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Touchdown Dynamics for Sample Collection in Hayabusa Mission

Takashi Kubota, Masatsugu Otsuki, Tatsuaki Hashimoto, *Member, IEEE*

Abstract— **Hayabusa spacecraft performed the final descents and touchdowns twice in November 2005. In final descent phase, terrain alignment maneuvers were accomplished to control both altitude and attitude with respect to the surface by using four beams Laser Range Finder onboard. Then Hayabusa spacecraft made dynamic touchdowns the surface of the asteroid by the sampler system to collect samples automatically. This paper presents the terrain alignment maneuver and touchdown scheme. This paper also describes the novel sample horn system and touchdown dynamics. Touchdown tests on the ground are presented. Then the flight results on descent and touchdown dynamics are shown and discussed.**

I. Introduction

IN-SITU observations of small bodies like asteroids or comets 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. NEAR spacecraft[1] was successfully put into the orbit of the asteroid 433 Eros in February 2000. The Institute of Space and Astronautical Science (ISAS) of Japan launched the MUSES-C[2] spacecraft toward Asteroid 1998SF36 Itokawa in May 2003. After the launch, the spacecraft was renamed "Hayabusa". Rosetta[3] spacecraft was successfully launched to explore the comet in 2004.

In deep space missions, 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 in advance, robotics technology is used for the spacecraft to approach, rendezvous with, and land on the asteroid safely. In MUSES-C mission, 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. This paper presents the autonomous guidance and navigation scheme used in MUSES-C sample return mission. This paper also describes the novel sample horn system and touchdown dynamics. Then the touchdown tests on the ground are presented. Finally the flight results on touchdown dynamics are shown and discussed.

T.Kubota, M.Otsuki, and T.Hashimoto are with Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Sagamihara, 2298510 JAPAN (phone: 81-42-759-8305; fax: 81-42-759-8305; e-mail: kubota@ nnl.isas.jaxa.jp).

II. Descent and Touchdown

The GNC scenario of Hayabusa mission is shown in Fig.1. The sampling scheme 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. 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 Another method is natural terrain tracking which is the backup method of TM tracking (TMT) and also for the engineering experiment. Even though AWT(Auto Window Tracking) mode described above can also be used for this purpose, only the correlation of designated areas on the image (FWT: Fixed Window Tracking) 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 surface 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.

After the alignment, the spacecraft starts descending again and touches down the asteroid surface to collect samples. During the touchdown descent, some potential obstacles are checked with Fan Beam Sensors (FBS). If any obstacle is detected, the sequence is terminated and emergency assent is initiated. When the touchdown is detected, the spacecraft collects the sample as soon as possible and then lifts off.

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speed, the spacecraft drops a Target Marker that can act as a navigation target.

The GNC logic is implemented in AOCU (Attitude and Orbit Control Unit), where a high performance microprocessor is equipped. Figure 3 shows the block diagram of GNC functions[5]. The core of onboard navigation system is an extended Kalman filter. The filter outputs the estimated position and velocity relative to ITOKAWA. The state dynamics for the Kalman filter[6] 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.

