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Automatic Landing Flight Experiment Flight Simulation Analysis and Flight Testing

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Preflight simulation analysis of flight experiment and flight test results are described. The automatic landing flight experiment was conducted in Woomera, Australia, in 1996, to develop the automatic landing technology required for the future Japanese uncrewed spacecraft. To ensure successful landings, computer simulation played an important role in the preflight analysis. Monte Carlo simulation was applied for the analysis. The root sum square method, which is commonly used in Japanese launcher rocket development projects, was also applied. Monte Carlo results were compared with the rss results and the flight test results. All 13 flight tests were successfully completed. Longitudinal guidance in the flare phase was found to be sensitive to some modeling errors. The cause is discussed.

Nomenclature

A_Z	= normal acceleration (normal to flight path), m/s^2
H	= altitude of the vehicle, m
p_d	= dynamic pressure, N/m^2
q	= pitch rate, deg/s
V_{EAS}	= equivalent air speed, m/s
V_{grd}	= ground speed, m/s
X, Y, Z	= vehicle position (runway axes), m
$X_{\max}, X_{\min}$	= maximum and minimum value of touchdown down range, m
$\dot{X}, \dot{Y}, \dot{Z}$	= vehicle velocity (runway axes), m/s
y_{nom}	= landing performance of the nominal case
y_{rss}	= rss value of landing performance
$y(3\sigma_i)$	= landing performance due to ith model error of 3σ deviation
$\Delta C_L, \Delta C_D, \Delta C_Y, \Delta C_l, \Delta C_n$	= aerodynamic coefficient error
ΔC_{mq}	= dynamic stability derivative error, %
$\Delta C_{n\delta a}, \Delta C_{n\delta r}, \Delta C_{Y\delta r}$	= control derivative error
ΔGE	= ground effect error, %
ΔM	= mass error, kg
$\Delta \mathrm{MLS}_{\mathrm{AZ}}$	= microwave landing system (MLS) measurement error (azimuth angle), deg
$\Delta P_{\mathrm{air}}, \Delta T_{\mathrm{air}}$	= atmospheric states model error, pressure, temperature, N/m^2, K
ΔRA, $\Delta \mathrm{RA}_{\mathrm{sf}}$	= radio altimeter measurement error, bias, scale factor, m, %
Δt_{MLS}	= MLS measurement time-delay model error, ms
ΔV_{EAS}	= V_{EAS} measurement bias error, m/s
$\Delta \mathrm{WIND}_{45}$	= maximum head wind at a 45 deg to the flight path, m/s
$\Delta X_{\mathrm{nav}}, \Delta Y_{\mathrm{nav}}$	= initial navigation error of position, m
$\Delta \dot{X}_{\mathrm{nav}}$	= initial navigation error of velocity, m/s
$\Delta\beta$	= measurement error of side-slip angle, deg
$\delta e, \delta a, \delta r, \delta$sb	= control surface deflection, elevator, aileron, rudder, speed brake, deg
σ	= standard deviation
Φ, Θ, Ψ	= attitude angle (Euler angle), roll, pitch, yaw, deg

Subscripts

com	= command
ref	= value of reference path

Introduction

THE automatic landing flight experiment (ALFLEX)[1] project was planned to develop automatic landing technology for the H-II orbiting plane (HOPE), which is the Japanese future uncrewed space transportation system. All 13 flight trials of ALFLEX were successful. Figure 1 shows a photograph of the ALFLEX vehicle in flight just after release from a helicopter.

Generally, a thorough preflight assessment is essential to ensure the success of a first flight experiment. In the ALFLEX experiment, the motion of the vehicle is controlled by an onboard computer with no provision for remote control. (In the event of an emergency, the vehicle can be forced to drop to the ground by emergency command.) The vehicle's motion heavily depends on the installed control law.[2–4] In the case of an uncrewed vehicle, the flight control system can be modeled to a high degree of accuracy, and this is an advantage for flight assessment by computer simulation, in which the vehicle motion is computed using mathematical models of the vehicle[5,6] and the environmental condition. However, in a real system there are many uncertain factors expressed as model errors, as shown in Fig. 2, and these modeling errors result in discrepancies between the real and simulated systems. Some of these modeling errors might significantly affect flight safety or degrade landing performance, but it is usually difficult to identify the magnitude of these modeling errors. Despite these factors, the vehicle must fly safely and its landing performance must satisfy specific requirements.

