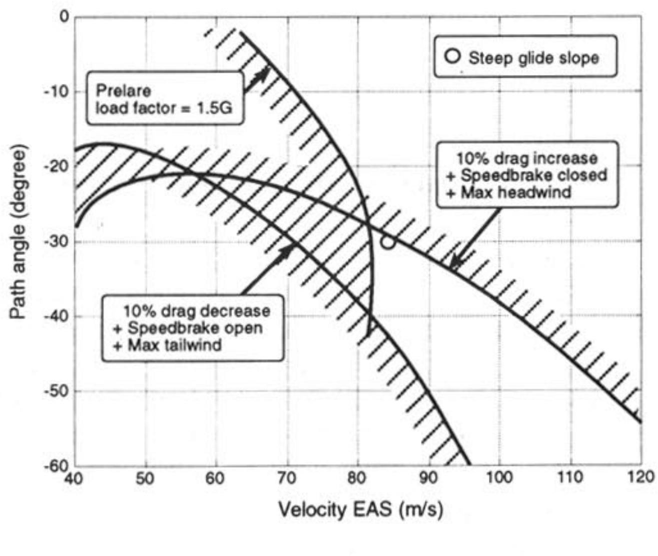


Fig. 5 Velocity vs. flight path angle under the maximum wind conditions. (mass=796kg)

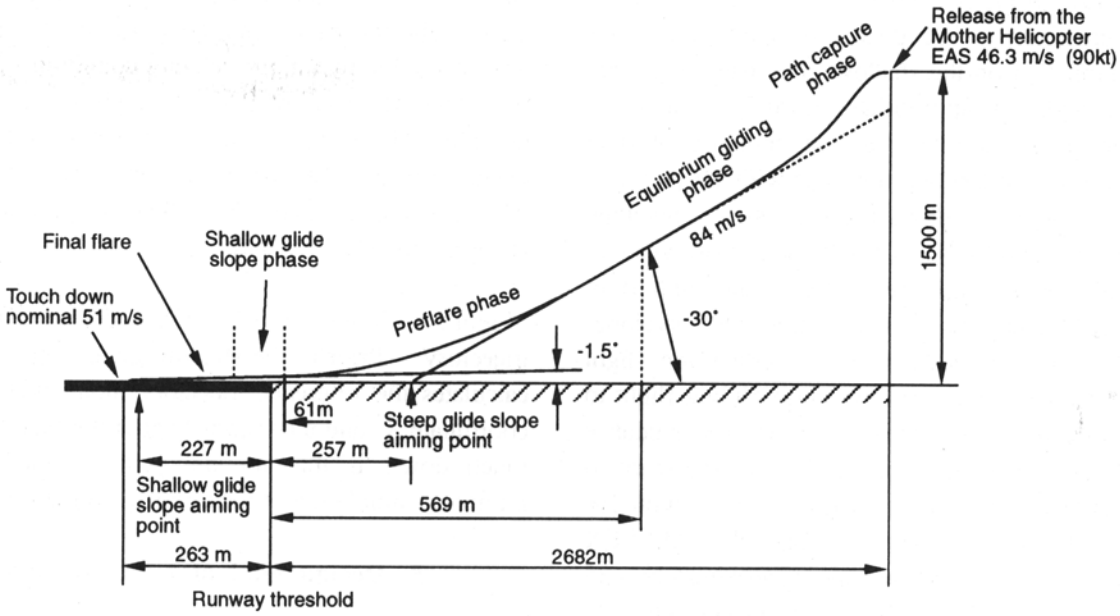


Fig. 6 Reference trajectory.

Table 2 Landing performance requirement for GNC design (3σ)

Evaluation point	Requirement
Touchdown	
Position	X: >0m Y: ±18m
Velocity	Ground speed: <62m/s、Airspeed: 51.5±8m/s、 Sink rate: <3m/s
Attitude	Pitch angle：<23 degrees、Bank angle：±10 degrees、Yaw angle：±8 degrees
Ground roll	Y: ±20m
Stop point	X: <1000m

6. GNC system's structure and function

The design of the GNC system for automatic landing was divided into three elements: navigation, guidance and control. Each function is as follows: navigation gives position and velocity estimation, guidance calculates reference trajectory and guidance command to reduce the position and velocity error, and control gives control surface command to stabilize the vehicle and track the guidance command. Guidance command controls the vehicle's attitude, and defined variables chosen for the ALFLEX guidance are kinetic normal acceleration for longitudinal motion and bank and side-slip angles for lateral-directional motion, where the side-slip angle command is always null. Speedbrake controls the vehicle velocity, and speedbrake command is one of the guidance commands. Figure 7 shows a function block diagram of the GNC system. A central component, the flight control computer and flight control program (FCC/FCP), processes data and communicate with sensors and actuators to realize these functions. Navigation uses an inertial measurement unit (IMU), differential global positioning system receiver (DGPS), microwave landing system receiver (MLSR), radio altimeter (RA), and guidance uses air data system (ADS) and IMU's attitude output and its rate. Section 11 describes the performance and characteristics of these components. Figure 8 shows the structure of these components and other major hardware.

