Development test of the GNC system for Small Re-entry Capsule Integrated into HTV

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Key Words: Guidance and Navigation, Reentry Capsule, Flight Software, Monte Carlo Simulation,

The Small Re-entry Capsule Integrated into HTV (HSRC) is an experimental spacecraft using real-time prediction guidance based on numerical integration and will be launched as part of HTV7 mission. The paper reports overviews development test of the GN&C system and preflight analysis by Monte Carlo Simulation.

HTV 搭載小型回収カプセル誘導制御系の開発試験

HTV 搭載小型回収カプセルは、地球大気圏内における揚力誘導の実証をミッションとした実証機であり、国際宇宙ステーション（ISS）から 4 日間でのサンプル回収を目指し、宇宙ステーション補給機（HTV）7 号機に搭載される．本カプセルのミッションの 1 つは、実時間予測積分によるダウンレンジ方向の誘導制御の実証である。誘導制御系は計算機、IMU、GPSR で構成され、これまで SW,HW を組み合わせた試験を実施してきた。本論文ではこれら開発試験及び誘導誤差解析の結果について報告する。

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I. Introduction

The Small Re-entry Capsule Integrated into HTV (HSRC) is an experimental reentry capsule having active guidance and control system and will be launched as part of HTV7 mission. Past Japanese capsule such as OREX (Orbital Re-entry EXperiment)[1], USERS capsule[2], and HAYABUSA reentry capsule[3] are ballistic reentry capsules. As a result, splashdown area is large and maximum aerodynamic acceleration is high. For reduction of maximum aerodynamic acceleration and improvement of guidance accuracy, HSRC controls range using real-time prediction guidance based on numerical integration. The paper reports overviews verification activity of the GN&C system and preflight analysis by Monte Carlo Simulation.

II. GN&C system and Mission Profile of HSRC

The GN&C system of HSRC is comprised of one Inertial Measurement Unit (IMU), one Global Positioning System (GPS) receiver, one GPS antenna and one flight computer installed GNC Flight Software. The GNC Flight Software is consists of control system module and navigation guidance module. The control torques are generated by 8 cold gas thrusters (4 rolls, 2 pitches, 2 yaws).

Figure 2.1 shows HSRC Mission Profile which consists of two phases (an on-orbit phase and a reentry phase). In an on-orbit phase, the HSRC change its attitude to direct the GPS antenna to the zenith direction. After initial acquisition the HSRC calculates target point. At an altitude of about 130 km altitude, before dynamic pressure increases, the HSRC change attitude for re-entry. In a reentry phase, the GNC Flight Software starts to calculate the attitude command using real time predictive integration for pin point landing. The guidance stops at an altitude 30 km. To meets the parachute development conditions, the HSRC drops altitude. Then the HSRC is recovered by ship, after splashdown into the Pacific Ocean.

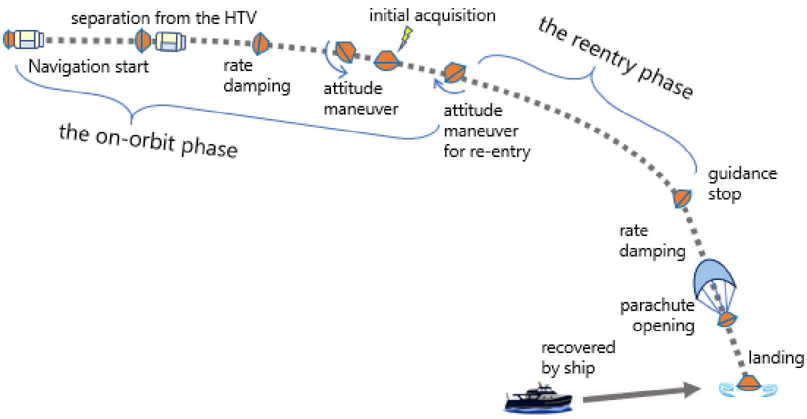


Figure 2.1 HSRC Mission Profile

III. Guidance algorism

A. Guidance algorism

The HSRC guidance algorithm will command multiple firings of the thrusters to control the capsule's lift vector direction. The GNC Flight Software outputs aerodynamic angle command. The angle of attack command outputs the trim angle as per nominal ground speed scheduling, and the sideslip angle command outputs 0deg. Range, down-range and cross-range, to the target point is control by bank angle. In the paper, down-range means the in-plane range from the capsule to the target, and cross-range means the out-of-plane range from the capsule to the target. The commanded bank angle is calculated by guidance algorithm using real-time prediction guidance using numerical integration. The guidance algorithm is in form explicit guidance law and control range with a small lift-to- drag ratio (L/D) of about 0.2~0.3. The merit of the guidance algorithm is that it is possible to decrease range error to the target point even when there is a high uncertainty. The bank angle command is shown in Eq. 1. The guidance calculation is performed at 1 Hz. The error of the cross range is corrected by bank reverse. The guidance command bank reverse when the cross-range cross a dead band threshold as per ground speed scheduling