To evaluate the influence of these modeling errors, two simulation methods were applied. They are the root sum square (rss) method and Monte Carlo simulation.[7,8] With the rss method, total variance of landing performance was derived by accumulating the variance of landing performance due to each model error. The Monte Carlo simulations analyzed the influence of various combinations of model errors, and its results were considered to be more reliable than those of the rss method. These simulation results were used in deciding whether or not to proceed with the automatic landing tests. These

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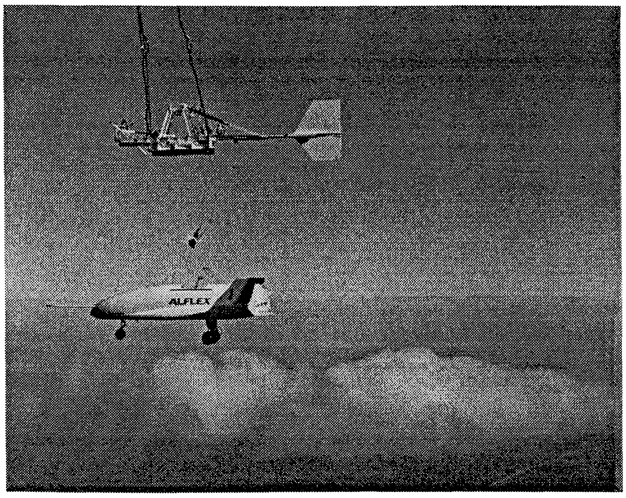

Fig. 1 Release of the ALFLEX vehicle.

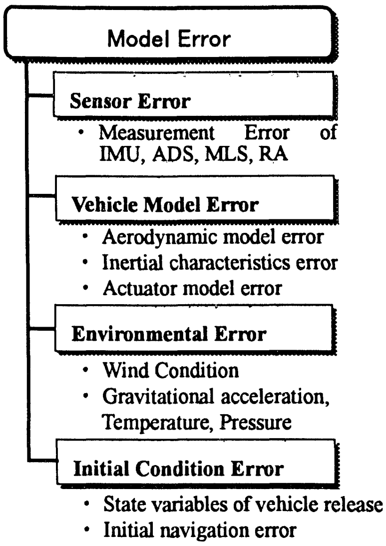

Fig. 2 Model error.

simulation methods and simulated results are described in this paper, and the simulation results are compared with flight-test data.

These simulation analyses use large amounts of computational resources. However, thanks to recent dramatic increases in the power of computers, it was possible to perform all of these simulation analyses prior to the first landing flight test.

In the actual flight tests, touchdown points were farther down the runway than the nominal point in all 13 flights. Certain model errors are considered especially to influence the touchdown point, and the causes are discussed. It is one of the important findings gained from the ALFLEX flight experiment.

Overview of ALFLEX Flight Test

Hanging Flight[9]

In the ALFLEX experiment, the ALFLEX vehicle was carried to its release point attached to hanging equipment suspended from a mother helicopter. The hanging equipment used a gimbal support system, as shown in Fig. 3. The advantages of this system are as follows:

1) A smooth transition to free flight is possible because there is no restriction to the vehicle's attitude in hanging flight and flight control can be started prior to release.

2) The control system can be validated by preliminary flight test in this configuration.

3) Aerodynamic characteristics can be estimated by using hanging flight-test data.[10] The important point is that aerodynamic characteristics can be estimated by using the actual vehicle rather than a model.

The hanging equipment was suspended 20 m below the mother helicopter, and the ALFLEX vehicle was suspended 4 m below the hanging equipment, supported by a single cable hooked onto the gimbal, which was located at the center of gravity of the vehicle. In this configuration, the vehicle could move with five degrees of freedom: three rotational and two translational. The attitude of the vehicle was stabilized by its flight control system.

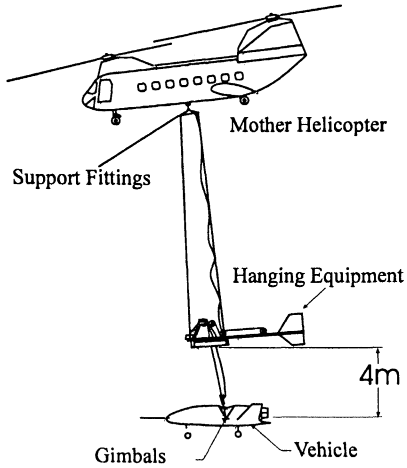

Fig. 3 Hanging flight.

Free Flight

The flight path of the vehicle is shown in Fig. 4. The mother helicopter flies horizontally down the runway at a speed of 90 kn. The vehicle is released 2700 m from the runway at a height of 1500 m and is then guided to the runway by its onboard computer. The longitudinal guidance is divided into several phases as follows: 1) path capture phase in which the vehicle accelerates and captures the equilibrium glide path; 2) equilibrium gliding phase in which the vehicle flies at a constant path angle of 30 deg and at a constant equivalent air speed; 3) preflare phase in which the flight-path angle changes and the airspeed decreases; 4) shallow glide slope phase in which the vehicle flies at a constant path angle of 1.5 deg; 5) final flare phase in which vertical speed is reduced to 0.5 m/s, sink rate is mainly controlled in this phase; and 6) ground roll phase in which the vehicle is brought to a halt.

The vehicle is guided to track the predetermined reference path. The reference path is calculated by the onboard computer using the vehicle's position derived from the navigation system.

Inertial position and velocity are derived from an inertial measurements unit–microwave landing system (IMU–MLS) hybrid navigation system. IMU measures attitude and angular rate, and MLS measures azimuth and elevation angle. When the height of the vehicle is less than 100 m, Z-axis values (height and sink rate) are derived from an IMU–radio altimeter (RA) hybrid navigation system.

