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Guidance and Navigation of Hayabusa Spacecraft for Asteroid Exploration and Sample Return Mission

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Abstract: The Japanese asteroid exploration spacecraft Hayabusa autonomously performed touchdown two times in November 2005. The autonomous guidance and navigation capability is installed aboard the spacecraft. The GNC system collects the laser altimeter, laser range finders and navigation cameras information aboard and is designed to estimate where the spacecraft is and to decide the path correction maneuvers. The programmed function includes the image processing designed to detect an artificial target marker location to approach and cancel the relative velocity. A terrain alignment maneuver is also accomplished by both altitude and attitude control. This paper presents how autonomous guidance and navigation was performed in Hayabusa mission.

Keywords: Hayabusa, Asteroid Exploration, Autonomous Descent, Touchdown, GNC.

1. INTRODUCTION

In-situ observations of small bodies like asteroids are scientifically very important because their sizes are too small to have high internal pressures and temperatures, which means they should hold the early chemistry of the solar system. In recent years, some rendezvous or sample-return missions to small body have received a lot of attention in the world. The Institute of Space and Astronautical Science (ISAS) of Japan launched the MUSES-C[1] spacecraft toward Asteroid 1998SF36 in May 2003. After the launch, the spacecraft was renamed "Hayabusa".

In deep space, ground based operation is very limited due to the communication delay and low bit-rate communication. Therefore, autonomy is required for deep space exploration. On the other hand, because little information on the target asteroid is known, robotics technology[2] is used for the spacecraft to approach, rendezvous with, and land on the asteroid safely. Hayabusa spacecraft introduced a dynamic touch down the surface of the target asteroid and then a method to collect samples automatically by using the novel sampler system.

Hayabusa spacecraft arrived at the target asteroid on 12th September in 2005 and observed the asteroid for about two months. And then two touchdowns were performed in November 2005 as shown in Fig.1. This paper presents the autonomous guidance and navigation scheme used in MUSES-C sample return mission. This paper also describes the flight results on the guidance and navigation for the descent and touchdown.

2. GNC SYSTEM

In the GNC(Guidance, Navigation and Control) system of Hayabusa, TSAS (Two axis Sun Aspect Sensor), STT (STar Tracker) and IRU(Inertial Reference Unit) are combined to determine the spacecraft attitude. ACM (ACceleroMeter) is used to accurately measure the velocity increment gained by RCS (Reaction Control System) firings. RW (Reaction Wheel) and RCS thrusters are used for attitude and position control. Twelve thrusters were installed on the spacecraft and this arrangement allows the control of translational and rotational motion independently.

The spacecraft has two kinds of optical navigation cameras. The narrow angle camera (ONC-T) is used for mapping and multiple scientific observations. The wide angle camera (ONC-W) is used for mapping and regional safety monitoring of surface obstacles. ONC-E (Electronics) works as image processor for the navigation purpose. Measurement of the altitude is performed by LIDAR (LIght radio Detecting And Ranging). LIDAR[3] covers the measurement range from 50[m] to 50[km]. Laser Range Finder (LRF) is used at a lower altitude. LRF has four beams that can measure the range from 7[m] to 100[m]. The four beams provide the height information as well as the attitude information with respect to the surface. In the final descent phase to the asteroid, the spacecraft orbit motion is synchronized with respect to the surface using image data. To cancel the relative horizontal speed, the spacecraft drops a Target Marker that can act as an artif icial navigation target[4].

Fig.1 Hayabusa mission

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The GNC logic is implemented in AOCU (Attitude and Orbit Control Unit), where a high performance microprocessor is equipped. Figure 2 shows the block diagram of GNC functions. The core of onboard navigation system is an extended Kalman filter. The filter outputs the estimated position and velocity relative to the target asteroid ITOKAWA. The state dynamics for the Kalman filter employs orbit dynamics model around ITOKAWA. Simple gravity field model is included in the dynamics. The observations for spacecraft position come from ONC, LIDAR and LRF.