$$\cos(\phi_{BC}) = \cos(\phi_{BC0}) + \frac{\left(\cos(\phi_{BC0} + \Delta\phi) - \cos(\phi_{BC0})\right)}{R_1 - R_0}(R_0 - R_{NV}) \qquad (1)$$

ϕ_{BC} : Bank angle command of present guidance cycle

ϕ_{BC0} : Bank angle command of previous guidance cycle

$\Delta\phi$: Increment of bank angle for calculation for range sensitivity

R_{NV} : Range to target from present position

R_0 : Predicted range to target from present position when the capsule flies at a present bank command (ϕ_{BC0})

R_1 : Predicted range to target from present position when the capsule flies at a previous bank command ($\phi_{BC0} + \Delta\phi$)

Navigation law[4)] is based on IMU inertial navigation. To improve navigation accuracy, we applied IMU-GPS integrated navigation in the on-orbit phase and IMU-DM navigation in the reentry phase.

B. Nominal Reference Trajectory

The nominal reference trajectory is shown in Fig. 2.2. The performance of the reference trajectory is shown in Table 4.1. The guidance error of cross range is remained, because cross range is guided by a dead band. However, the error is sufficiently small. The result satisfies the requirements for the GN&C system shown in Table 4.2.

Table 4.1 performance of the reference trajectory

Evaluation parameter	Performance
guidance error from the target point	3.63 km
maximum aerodynamic acceleration	3.45 G
fuel consumption	211.69 Ns (Onboard fuel 1050.0 Ns)