Simulation Analysis

The actual system has various model errors, as shown in Fig. 2. Despite these uncertainties, the landing performance must satisfy the requirements shown in Table 1. In the ALFLEX project, simulation analysis played an important role in investigating the influence of various model errors and disturbances. If no model errors exist in the system, touchdown performance should conform to the nominal case shown in Table 2, that was derived from a computer simulation that excluded model errors.

Two simulation methods were applied to investigate the influence of model errors. One method is the root sum squares method, which has been used in launcher rocket projects. This method, however, requires a linear relationship between a model error and its influence on touchdown performance. The other method is Monte Carlo simulation, which is considered to be more reliable.

The important model errors and their assumed 3σ values are shown in Table 3. The variation data of the Space Shuttle are basically used for the 3σ deviation of aerodynamic model errors. Wind condition is defined from the MIL-F-9490D low-altitude wind model.

RSS Method

In the rss method, total variance of landing performance is calculated by accumulating the variance of landing performance due to each model error. The result of the rss method is reliable provided that the following two conditions are satisfied:

1) There is a linear relationship between a change in model error and the resulting deviation of landing performance.

2) Model errors are independent of each other.

Calculation of RSS Value

Because the real system does not satisfy these two conditions, the following treatment was applied so that the rss method could be used. The deviation of the landing performance from nominal due to each model error of 3σ value was derived by computer simulation, where $3\sigma_i$ represents the 3σ value of the ith model error and $y(3\sigma_i)$ and $y(-3\sigma_i)$ represent landing performance due to $3\sigma_i$ and $-3\sigma_i$ model errors, respectively. Then $y_{3\sigma i}$, which represents the deviation of landing performance from nominal due to the 3σ value of the ith model error, is determined as

$$y_{3\sigma i} = \sqrt{\frac{\{y(3\sigma_i) - y_{\text{nom}}\}^2 + \{y(-3\sigma_i) - y_{\text{nom}}\}^2}{2}} \qquad (1)$$

where y_{nom} represents the nominal value of landing performance. When landing performance varies linearly with the value of the model error, $|y(3\sigma_i) - y_{\text{nom}}|$ and $|y(-3\sigma_i) - y_{\text{nom}}|$ should be the same value. The rss value shows total deviation of landing performance against all 3σ values of model error and is expressed as

$$y_{\text{rss}} = \sqrt{\sum_i y_{3\sigma i}^2} \qquad (2)$$

With the rss method, Eq. (2) represents the total 3σ deviation of landing performance. In the analysis, the model errors shown in Fig. 2 were included, and these number more than 90. The given wind condition was a headwind at 45 deg to the flight path at the maximum design steady wind speed. This direction was chosen so that the wind affected both longitudinal and lateral motions.

Table 1 Touchdown requirement

Direction	Guidance, navigation, and control requirement
Longitudinal	$\|X_{\max} - X_{\min}\| \le 450$, m
	$\dot{Z} \le 3.0$, m/s
	$42.0 \le V_{\text{EAS}}$
	$V_{\text{grd}} \le 62.0$, m/s
	$\Theta \le 23.0$, deg
Lateral	$\|Y\| \le 18.0$, m
	$\|\Phi\| \le 10.0$, deg
	$\|\Psi\| \le 8.0$, deg

Table 2 Touchdown states (nominal case)

State variable	Touchdown value
$\dot{Z}$, m/s	0.5
V_{EAS}, m/s	52.5
X, m	303
Θ, deg	13.7
Y, m	−0.4
Ψ, deg	−0.2
Φ, deg	0.5

Table 3 Assumed model errors

Model error	3σ Value
ΔV_{EAS}	2.0, m/s
$\Delta \text{RA}_{\text{sf}}$	3.1, %
ΔX_{nav}	25, m
ΔY_{nav}	25, m
$\Delta \dot{X}_{\text{nav}}$	0.5, m/s
$\Delta \text{MLS}_{\text{AZ}}$	0.127, deg
$\Delta\beta$	0.9, deg
ΔC_Y	0.0056
$\Delta\Theta$	0.153, deg
$\Delta\Phi$	0.153, deg
ΔGE	100%
ΔT_{air}	10, K

Total Touchdown Performance

The results of the rss analysis are shown in Fig. 5. These six graphs show influential model errors on the touchdown parameters of sink rate, X position, V_{EAS}, Y position, Ψ, and Φ. The 10 most influential model errors are shown for each touchdown parameter. The horizontal axis represents the value calculated by Eq. (1), which expresses the deviation from nominal in landing performance due to each model error. The rss value calculated by Eq. (2) is shown at the top of each graph. The rss value corresponds to the 3σ deviation of the touchdown state.