7. Landing performance breakdown to navigation and guidance

It is desirable that the GNC system has a balance between navigation and guidance accuracy, or these accuracies are comparable. Navigation error is mainly caused by hardware error. On the other hand, guidance error is caused by not only hardware error but wind and gust disturbances. Therefore, the guidance accuracy requirement is more critical than that of navigation. In the ALFLEX design, the navigation error is comparable to the guidance error when wind and gust disturbances are small, in order to realize the best performance in the calm wind condition. Table 3 shows the requirements for navigation error. The total performance and navigation error introduces the guidance error by using a concept of root sum square (RSS) assuming the navigation and guidance errors are independent. Since the guidance error is generally more than the navigation error, it is comparable with the total error except for the lateral position error.

8. Navigation design

Since HOPE will have a high-performance IMU and an integrated inertial navigation updated by appropriate navigation sensors, the ALFLEX navigation system is also designed to have the same structure, assuming that an IMU with similar performance is installed. Navigation sensors were selected to obtain the final accuracy from readily available hardware. Since the selection of sensors was limited from commercial products in order to reduce the cost, performances of sensors were not design parameters but were given, and the total accuracy was checked enough to satisfy the navigation requirement by designing navigation algorithms. A principle of navigation is inertial navigation that estimates position and velocity of the runway coordinate by integrating the velocity increment with attitude information measured by the IMU at 80 Hz. Other navigation sensors' information is integrated to correct the inertial navigation error. MLS was adopted in order to obtain the touch down position accuracy. RA is also used to obtain the touch down vertical position and velocity accuracy. Furthermore, a DGPS system was also developed and installed; DGPS is expected to be a promising navigation sensor for future aerospace vehicles. ALFLEX adopted a system developed for the HOPE at the NASDA Tsukuba Space Center. The system, however, was still under development, so it is not used as a flight critical component, where the performance can be monitored from the ground. A characteristic of the ALFLEX navigation is that it has

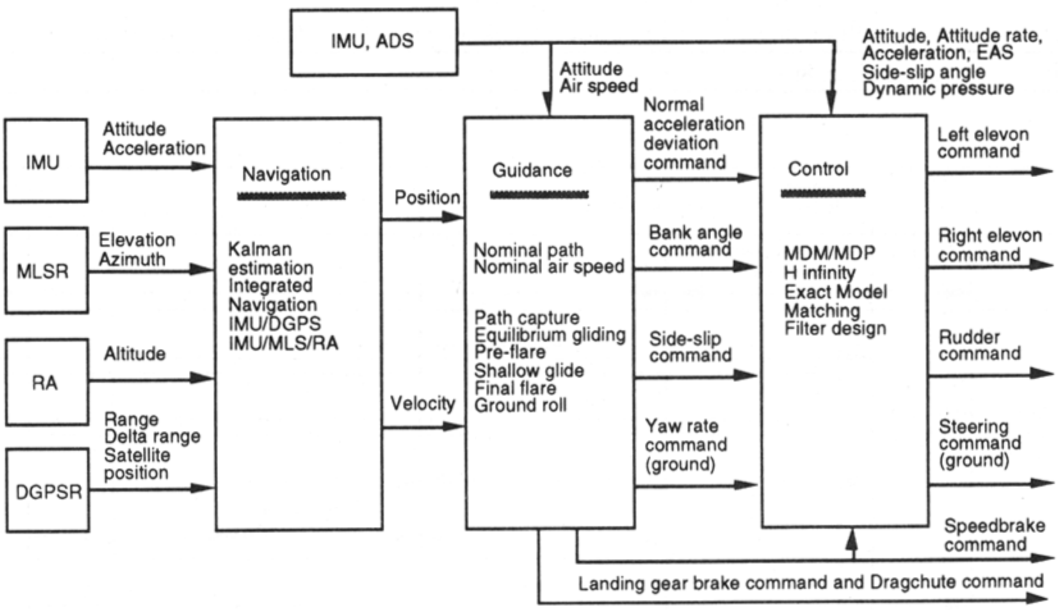


Fig. 7 Function block diagram of GNC system.

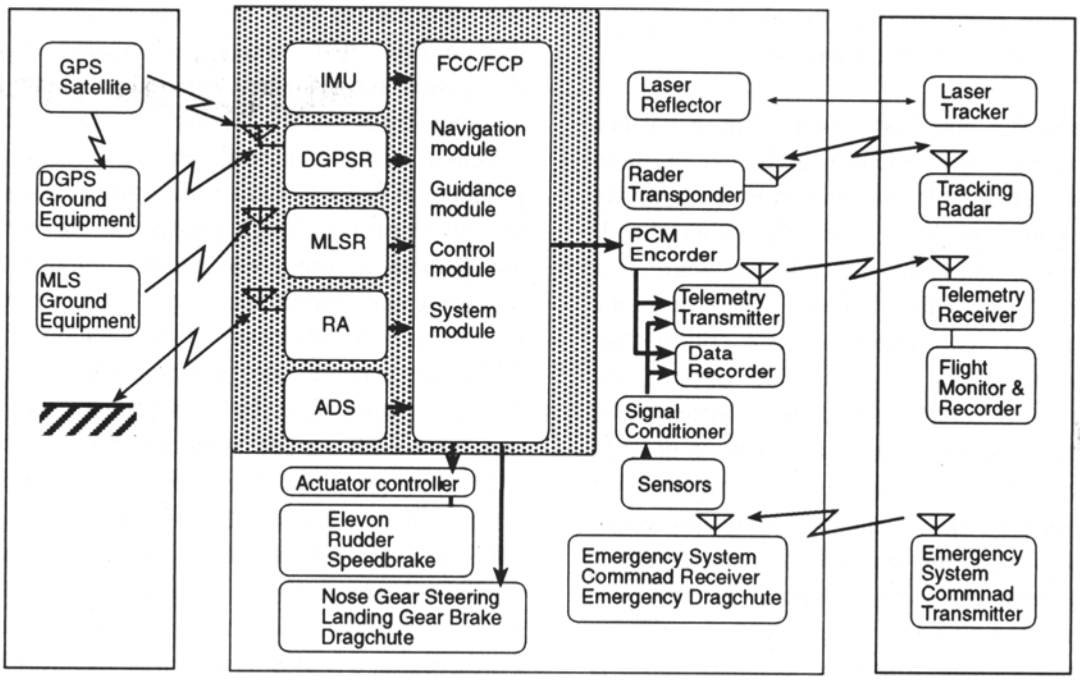


Fig. 8 Components of GNC and related systems.