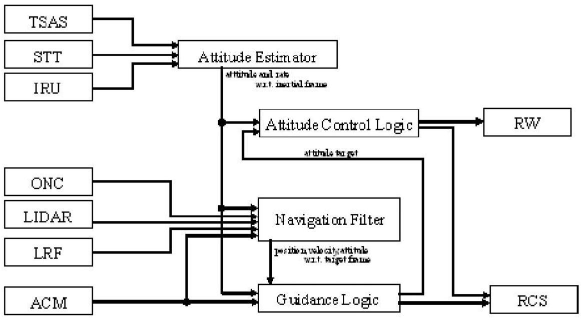

Fig.2 Functional block diagram of GNC

3. DESCENT AND TOUCHDOWN

The GNC scenario of Hayabusa mission[5] is shown in Figure 3. The sampling method of HAYABUSA is so-called touch and go way, that is, the spacecraft shoots a small bullet to the surface just after touch-down has detected, collects ejected fragments with sampler horn, and lifts off before one of solar cell panels might hit the surface[6]. Therefore, the control of the descending velocity and cancellation of the horizontal speed is essential for both the successful sampling and the spacecraft safety. The required conditions from the spacecraft system are that the relative velocity is within +/- 8cm/s in horizontal and 10 cm/s +0/-5 cm/s in vertical. To cancel the horizontal velocity, some kinds of strategies are prepared. The primary method is the usage of an artificial landmark, namely Target Marker (TM), which is released from the spacecraft at the altitude of about 30 m. By tracking TM on the surface, the spacecraft can cancel the horizontal relative speed (TMT mode). Another method is natural terrain tracking which is the backup method of TM tracking and also for the engineering experiment[7]. Even though AWT mode described above can also be used for this purpose, only the correlation of designated areas on the image (FWT mode) is enough to detect horizontal displacement, namely horizontal speed. After TM is successfully captured, the relative navigation logic is initiated to obtain the position with respect to TM. The spacecraft moves to the position right above the TM, and then the attitude of the spacecraft is aligned to the local horizon determined from four beams of Laser Range Finder (LRF-S1) measurements. The spacecraft is guided to the touchdown point and stays there until the relative velocity and attitude is stabilized within required value.

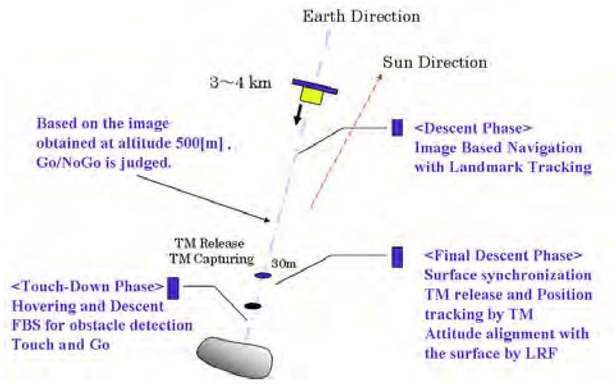

Fig.3 GNC scenario for final descent

4. NAVIGATION AND GUIDANCE

4.1 Navigation

To satisfy the stringent requirement on position and velocity estimation, a navigation filter that utilizes Kalman filter technique[8] is adopted. The outputs of the navigation sensors are used to update the propagated states. The update gain is calculated so that the estimation error is minimized. The linearlized state dynamics and observation equations used in the position filter are as follows.

$$\mathbb{x}_i = \phi\, \mathbb{x}_{i-1} + \varphi\,(d\mathbb{v}_{i-1} + d\mathbb{v}_G),\ \xi_i = \mathbf{G}(\mathbb{x}_{0i})\mathbb{x}_i \quad (1)$$

where,

$$\mathbb{x} = (\mathbb{r}_{SC/\#}^{\,T} \quad d\mathbb{r}_{SC/\#}^{\,T}) \quad (2)$$

$$\phi = \begin{bmatrix} \mathbf{I}_{3X3} & \Delta T\, \mathbf{I}_{3X3} \\ \mathbf{0}_{3X3} & \mathbf{I}_{3X3} \end{bmatrix} \qquad \varphi = \begin{bmatrix} (\Delta T/2)\mathbf{I}_{3X3} \\ \mathbf{I}_{3X3} \end{bmatrix} \quad (3)$$

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ΔT :state integration interval
$d\mathbb{v}_{i-1}$:velocity increment measured with ACM
$d\mathbb{v}_G$:estimated gravitational effect

4.2 Guidance

When the spacecraft has approached near the surface, the velocity control law is switched to the simplified form:

$$\Delta v_Z = k_{VC}(v_{CC} - v_Z) \quad (5)$$

v_{CC} :Planned descending velocity

The delta V for lateral control is executed at the interval of dT_G.

$$\Delta v_X = k_P\ r_X / dT_G + k_D\ v_X \quad (6)$$
$$\Delta v_Y = k_P\ r_Y / dT_G + k_D\ v_Y \quad (7)$$

where k_P and k_D are control gains, and r_X, r_Y, v_X, v_Y are the navigation solution for lateral position and velocity.