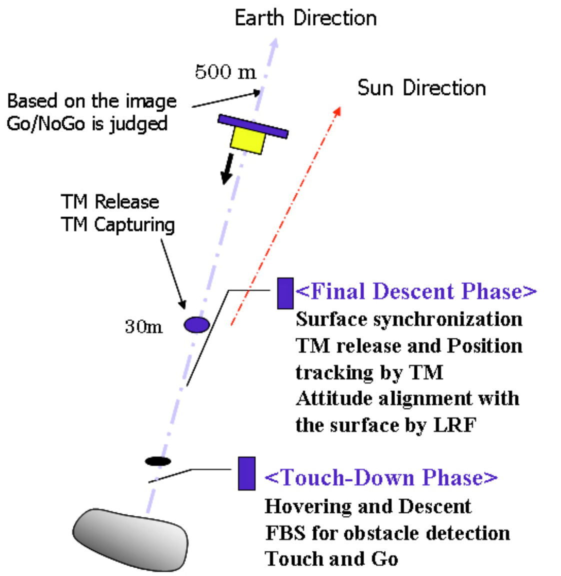


Fig. 1. GNC Scenario for Final Descent and Touchdown

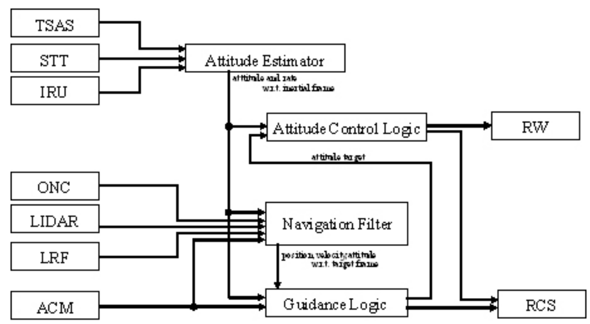


Fig. 2. AOCS and GNC Components

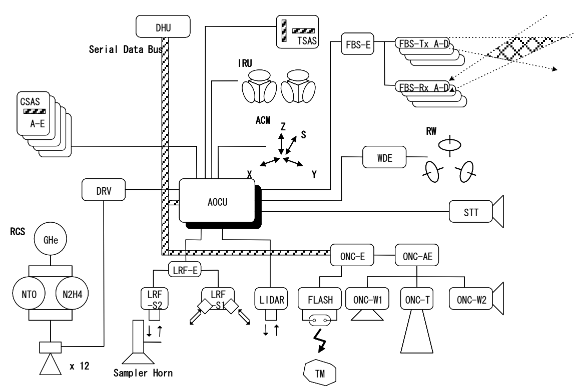


Fig. 3. AOCS and GNC Components

III. GNC System

When the spacecraft was designed, the exact size, the shape, and the surface condition of the target asteroid were unknown. The GNC system was designed so that it could cope with various situations within the severe weight and power restrictions for the spacecraft.

Figure 2 shows the GNC 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 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

IV. Navigation Sensors

A. ONC-W

Hayabusa spacecraft[4] has one telescopic camera ONC-T and two wide FOV cameras: ONC-W1 and W2. ONC-W1 whose FOV aligned to -Z axis of the spacecraft is used for on-board navigation. ONC-W2 has the FOV of -Y direction, which is used for terminator observation phase. The FOV of ONC-W1 is 60deg x 60deg and the resolution is 1000(H) x 1024(V). The overview of ONC-W1 is shown in Fig.4.

B. LIDAR

LIDAR(LIght Detection And Ranging sensor) is a pulse laser radar which measures the travelling time of the pulse between the spacecraft and the asteroid surface. A Photo of the prototype model is shown in Fig.5. Since the magnitude of received signal will change about 10 to the power of six order between 50km and 50m, LIDAR has automatic gain control function of APD. Transmitting pulse can be synchronized with external signal such as AOCS timing. This function is not only for precise range measurement but also synchronization with the exposure of ONC-T, which helps the alignment measurement of both sensors. To minimize the weigh of optics, the reflecting mirror is made of SiC.

C. LRF

LRF(Laser Range Finder) consists of four beams sensors for navigation(LRF-S1), one beam sensor for touchdown detection(LRF-S2), and an electronics circuit. Photos of LRF-S1 and LRF-S2 are shown in Fig.6. LRF detects the range to the surface with the phase deference between AM-modulated transmitting and receiving laser light. LRF-S1 has four beams canted 30deg from vertical direction and AOCU can calculate relative attitude and position to the surface using four beam range information. The target of LRF-S2 is the side surface of the sampler horn and it detects the change of the length of the horn which means that the horn has collided with the surface. LRF has single electronics and S1 and S2 are switched by commands when used.

D. FBS

FBS(Fan Beam Sensors) are sensors for detecting obstacles bigger than 10cm. A pair of a transmitter (FBS-T) and a receiver (FBS-R), shown in Fig.7, forms a three-dimensional detection area. Four pairs of FBS cover almost half of the area beneath the spacecraft's solar cell panels.