From Figs. 5d–5f, it is clear that the effect of model errors on the touchdown parameters related to the lateral motion is small and that landing performance has sufficient margin for the requirements. The rss values are also sufficiently small and meet the requirements. On the other hand, longitudinal touchdown parameters, downrange X, sink rate, and V_{EAS}, are shown in Figs. 5a–5c. The rss value of the X position is about 270 m, and this results in a $\pm 3\sigma$ dispersion range of 540 m. This does not satisfy the requirement of 450 m. The rss value of sink rate is 2.5 m/s, and the nominal value is 0.5 m/s. The sink rate barely satisfies the requirements of Table 1. Furthermore, the 3σ dispersion range of V_{EAS} is larger than the requirement. The nominal value of 52.5 m/s minus 3σ dispersion range of 11.8 m/s exceeds the minimum requirement of 42 m/s. The result of the rss

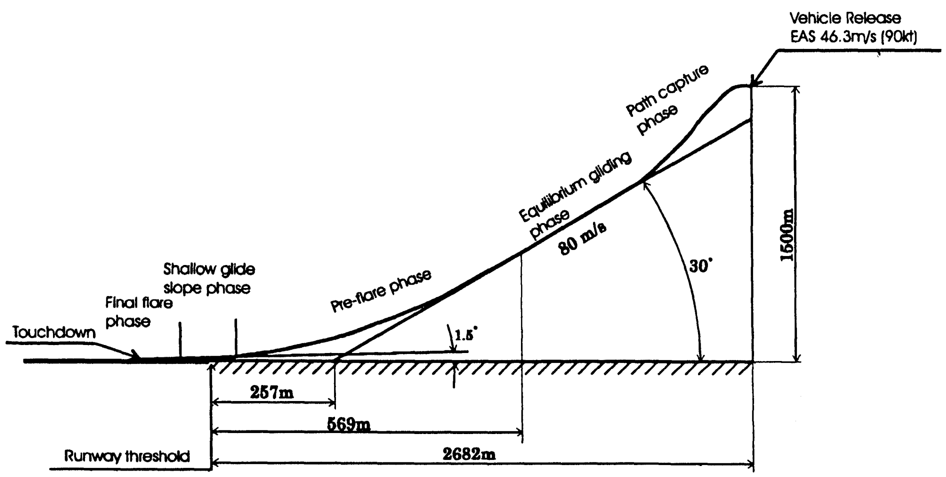

Fig. 4 Flight path.

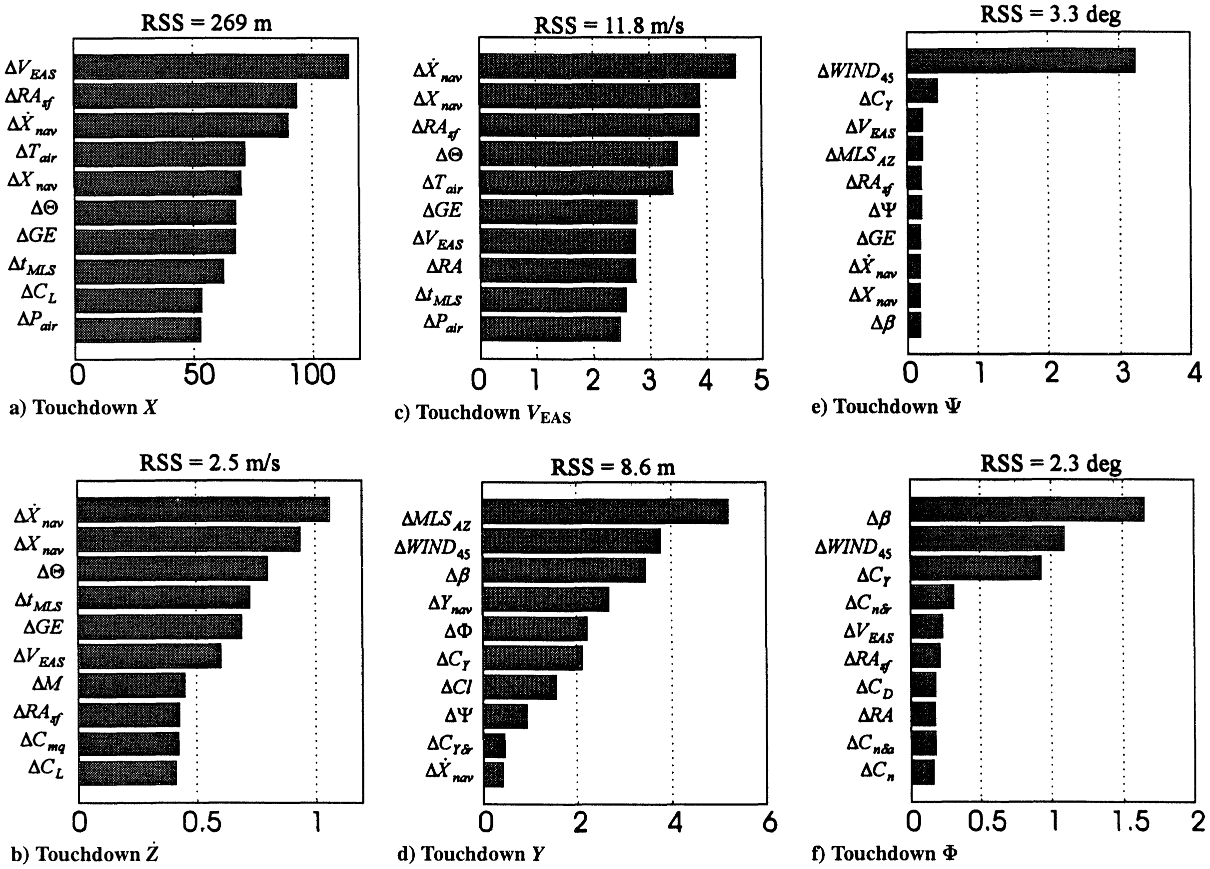

Fig. 5 RSS result.