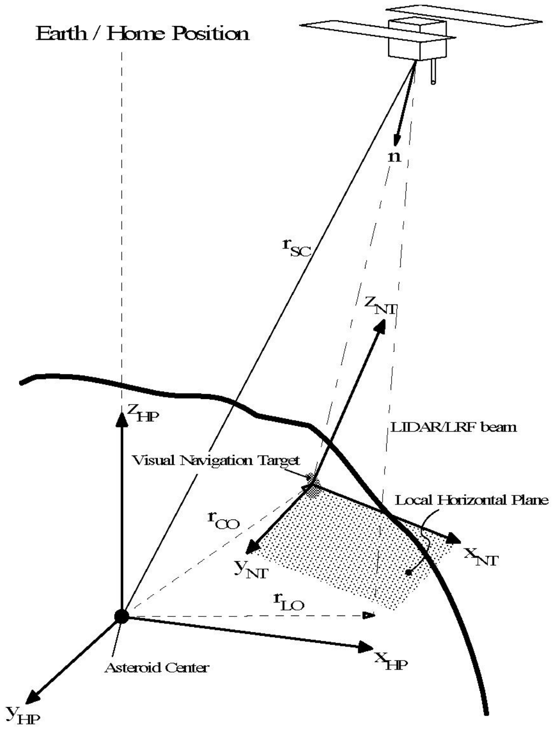

Fig.4 Geometry of reference flames

5. CONTROL SCHEME

In the final descent and touchdown phase, various operations, such as surface synchronization, attitude alignment with respect to the local horizon, and stable hovering is required. Six degree-of-freedom variables, three for position and three for attitude, are independently controlled by the thruster control law that utilizes the thruster switching curves defined on the phase plane. The outline of the switching curve is shown in Fig.5. In the fine control region, attitude is controlled by RW. Details of the control law has been presented in the paper[9].

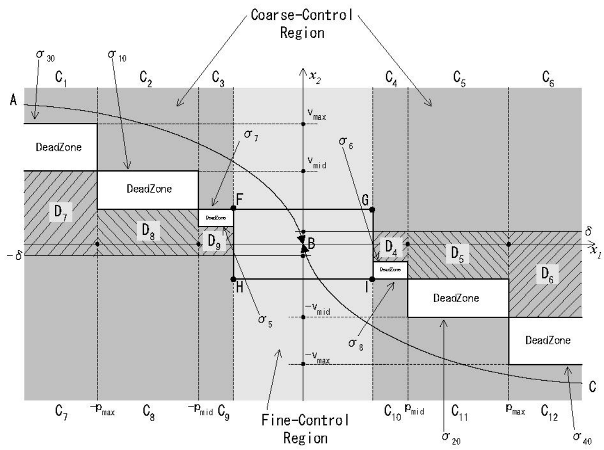

Fig.5 Thruster switching curve

6. FLIGHT RESULTS

6.1 Landing and sampling site

Landing and sampling site was selected at the Joint Science Team meeting held in the end of October 2005, considering the scientific interest and the spacecraft safety. From the results on the global mapping of Itokawa from Home Position, it was found that most of the surface of Itokawa were rocky or steep area, and "Muses-sea" was the only one candidate of landing points are shown in Fig.6.

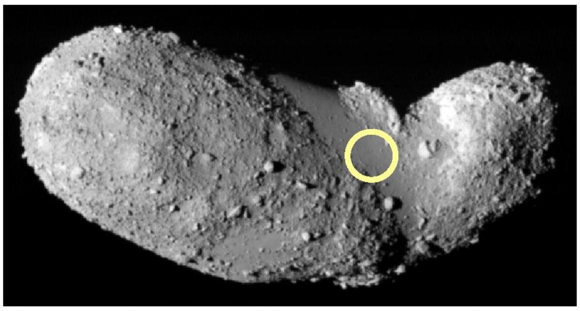

Fig.6 Landing site MUSES-Sea

6.2 1st touchdown

The first landing for sampling was tried on November 20th 2005. The guidance and navigation were all performed in order as planned. The guidance accuracy was within 30 meters in terms of the hovering point. TM with 880,000 names was released at about 40m altitude, and ONC-W1 could track TM properly. Figure 7 shows the low-altitude image, in which the shadow of Hayabusa spacecraft on the surface and the shinning released TM could be seen. The first touching-down was unfortunately terminated by the obstacle detection of FBS, which has fan-shaped detection area beneath the solar cell panels.