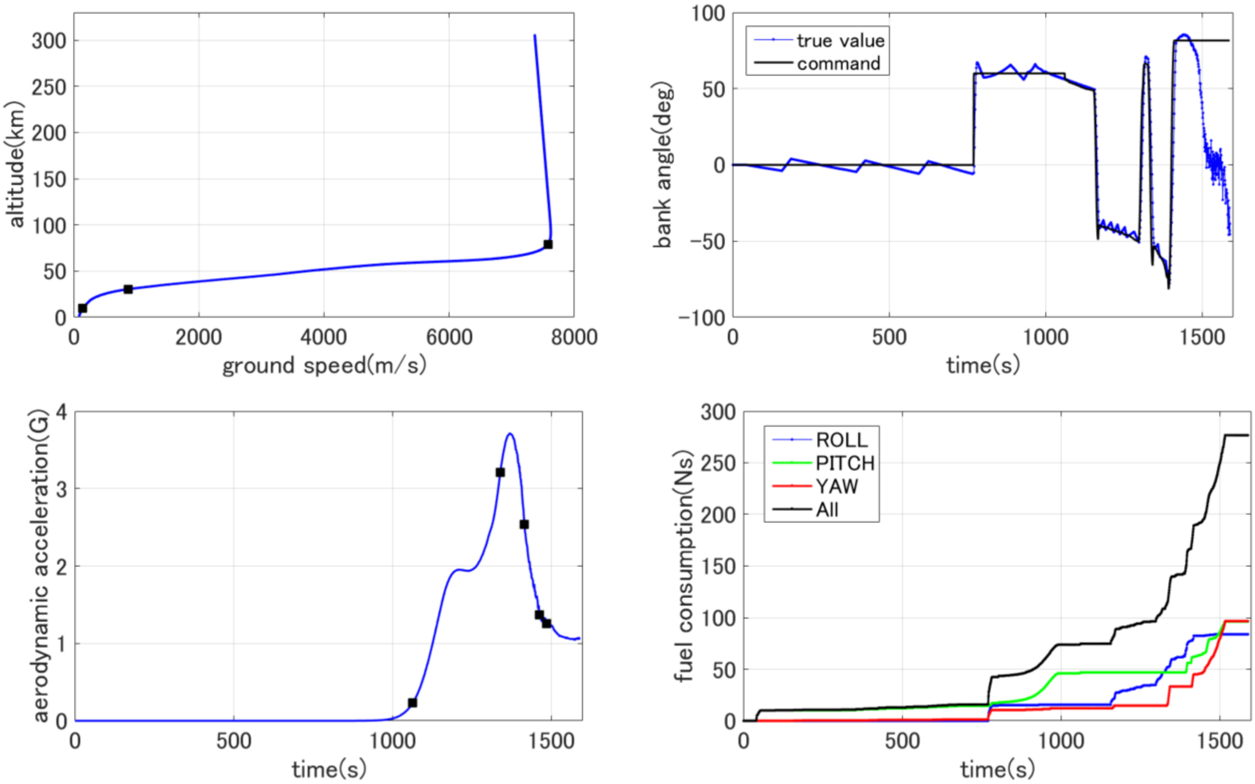


Figure 2.2 Reference trajectory of the HSRC

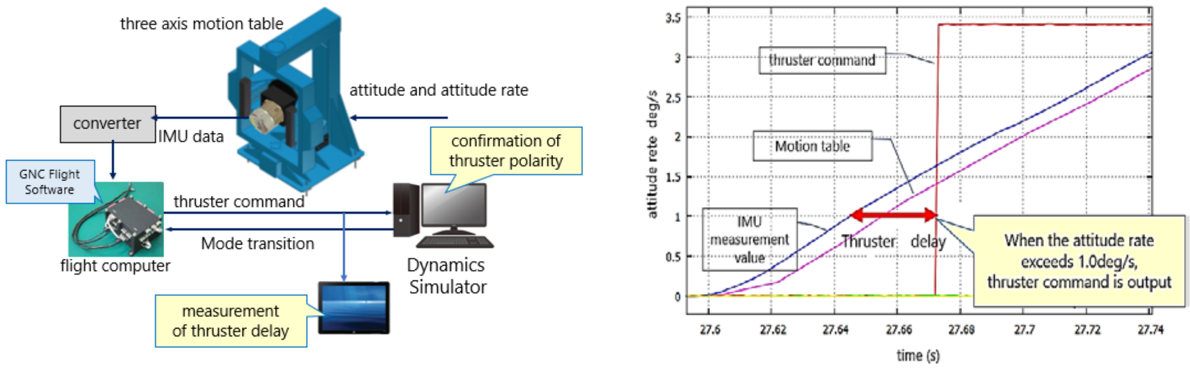
IV. Development test of the GN&C system

A. Verification activity of the GN&C system

To improve reliability of GN&C system, we conducted the following three tests using H/W.

(1) Confirmation test of thruster polarity and delay

The purpose of the test is to confirm thruster polarity and to measure thruster delay. Figure 4.1 shows test configuration and result. While an three axis motion table installed the IMU is controlled to rotate at a constant rate, thruster command by the flight computer is verified. As a result, the flight computer commands to the correct thruster within the acceptable delay.

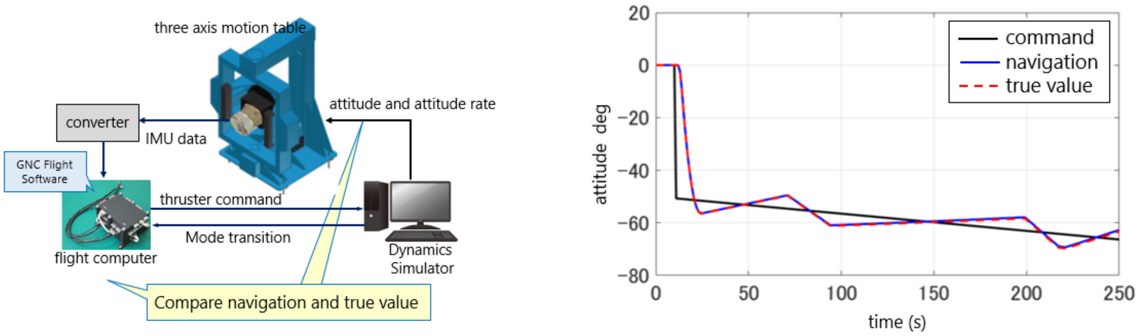


(a) test configuration (b) measurement result

Figure 4.1 test configuration and result for the confirmation test of thruster polarity and delay

(2) Dynamic Closed Loop Testing (DCLT) using IMU

The purpose of DCLT is to validate the GN&C system performance and function with the flight computer and IMU. Figure 4.2 shows test configuration and result. We conduct closed loop test simulating attitude maneuver and confirm that GN&C system works properly under dynamic motion.