analysis, therefore, shows that lateral touchdown performance has adequate margin, but longitudinal touchdown performance does not have any margin, and there appears to be difficulty in satisfying the longitudinal touchdown requirements.

Influential Model Errors

Influential model errors on the longitudinal touchdown performance are initial navigation errors of downrange X velocity and position. Generally, the effects of initial errors are thought to become smaller as the vehicle approaches the ground. In reality, however, although navigation data (velocity and position) are updated online by using MLS and RA data, no data are provided to update the downrange values, and so the downrange navigation error increases with vehicle flight time. For this reason, initial navigation errors of downrange are influential on the longitudinal touchdown performance. Other than the initial navigation error, the most influential parameters on the touchdown X position are V_{EAS} bias error and RA scale factor error.

For lateral touchdown performance, wind is one of the most influential model errors. Other than the wind condition, azimuth bias error of MLS and β bias error are also influential on the touchdown Y position.

Bounds of the rss Method

With the rss method, total dispersion of landing performance is calculated by Eq. (2), which accumulates the effect of each model error. It is, therefore, impossible to derive their combined effect. Furthermore, the mean value of touchdown parameter dispersion is considered to be the same as the nominal value because of the assumption of linearity between a change in model error and the resulting deviation of the touchdown parameter. In an actual system, however, this relationship is usually nonlinear, and the mean value is not necessarily the same as the nominal value. To investigate the combined effect of model errors, Monte Carlo simulations were conducted. The results are compared with the rss results.

Monte Carlo Simulation

Monte Carlo simulation is more reliable for evaluating total landing performance than the rss method because it does not assume linear influence of model error and the combined influence of model errors can be derived. In this analysis, it was assumed that the distribution of model errors is basically Gaussian and that the model errors are independent of each other. The distribution of wind power and direction were assumed to be uniform. In each simulation run, which simulated flight from release to landing, model errors were generated depending on their assumed distribution before release. In addition to the model errors shown in Fig. 2, random measurement errors and gusting wind were incorporated into the simulation. All model errors were incorporated simultaneously and varied randomly. Landing performance was estimated statistically from a large number of runs.

Total Landing Performance

The distribution of touchdown states obtained from Monte Carlo simulation of 1000 runs from release to landing is shown in Fig. 6. Figures 6a–6c show touchdown states of position, velocity, and attitude, respectively. The dotted lines show the requirement values from Table 1. An important point is how often the results fail to meet the requirements. Table 4 shows mean and 3σ values of touchdown states and the number of cases that did not meet the requirement. In Monte Carlo result, 3σ dispersion is from mean value, not from nominal. From the results of the Monte Carlo simulation, the most critical touchdown parameter is sink rate, which is greater than the requirement value of 3.0 m/s in about 1.0% of cases. However, Fig. 6b shows that 7 of the 11 cases in which touchdown state values were worse than the requirement had sink rates less than 3.5 m/s. (The sink rate of two cases is more than 5 m/s, and so only nine cases appear in Fig. 6b.) In these cases, the vehicle would not be damaged significantly on landing, so the remaining four cases are the critical ones. These critical cases represent much less than 1.0% of all cases.

Although the other parameters are not as critical as the sink rate, their 3σ values are not necessarily sufficiently small. For example,

Table 4 Monte Carlo result of 1000 runs

Touchdown state	Mean	3σ	Requirement exceeding case
X, m	359	220	$2(X < \text{mean} - 225)$
$\dot{Z}$, m/s	1.2	1.9	$11(\dot{Z} > 3.0)$
V_{EAS}, m/s	49.2	9.0	0
V_{grd}, m/s	48.6	10.8	$2(V_{grd} > 62.0)$
Y, m	−0.7	13.3	0
Ψ, deg	0.1	7.9	$2(\lvert\Psi\rvert > 8.0)$
Φ, deg	0.3	4.8	0

3σ of touchdown V_{EAS} is 9.0 m/s, and the mean value is 49.2 m/s, giving a 3σ dispersion range from 40.2 to 58.2 m/s, which exceeds the minimum requirement of 42 m/s. The minimum V_{EAS} over 1000 runs was 43.4 m/s. The distribution of touchdown V_{EAS} was not exactly Gaussian, and so a 3σ probability of Gaussian distribution does not always give the correct probability of the actual distribution.