Table 3 Performance requirement for Navigation (3σ)

Evaluation point	Accuracy requirement
20 seconds to Release	
Position	X, Y, Z direction: ±25m
Velocity	X, Y, Z direction: ±0.5m/s
Touchdown	
Position	X: ±60m, Y: ±8m, Z: ±0.8m
Velocity	X: ±2m/s, Y: ±0.5m/s, Z: ±0.5m/s
Attitude	Pitch angle : ±0.15 degrees, Bank angle : ±0.15 degrees, Azimuth angle : ±0.72 degrees
Ground roll	Y: ±8m

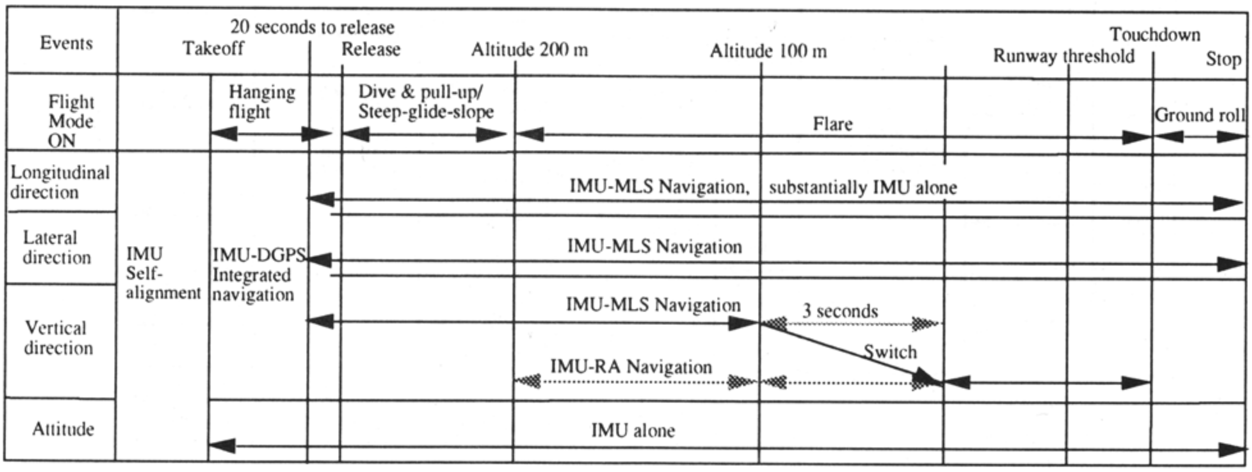


Fig. 9 Integrated navigation switching sequence.

three sets of states corresponding to DGPS/IMU navigation, MLS/IMU navigation and RA/IMU navigation, other than unique set of states that integrate all sensor data. This type of algorithm makes the ground and flight test evaluation simpler, i.e. if some problem occurs, it would be easier to find the cause and to correct it.

Figure 9 shows switching sequence of integrated navigation for each state variable.

(a) attitude

IMU itself has a function of inertial navigation and it provides attitude angles relative to the local horizon compensating earth curvature and rotation. It has a self-alignment function that performs on the ground prior to the flight, and attitude output without any correction maintains enough accuracy during the flight experiment of about 1 hour. Therefore, the attitude output from IMU is used directly. The maximum errors of attitude angles are less than 0.05 degrees for pitch and roll, and less than 0.65 degrees for yaw angle at 1 hour after the self-alignment.

(b) position and velocity

Position and velocity are outputs of navigation. The navigation algorithm is for the vehicle's translational motion. Error budget for each component gives the optimal gain for position and velocity estimation. Optimal and sub-optimal estimators are designed for the navigation filter.

(c) DGPS/IMU Integrated navigation

Since DGPS was under development when the ALFLEX program started and the receiver's reliability against different vehicle's attitude angle is not established, navigation perform DGPS/IMU Integrated navigation only during hanging flight prior to release. Data after the switch to other algorithms are stored and sent to the ground for post-flight analysis. The steady state error for navigation is required less than 25 m and 0.5 m/s for position and velocity, respectively, in 3 sigma values. In the experiment, the navigation performance can be evaluated by comparing laser tracker data in real time and after checking its performance, the navigation is switched from DGPS/IMU to MLS/IMU 20 seconds prior to release. DGPS/IMU uses 11 states, and the Kalman estimator is time-variant. One feature is that IMU alone inertial navigation is calculated in parallel and 6 states of DGPS/IMU for position and velocity are errors from the IMU-alone inertial navigation. This structure was chosen because DGPS reliability was not known at the design start, and this feature enables easy initialization when the filter diverges. The DGPS/IMU integrated navigation has an integrity function that judges and deletes invalid data. Since performance requirement for the DGPS/IMU navigation was given at the straight approach hanging flight, the time delay of DGPS data was compensated for by simply assuming constant acceleration motion.