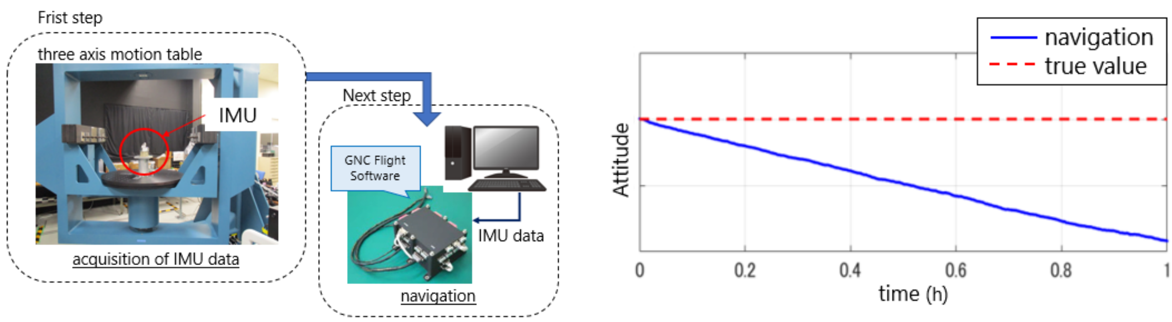


(a) test configuration (b) result

Figure 4.2 test configuration and result for the DCLT

(3) Navigation test using IMU actual data

The initial bias of IMU is a factor in increasing the navigation errors, because the HSRC can't calibrate initial bias of IMU. The purpose of navigation test is to assess the initial bias of actual value. Figure 4.3(a) shows test configuration. At first step we acquire IMU data when IMU is still on the earth. At the next step GNC flight software calculates IMU's attitude using the real IMU data. The navigation error increases as shown in Fig. 4.3(b). We confirm that the initial bias is within specification by those tests.



(a) test configuration (b) result

Figure 4.3 test configuration and result for the navigation test

B. Monte Carlo Simulation (MCS)

B.1 Success criteria of GN&C system

There are three requirements to the GN&C system. The first one is pin point landing. The second is reduction of maximum aerodynamic acceleration during flight. The last is stable flight in a reentry phase.

Those performance of the GN&C system is evaluated by MCS. In the actual flight of the HSRC, it is assumed that there are causes of large navigation error such as an initial attitude error and IMU gyro bias, which cannot be eliminated on-orbit. Because of the expected navigation error, the splashdown area is predicted to be large. Therefore, as for the evaluation of the pin-point landing, we evaluate the guidance accuracy by the MCS without error sources which could be eliminated if the HSRC had an absolute attitude sensor such as a star-tracker. For the above reasons, we perform two case simulation as pre-flight analysis by MCS. Each success criteria are shown in Table4.2. When all criteria shown in Table4.2 are satisfied, GN&C system achieve the requirements.

Table 4.2 Evaluation parameter and Requirement

(a) before calibration of navigation

Evaluation parameter	
angle of attack (*1)	$-10.0 \leq \alpha \leq 40.0deg$
sideslip angle (*1)	$\lvert\phi\rvert \leq 10.0deg$
guidance accuracy	—
maximum aerodynamic acceleration	$\lvert G\rvert \leq 6.2G$
height of opening parachute	$h \geq 2.0km$

Requirement	
Failure rate (*2)	less than 1.00%

(b) after calibration of navigation

Evaluation parameter	
angle of attack (*1)	$-10.0 \leq \alpha \leq 40.0deg$
sideslip angle (*1)	$\lvert\phi\rvert \leq 10.0deg$
guidance accuracy	$\lvert r\rvert \leq 10.0km$
maximum aerodynamic acceleration	$\lvert G\rvert \leq 4.0G$
height of opening parachute	$h \geq 2.0km$

Requirement	
Failure rate (*2)	less than 4.55%

(*1) in a reentry phase (*2) Statistically significant 0.05

B.2 Simulation Condition and Restriction

The model of HSRC is shown in Fig. 4.4 and Table 4.3. The main error models used for MCS are shown Table 4.4. The simulation range is from start inertial navigation to altitude 2km. In the simulation GPS black out occurs from an altitude of 95km or less.