Comparison with the RSS Result

To compare the results of Monte Carlo simulation and the rss analysis, the 3σ value should be used because the rss value corresponds to the 3σ deviation of the touchdown state. The 3σ rss dispersions are from nominal, whereas 3σ Monte Carlo dispersions are from mean. Fundamentally, 3σ dispersions should be from mean. In the rss analysis, nominal is considered to be equal to mean.

The 3σ deviation of touchdown X position shown in Fig. 6a is 220 m, and this value is much smaller than the rss result of 269 m. Furthermore, the mean value, 359 m, differs from the nominal value of 303 m. This shows the influence of nonlinearity between model error and touchdown X position. The Monte Carlo simulation shows that the touchdown X position tends to be farther down the runway than the nominal point. On the other hand, the 3σ deviation of the touchdown Y position is 13.3 m, and this is larger than the rss result of 8.6 m.

Figure 6b shows the sink rate and equivalent airspeed. These variables are important for the vehicle's longitudinal motion. The 3σ deviation of the sink rate is 1.9 m/s, which is smaller than the rss result of 2.5 m/s. However, the mean value of 1.2 m/s is larger than the nominal value of 0.5 m/s because of the nonlinear influence of model errors. On the other hand, the 3σ deviation of the touchdown equivalent airspeed is 9.0 m/s. This value also differs from the rss result of 11.8 m/s.

Figure 6c shows the touchdown parameters related to the vehicle's lateral motion, Φ and Ψ. The 3σ deviations of both parameters are quite small in the rss result, but the Monte Carlo simulation shows that the deviation of touchdown Ψ is not necessarily sufficiently small. In addition, the Monte Carlo result shows that Φ and Ψ are correlated strongly with each other.

These results show that the rss method does not necessarily give a correct 3σ dispersion range of the touchdown parameter. In spite of this drawback, the rss method is still useful for finding influential model errors as shown in Fig. 5, which is difficult to do using Monte Carlo simulation.

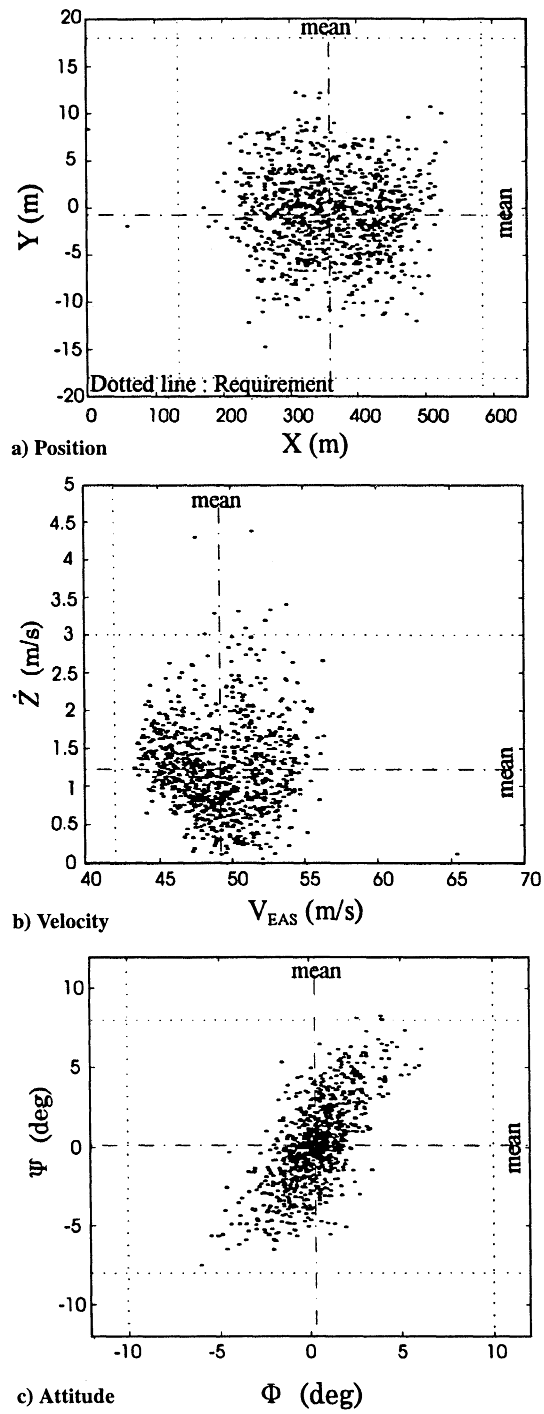

Fig. 6 Monte Carlo result (touchdown states).

Further Discussion

The Monte Carlo result showed that lateral motion had sufficient margin against the influence of model errors. On the other hand, longitudinal motion was significantly affected by model errors. In longitudinal guidance, the vehicle is controlled to track a predetermined reference path. Open-loop control is predominant, particularly in the preflare flight phase. Although closed-loop command exists, this open-loop command makes the longitudinal motion sensitive to model errors. Lateral guidance is implemented only by closed-loop control, which works to decrease the deviation from the reference; lateral motion has more robustness against model errors.