(d) MLS/RA/IMU Integrated navigation

The navigation is switched from DGPS/IMU navigation to MLS/RA/IMU navigation 20 seconds prior to release. The DGPS/IMU navigation gives MLS/IMU navigation's initial values for position and velocity at the switch. The ALFLEX's MLS does not have DME/P and it gives azimuth and elevation angles from each ground station. This angle information can correct inertial navigation mainly in the y and z directions; because it can not improve accuracy in the x direction, range errors to ground stations increase with time. The range error does not affect the y direction error in using MLS azimuth angle, but it affects the z direction error, because the nominal flight has some elevation angle. The accuracy of MLS/IMU navigation obtained for the z direction does not satisfy the requirement. On the other hand, radio altimeters have a range limitation and it needs level ground surface of certain length before the runway threshold. For the z direction, MLS/IMU is switched to RA/IMU navigation at 100 m altitude gradually for 3 seconds. RA/IMU Integrated navigation starts calculation at 200 m altitude from initial data of altitude and rate given by the MLS/IMU navigation. MLS/IMU navigation uses a time-invariant Kalman filter of 10 states. According to sensitivity change of azimuth and elevation angles to Y and Z position, the flight path is divided to 5 sections and different constant gains are used for each section. RA/IMU Integrated navigation uses a time-invariant Kalman filter of 4 states. The updating cycle is 10 Hz. Since the range accuracy of MLS is limited not only in the ALFLEX but in a system with DME/P, altitude estimation has inherent error, because a re-entry space vehicle has a high elevation angle on approach. On the other hand, lateral direction error, or Y error, is not affected by the range error because the azimuth angle's nominal is always 0. Since an altitude navigation error prior to the final flare influences the touch down sink rate, the altitude error should be suppressed in the preflare maneuver. The range accuracy of inertial navigation at 1 minute after switching the navigation algorithm from DGPS/IMU to MLS/IMU affects the altitude error at switching MLS/IMU to RA/IMU. The altitude error was evaluated by numerical simulations, and the accuracy was checked. This problem was most critical in the ALFLEX navigation design.

9. Guidance

The guidance system was designed by dividing it into several phases consisting of path capture phase, equilibrium gliding phase, preflare and shallow glide phase, final flare phase and ground roll phase. Furthermore, it was divided to longitudinal and lateral guidance. Longitudinal guidance generates normal acceleration command and speedbrake angle command in order to reduce altitude and velocity errors from reference trajectory and velocity. When the reference trajectory is not a straight line, the open loop command is also considered. Lateral guidance generates a bank angle command in order to reduce a lateral path error. Since the horizontal reference trajectory is a straight line, the guidance is simple. The design was checked by 6 degrees of freedom numerical simulations including control. The system shows enough margins of landing performance against vectored shear wind as well as gust.

(a) Longitudinal guidance design

Longitudinal guidance was divided into path guidance and velocity guidance. In the path capture phase that is unique for ALFLEX, a nonlinear guidance law is designed to transfer the vehicle smoothly to equilibrium gliding through a free fall with zero lift after release. In the equilibrium gliding phase and its following phases, the reference trajectory altitude corresponding to X coordinate introduces an altitude error and its rate, which generates a normal acceleration guidance command in order to reduce the error. In the preflare and shallow glide phase, the reference trajectory is curved, so it adds an open loop command that is necessary to follow the curve to the feedback acceleration command. The final flare guidance is a mixed control that consists of exponential type feedback control of 0.5 m/s sink rate lower limit and fading out feedforward control generated when the landing gear is 5 m above the ground. Velocity guidance is a simple ID feedback, the reference of which is 84 m/s in equilibrium gliding and changes with a 2nd order polynomial function of the X coordinate in the preflare phase. The guidance command is simply for a speedbrake angle. After the final flare, the speedbrake is fixed so as not to generate a pitching moment disturbance. Longitudinal path following guidance feedback control is a simple PID controller, which should be a trade-off between suppressing the effects of disturbance on the reference trajectory and being independent from inner-loop attitude control response. After control system design, guidance gains are adjusted not to be coupled with the control, and then the performance was evaluated. Linear analysis and 6 degrees of freedom simulation determine the gains. Phases were switched by using altitude, altitude rate, and altitude error.

(b) Lateral guidance law design

ALFLEX's reference trajectory on the horizontal plane is straight to the runway centerline, so lateral guidance can be simple. Furthermore, the dynamics of lateral deviation due to bank angle is basically independent from the vehicle's velocity, and the lateral deviation acceleration is approximately proportional to the bank angle, where the side-slip angle is suppressed by the control. Bank angle command controls the lateral deviation with constant gain PID controller. As with the longitudinal guidance law design, lateral guidance gain is determined by compromising between the two factors; not to be coupled with inner-loop lateral-directional control, and to satisfy the landing performance requirement. In the path capture phase, the bank angle command is fixed to zero. The maximum bank angle command is 45 degrees in the equilibrium gliding phase. An appropriate limitation on the bank angle command is set depending on altitude, dynamic pressure, and azimuth angle. In case of a cross wind, ALFLEX approaches the runway with a wing-level crab state to compensate for the wind, and lands without a decrab maneuver before touch down. Concerning the decrab maneuver, it is checked that loads on landing gears and motion after touch down are limited and permissible without it. In the ground roll phase, guidance generates a yaw rate command that is proportional to the bank angle of free flight. Weight on Wheel switch (WOW) or pitch attitude trigger the switch to the ground roll phase.