Table 4.3 Vehicle model

Model Parameter	value
Mass	197.8 kg
Reference length (capsule diameter)	0.84 m
Reference Cross Section	0.5542 m^2
Curvature Radius of Nose	1.0 m

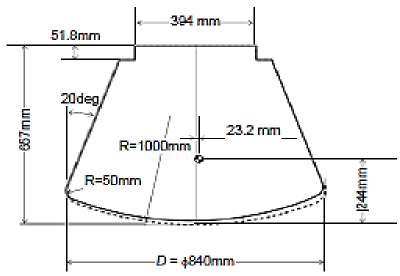


Figure 4.4 Vehicle Shape

Table 4.4 Main Error Factors using MCS

Error Factors		Error (3σ)
Vehicle Error	Weight	11.0kg
	Position of the center of gravity	5.0mm
	Moment of inertia	20.0%
Initial navigation error	attitude	2.0deg (*1) 0.02deg (*2)

Error Factors		Error (3σ)
Thruster	Thrust	0.15N
	delay	6.0msec
Air Density Error	Set the following error in the standard atmospheric model Altitude 10-30km :10.0% 60-80km :50.0% 100-120km:70.0%	

(*1) before calibration of navigation (*2) after calibration of navigation

B.3 MSC (pre-flight analysis)

The simulation result of MCS is shown Table 4.5 and Fig. 4.5. Because failure rate is less than the value shown in Table 4.2. we conclude that those result meet the requirements for the GN&C system.

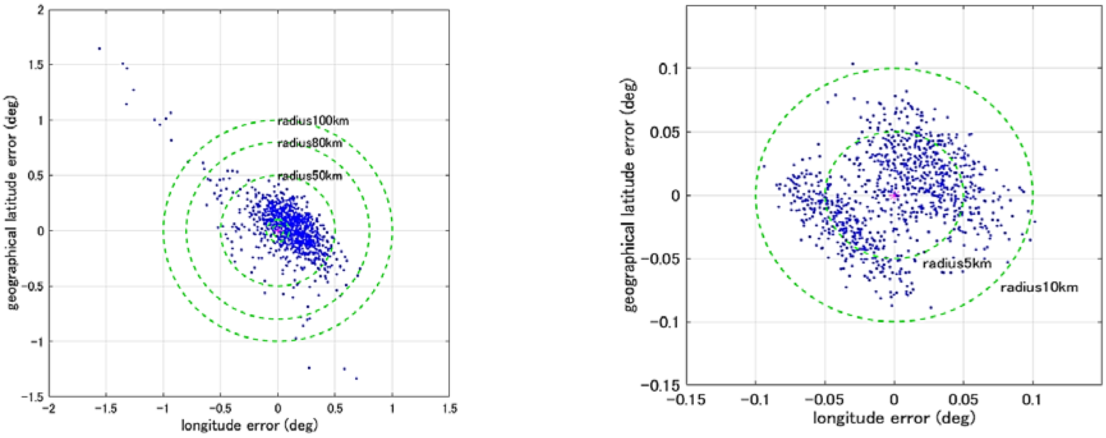
Table 4.5 Summary of MSC results

(a) before calibration of navigation

Evaluation parameter	result
Failure rate	0.676 %
Maximum aerodynamic acceleration	average : 3.64 G max : 4.83 G
guidance accuracy	average : 27.04 km max : 90.20 km

(b) after calibration of navigation

Evaluation parameter	result
Failure rate	1.090 %
Maximum aerodynamic acceleration	average : 3.45 G max : 3.73 G
guidance accuracy	average : 4.65 km max : 8.39 km



(a) before calibration of navigation (b) after calibration of navigation

Figure 4.5 Guidance accuracy at altitude of guidance end

V. Conclusion

The paper overviews the GN&C system of HSRC and the development test. The HSRC controls down range with a small lift-to-drag ratio (L/D) of about 0.2~0.3 using real-time prediction guidance based on numerical integration for reduction of maximum aerodynamic acceleration and improvement guidance accuracy. We confirmed the GN&C system performance and function with the flight computer and IMU. Tn addition the GN&C system meet requirements by Monte Carlo Simulation.

VI. Reference

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