Other Simulation Analysis

The influence of model errors can be analyzed by Monte Carlo simulation. However, the Monte Carlo simulation is not a panacea. For example, actual model errors are not as simple as bias error or scale factor error, and it is difficult to model real wind conditions. Thus, some model errors are more complicated than those considered in the simulation. Furthermore, the planning of flight-test cases often changes during the flight-test term depending on the results of earlier tests, and in these test cases, flight safety and landing performance must also be ensured. Therefore, to ensure successful landings, the following simulation analyses were performed on site at Woomera Airfield:

1) The effects of release position and magnitude of control surface excitation commands were investigated to confirm flight safety and landing performance in each planned test case.

2) Real wind data, which were measured 1.5 h before each automatic landing test, were incorporated into the simulation analysis. The simulated result was used as one of considerations for the test go/no-go decision.

3) Error models that incorporated the results of hanging flight tests or other system tests were developed, and their effects were

investigated by simulation. Specifically, aerodynamic model error and measurement errors of RA, MLS, and air data system (ADS) were considered.

Flight Test

Touchdown Performance

Figures 7a–7c show the touchdown parameters of all 13 automatic landing flight trials. The graphs correspond to the Monte Carlo results of Fig. 6. The Monte Carlo derived mean values and the requirement values are also shown in Fig. 7 to allow comparison of the flight-test results with the simulation results.

Figure 7 shows that all flight data were within the requirement range. In particular, the touchdown X positions of both the simulation result and flight-test data are farther down the runway than the nominal value. The flight-test result agrees with the simulated result, both results showing that model errors tend to make the touchdown point farther down the runway. The flight-test data show that simulation analysis is an effective and useful tool for the preflight evaluation of landing performance.

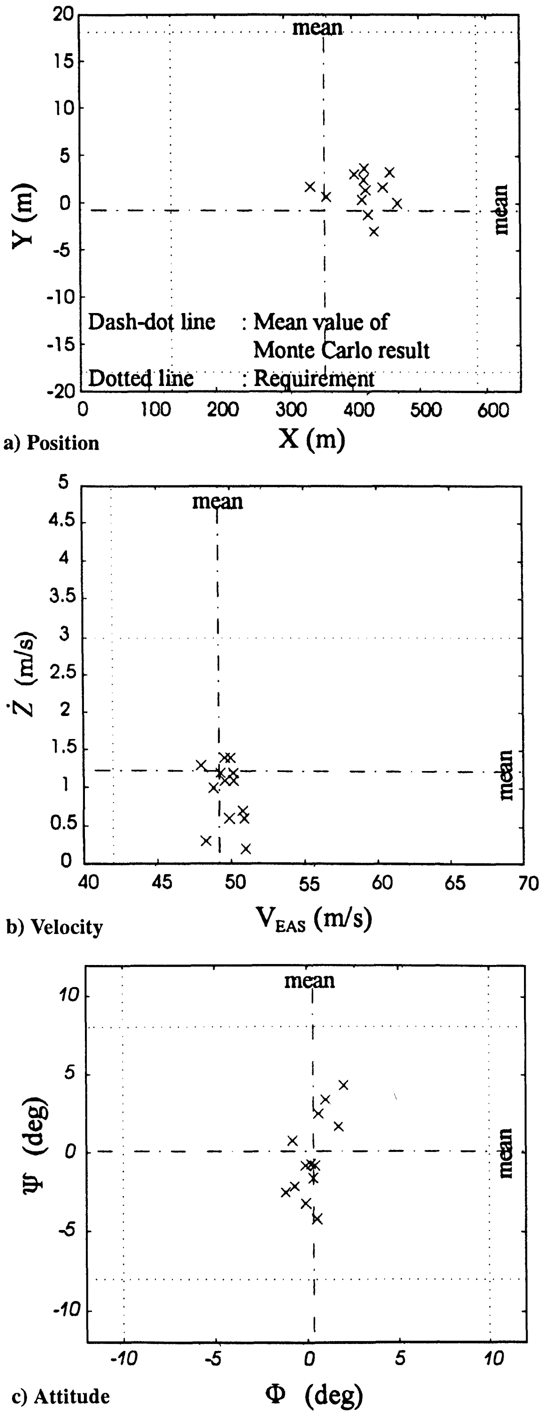

Fig. 7 Flight-test data (touchdown states); comparison with Monte Carlo result.

Longitudinal Guidance

Figure 8 shows the vehicle trajectory of all 13 flight tests. It appears that the vehicle had a tendency to float prior to touchdown in all 13 cases. As a result, touchdown points were farther down the runway than the simulated nominal case indicated.

At first, ground effect was considered to be the cause of this phenomenon, but it was subsequently discovered not to be the cause of the floating for the following reasons:

1) The results of wind-tunnel testing indicate that ground effect is influential when the vehicle is at a height of less than one-span length above the ground, about 3 m. However, the floating occurred at a height of greater than one-span length.

2) The actual ground effect was estimated from the flight-test data,[11] and the discrepancy between the wind-tunnel-test and flight-test estimates was found to be quite small, the wind-tunnel-test model was found to give almost the same results as the actual observed characteristics. The simulation model, of course, included the ground effect, estimated from wind-tunnel results.