10. Control law design

ALFLEX as well as HOPE has a special characteristic in flight control when it is compared with ordinary airplane. The center of gravity is rearward of the aerodynamic center; that is to say, it is unstable statically in pitch axis. In roll and yaw axes, it has negative weathercock stability and a strong dihedral effect, and lateral-directional motion is unstable. Therefore, it is necessary to stabilize the vehicle by feedback control and to give appropriate response performance in order to suppress the effects of disturbance and to respond to longitudinal guidance commands to land safely. Elevator controls kinetic normal acceleration. Rudder and aileron, asymmetric movement of right and left elevons, control bank and side-slip angles. Lateral-directional control has other special difficulties in flight control; the stability characteristic changes along with the angle of attack, the rudder has a strong coupling effect on the rolling moment, and the aileron has adverse yaw. The design was a trade-off between high performance, or good response to command, and robustness against dynamics change and uncertainty. The dynamics change and uncertainty come from flight characteristic variation with flight condition, error in aerodynamics, structural mode, control surface actuator dynamics, delay in data processing and transferring, and sensor dynamics. The design should be conducted to obtain maximum performance assuming these uncertainties and margins.

(a) longitudinal control law design

For the longitudinal control law design, two types are studied, one is that the normal acceleration command is directly compared with acceleration measured by an accelerometer and is fed back to the elevator, the other is that the normal acceleration command is transformed to a pitch rate command with an appropriate filter, then the pitch rate is controlled by the elevator. The former has a simple structure, but it is susceptible to noise and flexible mode, and response performance is limited because accelerometer output is fed back.. Although the latter is sensitive to transforming filter error, better response performance can be expected. Because the response performance after the preflare phase is the most important to obtain landing accuracy, the latter structure was adopted. A control design technique called multiple-delay-model and multiple-design-point (MDM/MDP) approach introduced a basic control law for pitch rate control. Since the control surface effect is proportional to dynamic pressure, the control gain must be inversely proportional to dynamic pressure in order to compensate for it. Another design technique called the H infinity exact model matching (H_∞EMM) method, which enhances robustness without changing command response, introduced the final control law. Power spectra of disturbance and measurement noise are used to adjust the robustness by evaluating sensitivity and complementary sensitivity functions. Pitch rate command has a limitation in that it can not avoid going over the upper bound of attack angle or abrupt maneuver.

(b) lateral-directional control law design

The objective of lateral-directional control is to bend the normal aerodynamic force on the vehicle to a commanded angle from the vertical direction. Generally, there are two approaches; one is that side-slip is always suppressed and only bank angle performs this control, and the other is that the side force generated by permitting side-slip is mixed with bank angle control. ALFLEX has a strong dihedral effect and generating side-slip introduces coupling with roll axis, so the former approach was adopted. Two variables, side-slip measured by ADS and lateral acceleration measured by IMU, were studied for the feedback signal to suppress the side-slip angle. Since it is easy to enhance robustness with the former variable, side-slip angle was used for lateral-directional control. The same approach with the longitudinal control law produced the lateral-directional control law, that is MDM/MDP and H_∞EMM design techniques introduced the final dynamic pressure compensated constant gain control law. In the lateral-directional control, rudder that does not have static balance has inertial coupling to the ADS's side-slip output on top of the boom and the IMU's roll rate output. Due to these couplings, the lateral-directional control law was modified to avoid control/structure coupling after the ground vibration tests.

(c) Specification for control law design

Response to command and stability margins are evaluated in the design. Specification for command responses is described by settling the time and overshoot amount, such as settling times for pitch, bank, and side-slip angles to less than 1.5, 3, and 5 seconds, respectively. Overshoot should be less than 10%. Roll-yaw coupling in the lateral-directional control is specified such that side-slip angle coupling due to 45 degrees bank angle command is less than 2 degrees, and bank angle coupling due to side-slip command is less than 20% of the side-slip command. Requirements for stability margin are 6 dB gain margin and 45 degrees phase margin for every loop broken at each control input. After obtaining each component data from ground tests in the design follow phase, these margins can be relaxed to half. Concerning parameter variations, it is checked that the vehicle should be tolerant against each parameter variation, but it is not requested to be tolerant against the worst on worst condition. Total landing performance with the parameter variations was evaluated by a huge number of numerical simulations.

(d) Ground roll control law design

For the ground roll, a lateral control law was designed. Steering nose landing gear and actuating control surfaces control the vehicle's directional motion in order to follow the yaw rate guidance command. A solution of the optimal servo problem introduced a constant gain feedback controller, where it considers uncertainty in model dynamics and changing dynamics along with ground velocity.

11. GNC system hardware

The Navigation and Guidance and Control (GNC) system consists of the following 6 instruments, and their main performance are shown by Table 4. Figure 10 shows their arrangement in the ALFLEX vehicle. The environment in the ALFLEX vehicle is the same as one in a non-engined aircraft.