After the obstacle had detected, the spacecraft continued descending because the attitude error was so large enough to prevent ascending thruster firing. As a result, the spacecraft did unexpected touch-down without sampling sequence, and stayed on the surface for about 34 minutes until the forced ascent was commanded from the ground.

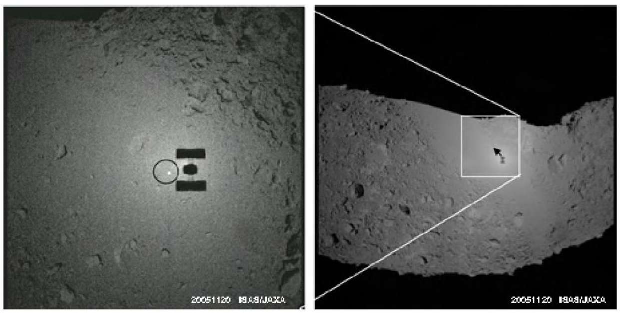

Fig.7 Navigation image

6.3 Flight profile

Figure 8 shows the flight profile in the final descent phase. The topmost graph plots the data from ONC operated in TMT mode. The image of the target marker was successfully acquired with ONC-W1 and the processor in ONC output the direction of the marker in its field of view. During this operation, until the target marker left the field of view of ONC-W1, the marker was kept tracked. Also plotted in this graph are the navigation residuals of ONC observation. The four lines in the second graph show the data from each channel of LRF. Data from LRF-C was initially different from the data of other channels. The data later became almost the same with other channels. This means the spacecraft attitude and position is properly guided so that the attitude aligns the local surface.

Figure 9 shows the sequential image data obtained by ONC-W. The spacecraft Hayabusa started the final vertical descent at (13) in Fig.9.

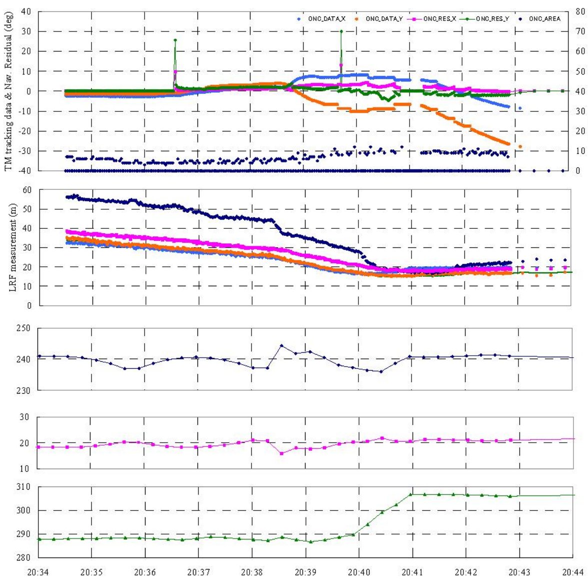

Fig. 8 Flight profile in final descent phase (TD#1)

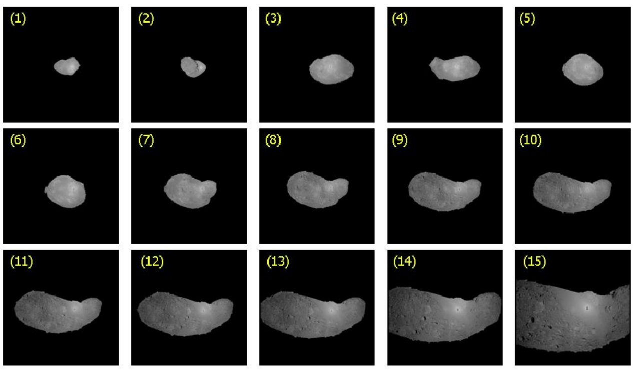

Fig. 9 Image sequence data (TD#1)

5. CONCLUSION

This paper has presented the GNC schemes in the final descent and touchdown phase for Hayabusa spacecraft. Target marker tracking and attitude alignment have been described. And also the navigation and guidance algorithms have been presented. The flight data showed the effectiveness of the proposed and installed schemes.

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