From the result of the rss analysis, the influential model errors in the touchdown X position were found to be V_{EAS} measurement bias, RA scale factor, navigational error of downrange velocity, and so on. Among these model errors, the V_{EAS} measurement bias error is considered to be the likely cause of the floating because it is measured by an ADS. From aerodynamic considerations, the ADS output tends to include position error and so the measured V_{EAS} is likely to have a bias error. The magnitude of bias error was estimated to be approximately -1.5 m/s. Figure 9 shows the simulated result, which includes the influence of V_{EAS} measurement bias error, and this simulation result shows the same tendency as the flight-test result. Thus, V_{EAS} is considered to be the most likely model error on the actual touchdown X position. Other than V_{EAS} measurement error, navigational error of downrange measurements (velocity and position) is considered to be influential on touchdown X position.

The longitudinal control system of the preflare phase is shown in Fig. 10. The guidance law causes the vehicle to track the reference trajectory. This law consists of a conventional proportional plus

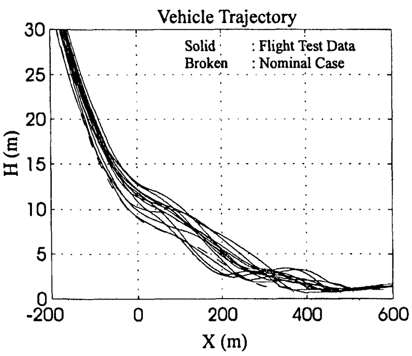

Fig. 8 Flight-test data for all 13 flights.

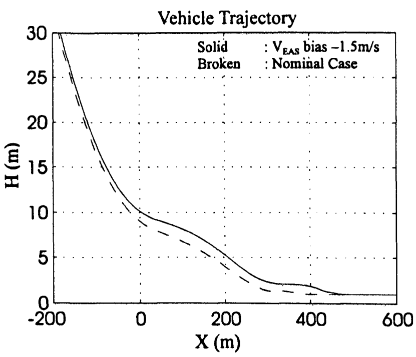

Fig. 9 Influence of V_{EAS} bias error.

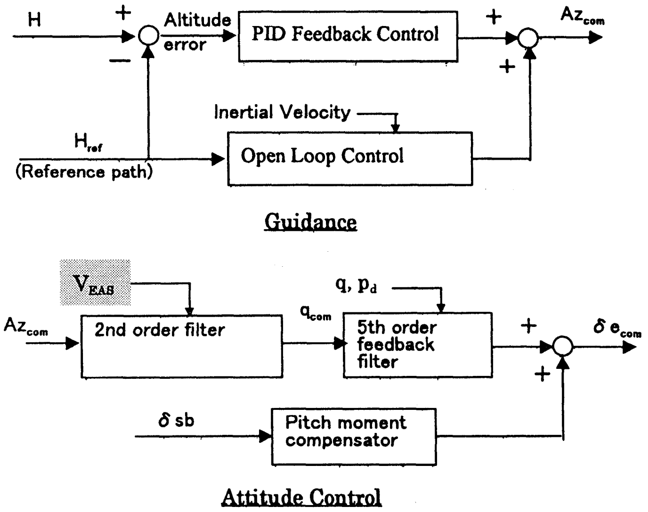

Fig. 10 Longitudinal guidance in preflare phase.

integral plus derivative (PID) control law, and the output is a normal acceleration command Az_{com}. However, the input to the attitude controller is a pitch rate command q_{com}, so a second-order filter is used to convert Az_{com} into q_{com}. This second-order filter requires an equivalent air speed input, which is used to divide the acceleration for the conversion. If the equivalent airspeed is lower than the true value, the pitch rate command becomes larger than the appropriate value, and as a result, an excessive pitchup command is generated. For this reason, bias error of equivalent air speed influences the path error.

Conclusion

Landing performance was investigated prior to the first landing flight test by simulation analyses using the rss method and Monte Carlo simulation. Flight-test data showed that simulation analysis is effective and useful for preflight performance evaluation. Furthermore, some lessons were learned from the flight tests and these lessons will be incorporated into the HOPE experiment (HOPE-X) project, which is now underway. The major points are as follows:

1) The rss method was used to determine influential model errors.

2) Monte Carlo simulation gave the distribution of landing performance statistically.

3) The results of the Monte Carlo simulation and the rss method were compared, and the differences were quantified.

4) The flight-test data agreed with the preflight simulation analysis; simulation analysis were, thus, found to be effective for preflight evaluation.

5) As a result of flight-tests, touchdown points were farther down the runway than the nominal position. This phenomenon is within the prediction of simulation analysis. The causes were investigated and the conclusion was made that the most likely model error was a bias error in V_{EAS}.

From the simulation analysis, the rss method is useful for identifying influential error parameters, whereas Monte Carlo simulation can statistically predict the total landing performance accurately and is appropriate for analyzing the combination effect of model errors and the nonlinearity between model error and landing performance. The application of these simulation techniques proved effective in evaluating landing performance prior to the first automatic landing test.

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