(1) Flight Control Computer (FCC) / Flight Control Program (FCP)

The FCC is the main computer of ALFLEX. Since the FCC executes the FCP, it reads the data from many kinds of on-board sensors, and computes command signals to operate the control surfaces such as the elevon and rudder. The CPU of FCC is a programmable DSP (TMS320C30), as it requires powerful calculating performance. The FCC has five sheets of circuit board, they are the master board which contains the CPU, the communications board which uses the MIL-1553B format, the PCM board, the discreet I/O board, and the analog I/O board. The VME-bus is adopted. The interface between the FCC and the other instruments is as follows. The A channel of MIL-1553B format is used for the transmission protocol between the FCC and the IMU / ADS / DGPSR / MLSR. The analog I/Os (12-bit A/D) are used for the interface between the FCC and the RA, and between the FCC and the actuator (for the command and the monitor). The discreet I/Os are used for the interface between the FCC and the Mother Helicopter's on-board computer, and they are used for the signal lines used to detect the release's, the weight on wheel, the braking parachute's open command, and the braking command. The RS-422 format is used in one between the FCC and the GNC System Checkout Equipment. The flight data which displays the status of the flight condition and the result of calculation is transmitted to the PCM encoder, and the transmission's performance is 81.92 [kbps] (80 [Hz cycle], 128 [word/frame], 8 [bit/word]).

For the FCP, "C" language is adopte . The functions of the FCP are:

a) hardware control function, which consists of the operation system, the input/output control, and the control of CPU.

b) the calculation of GNC.

c) system management function, which consists of the sequence control, the program mode's management, and the control of the telemetry data.

d) GNC's system management function, which consists of the support program of GNC's system checkout and the Umbilical system.

The minor cycle of calculation is 80[Hz], which calculates the position / velocity / attitude of the inertial navigation, and the control command signal. The major cycle of calculation is 10[Hz], which calculates the position / velocity of the integrated navigation (excepted the IMU-DGPS integrated navigation), and the guidance command. The cycle of calculation of the IMU-DGPS integrated navigation is 0.5[Hz]. The FCC has enough performance to execute the FCP.

(2) Inertial Measurement Unit (IMU)

The IMU of ALFLEX is the strapped down type, equipped with three small-ring laser gyroscopes for aircraft and accelerometers. The fundamental design is equivalent to that of the HYFLEX. The ALFLEX's

IMU has the same accuracy as those used in aircraft. The IMU has the self-alignment function, it takes about 30 minutes to execute the self-alignment in steady situation on the ground. The IMU has the function which is to calculate the inertial navigation, but in ALFLEX's design, the only use of calculating result of the IMU is the attitude. In fact, to execute the inertial navigation in the FCP, the velocity increment output, the angle increment output, and the attitude output are used. The output update cycle of the IMU is 80 [Hz], which is the same as the FCC's minor cycle, but there is no synchronism between the FCC and the IMU.

(3) Air Data System (ADS)

The ADS consists of a Pitot-probe which is on a boom installed in front of the vehicle, and the Air Data Computer (ADC) which calculates the ADS's output such as the dynamic pressure, the angle of attack, and the side slipping angle. The Pitot-probe is located enough far from the head of the vehicle that the air stream which is sensed by the Pitot-probe is not disturbed by the vehicle's body. The Pitot-probe has five holes, one on each of the five planes of the quadrangular prismoid which is located on the top of the boom, and it is calibrated with the window tunnel test. The ADC measures the pressure of the five holes, and calculates the dynamic characteristics by using of five hole-pressures and the approximate polynomials which are selected according to the mach number of the air speed. The output update cycle of ADS is 32 [Hz], and there is no synchronism between the FCC and the ADS.

(4) Radio Altimeter (RA)

The RA of ALFLEX is a pulse type that uses a short period pulse of microwave (4300 [MHz]), and the vehicle's altitude is measured with the time interval between the radiation and its echo back from the ground. Although the output range of RA is ≤762 [m], the practical range is ≤380 [m], which is realized with adopting the adequate A/D converter of FCC. The reason is the range of designed point is less than 200 [m] and the electronic noise is reduced. Concerning the attitude of vehicle where the RA works normally, there are generally no problems including in the landing phase where the vertical attitude change is biggest of all the phases.

(5) Microwave Landing System Receiver (MLSR)

The MLSR measures the vehicle's position, the azimuth and the elevation from the ground equipment near the runway. It does so by measuring the receiving time period of the microwave scanning with the constant speed. The microwave beam is the fan beam, and is transmitted from the azimuth MLS ground equipment and the elevation MLS ground equipment. In addition, the characteristics of ALFLEX's MLSR are as follows:

a) The valid range is wider than for aircraft.

b) The azimuth angle is valid on the runway.

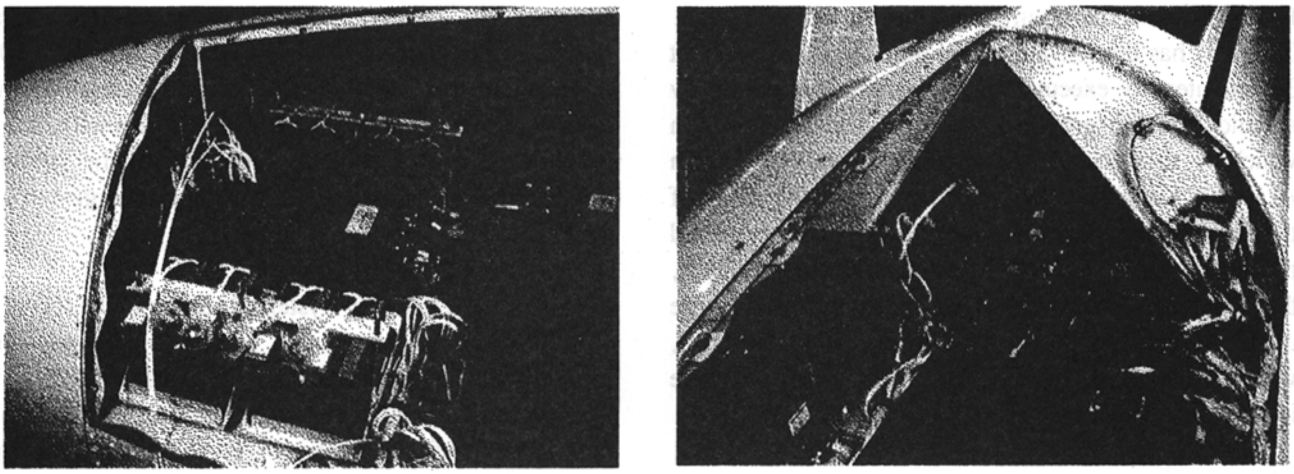
c) The output update cycle is 10 [Hz] by using the moving average filter to improve accuracy

d) The antenna-selecting function according the receiving intensity.

(6) Differential Global Positioning System Receiver (DGPS)

DGPS achieves higher position and velocity accuracy using information from pseudolite ground station than that of normal GPS. Pseudolite ground station generates correction data from the signal of GPS satellites and transmits it to the DGPSR. In addition, pseudolite ground station works as GPS satellites on the ground. This increases the availability of the GPS satellite and GDOP (Geometrical Dilution Of Precision). In addition, ALFLEX DGPSR has functions as below:

- Sampling triggered by synchronization pulse from FCC.
- Antenna selection using attitude information from FCC.



(Front side of the front bay, FCC and ADC) (Rear side of the front bay, MLSR, GPSR, IMU and RA)

Fig.10 Photographs of GNC components.

Table 4 Navigation, Guidance & Control System components' main performances.

Flight Control Computer (FCC)	
CPU	TMS320C30(33MHz)
	16.5 MIPS
Memory Capacity	EEPROM : 512Kbytes
	SRAM : 512Kbytes
I/O	MIL-STD-1553B
	PCM output (based on the H-II format)
	Discreet Input : 24ch
	Discreet Output : 10ch
	Analog Input : 13ch (12bitA/D)
	Analog Output : 8ch (12bitD/A)
Dimension / Mass	389×127×200 mm / less than 12 kg
Power Consumption	less than 128 W
Inertial Measurement Unit (IMU)	
Velocity Increment Output	Range : ±20 G
	Bias Stability (after 1 year): 150 μ G (less than ; 3 σ)
	Scale Factor Stability (after 1 year) : 241 ppm (less than ; 3 σ)
	Scale Factor Non Linearity(after 1 year) : 18 μ G/G^2 (less than; 3 σ)
	Bias Vibration Sensitivity(after 1 year) : 3 μ G/G^2 RMS (less than; 3 σ)
Angle Increment Output	Range : ±400 deg/s
	Bias Stability (after 1 year): 0.075 deg/h (less than ; 3 σ)
	Scale Factor Stability (after 1 year) : 40 ppm (less than ; 3 σ)
	Scale Factor Non Linearity(after 1 year) :
	0~120 deg/s ; 60 ppm (less than; 3 σ)
	120~220 deg/s ; 250 ppm (less than; 3 σ)
	220~400 deg/s ; 60 ppm (less than; 3 σ)

	Random Walk Factor (after 1 year) : 0.048 deg / $\sqrt{h}$ (less than; 3 σ)
	Random Noise(after 1 year) : 0.66 deg/$s_{0\text{-}P}$ (less than; 3 σ)
Miss Alignment	less than 30 s(after 1 year ; 3 σ)
Initial Alignment Accuracy	Yaw : less than 0.6 deg (3 σ)
	Roll : less than 0.03 deg (3 σ)
	Pitch : less than 0.03 deg (3 σ)
Output Update Cycle	80 Hz(Minor Cycle)
Dimension / Mass	389×210×211 mm / less than 16 kg
Power Consumption	less than 100 W
Air Data System (ADS)	
(Air Data Computer)	
Barometric Altitude Output	Range : -305 ~ 1829 m Error : ±6.1 m (3 σ)
CAS Output	Range : 25.7~103 m/s Error : ±2.1 m/s (at 25.7 m/s ;3 σ)
Angle of Attack Output	Range : -25 ~25 deg Error : ±0.3deg (1 σ)
Side Slip Angle Output	Range : -25 ~ 25 deg Error : ±0.3deg (1 σ)
Mach Number Output	Range : 0.1 ~ 0.4 Error : ±0.01 (at 0.15M;3 σ)
Dynamic Pressure Output	Range : 0~6.77 kpa Error : ±50.8 pa(3 σ)
Static Pressure Output	Range : 77.9 ~ 108 kpa Error : ±50.8 pa(3 σ)
Output Update Cycle	32 Hz
Dimension / Mass	436×155×242 mm / less than 8.6 kg
Power Consumption	less than 70 W
Radio Altimeter (RA)	
Altitude Output	Range : 762 m Error : ±(0.91+(real Alti)×0.03) m (3 σ)
Measurable Attitude (Roll / Pitch) of Vehicle	0 ~ 91 m ; ±15deg
	91 ~ 457 m ; ±30deg
	457 ~ 762 m ; ±10deg
Frequency	4300 MHz ±5.375 MHz
Output Power	5W
Dimension / Mass	129×96×84 mm / less than 1.4 kg
Power Consumption	less than 25 W
Microwave Landing System Receiver (MLSR)	
Frequency	5090.7 MHz
Output Data	Az, EL, Received signal level, Status
Output Update Cycle	10Hz
Range	Az : -40 deg ~ 40 deg
	EL : 0.9 deg ~ 40 deg
Accuracy	Bias: Less than 0.017 deg (at -81 dBm)
	Noise: Less than 0.015 deg (at -81 dBm ; 2 σ)
Mass	10 kg
Power Consumption	Less than 40 W
Differential Global Positioning System Receiver (DGPSR)	
Frequency	GPS Satellite: 1575.42 MHz (C/A code) / Pseudolite: 1624.61 MHz
Number of Channels	For GPS Satellite: 5 ch , For Pseudolite: 1 ch

Maximum acceleration	± 25 m/s^2
Output Data	Observation time, Pseudorange, Deltarange, Carrier phase, GPS message, Pseudolite message
Output Update Cycle	2 sec
Accuracy	Pseudorange : 25 m (3 σ)
	Deltarange : 5.0 cm (at 100 ms ,3 σ)
	Carrier Phase : 3.3 cm (3 σ)
	Clock : 10^{-9}
Mass	DGPSR: 7.5kg, Preamplifier: 0.35 kg
Power Consumption	Less than 30 W

12. The series of the development tests of the GNC system

The development tests of the GNC system are as follows, which were executed after the certification test of each instrument.

(1) The test of the FCP's conformity with the FCC

The test is the check of FCP's execution on the FCC. After the communications check between the FCC and Guidance / Navigation / Control system Aerospace Ground Equipment (GNCAGE) by the RS422 device, the check of FCP's interface functions (i.e., MIL-1553B, analog signal, digital signal) is executed with the FCC and the GNCAGE which simulates the GNC's instruments. The check of the FCP's GNC function is executed, and the output of the FCC / FCP in using the simulated signal from the GNCAGE is compared with the calculated one. In addition, the time of calculation and the output rate of the signal are measured. There is no problem in any of the cases.

(2) The test of the interface between the FCC and the other instrument

The FCC is connected with other instruments (IMU / ADS / RA / MLSR / DGPSR / Power Sequence Distribution Box / PCM encoder / Rudder actuator / Elevon actuator / Speed brake actuator / Steering actuator), and the check of the interface and the communication is executed. There is no problem in any of the cases.

(3) The physical simulation test

The test is the closed loop and flight simulated. The way of test is that the FCC / FCP is connected with the 7 real actuator and the GNCAGE which uses for simulating the other GNC's output. The test's results shows that there is no problem in physical simulation. In addition, it is certified that the stability margin (gain margin and phase margin) in the hanging flight is enough.

(4) The closed-loop test

In the closed-loop test, all instruments are on board, and the GNCAGE simulate the GNC's output as the physical simulation. The characteristic of this test is that all vehicle systems, including the GNC system, can be checked in the flight configuration, and that in flap actuator the characteristic of structure is included (which is the difference from the physical simulation test). As the closed-loop test is the final test of vehicle's check, it executes whenever the vehicle is re-built, and whenever any problem is resolved before the Flight Test.

13. Concluding remarks

This paper describes the general features of the ALFLEX GNC system's development. In the landing phase, a re-entry space vehicle needs the highest accuracy because the runway is very small like a tiny pinpoint compared huge space and sky, and special consideration is required when designing the GNC. The requirement of high accuracy is different from rendezvous and docking in the points of disturbance, uncertainty, and time scale, which causes the following difficulties.

- The navigation system should satisfy the high accuracy requirement.
- The control system should realize agile response requirement for an unstable vehicle.
- The control law should be robust against uncertainty estimated from analysis and ground

tests, such as wind-tunnel tests and actuator dynamics tests.

- The guidance law should be robust against measurement error, disturbance, and control error.

The ALFLEX GNC system basically satisfies the performance and robustness requirements.

In the ALFLEX program, GNC design was the most important element for our country's future re-entry space vehicle development. Landing technology development has a long history, represented by lifting body vehicle's landing experiment at Edwards Air Force Base, California in 1960s and development of the US space shuttle. These results are publicized and it was expected for our country to develop similar technology for itself. The ALFLEX program was intended to demonstrate this and to make the HOPE-X development efficiently. Consequently, the US shuttle GNC had some influence on the ALFLEX design. When some consideration is necessary in the design, the space shuttle results are always referred to. Various unique trials, however, have also been adopted; for example, the Pseudo-satellite type DGPS system was developed and adopted partly, side-slip angle measured by ADS other than lateral acceleration is directly used to suppress the side-slip, normal acceleration is generated by transforming normal acceleration guidance command to pitch rate by an appropriately designed feedforward filter for longitudinal control, advanced linear control system design techniques such as MDM/MDP and H_∞EMM are adopted for robust flight control design and a high-order system realizes the control law, the shallow glide phase is very short and guidance error is suppressed in the preflare maneuver, the system is fully automatic and is independent from a human pilot, consequently the designed system was evaluated and justified by huge amount of numerical simulations, and finally, the hardware used utilizes digital technology extensively. These trials are evaluated in the ALFLEX flight tests, and they will be further evaluated through the HOPE-X development and flight test. Some of the unique trials would be reasonable as a trend in the history or they would reward the designers' effort, but some of them might give rise to unexpected problems. Only the right challenge, however, could create new technology that will not soon be replaced as technology marches on.

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