Fig. 4. Overview of ONC-W

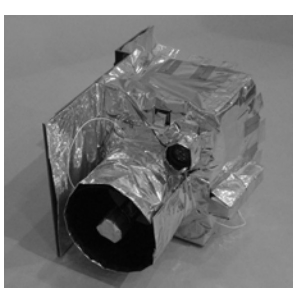


Fig. 5. Overview of LIDAR

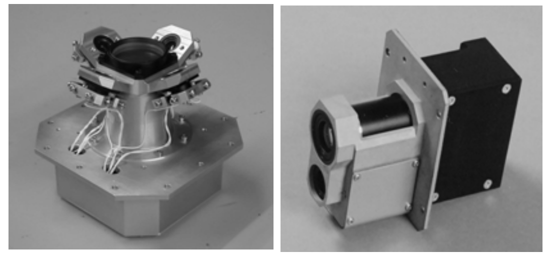


Fig. 6. Overviews of LRF-S1 and LRF-S2

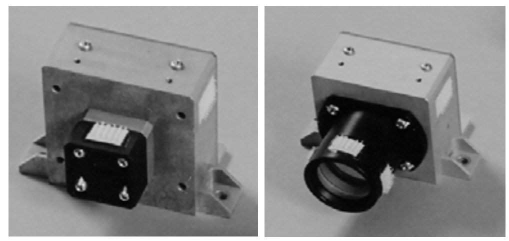


Fig. 7. Overviews of FBS

V. Final Descent and Touchdown

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. 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.

A. Final Descent

Figure 8 shows the final descent and touchdown sequence. To cancel the horizontal velocity, the novel scheme is prepared. The new 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). 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. The Six DOF controller[6] is activated after the navigation filter solution converges.

B. Touchdown

After the alignment, the spacecraft starts descending again and touches down the asteroid surface to collect samples. During the touchdown descent, some potential obstacles are checked with Fan Beam Sensors (FBS). If any obstacle is detected, the touchdown and sampling sequence is terminated and emergency assent is initiated. When the touchdown is detected, the spacecraft collects the sample as soon as possible and then lifts off. Figure 9 shows the sensors used for touchdown detection. Before the touchdown descent, AOCU changes the sensor from LRF-S1 to LRF-S2, which can sense the distance between LRF and the target on the horn and also sense the brightness of the target on the horn. LRF-S2, ACM and IRU are used for touchdown detection.

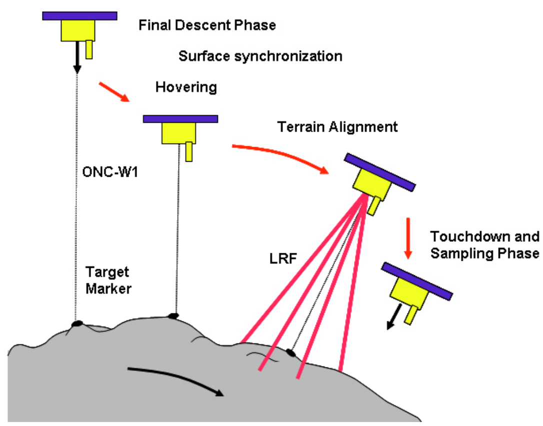


Fig. 8. Final Descent and Touchdown Sequence

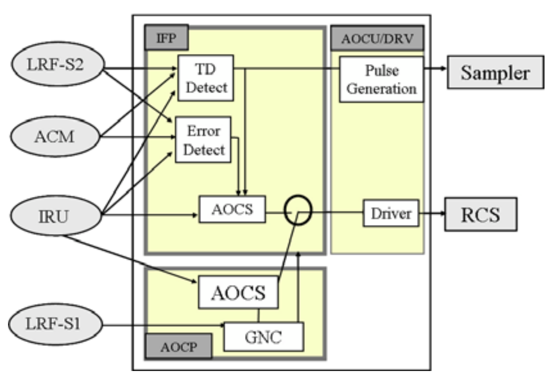


Fig. 9. Touchdown Detection

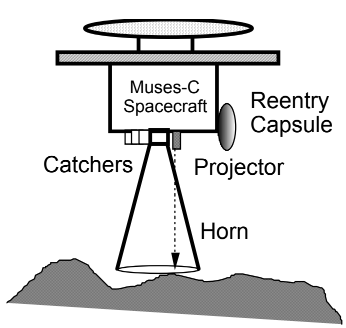


Fig. 10. Sampling System

C. Sample Collection

A sample collection technique is what the Hayabusa spacecraft demonstrates first in the world. Different from the large planets, the asteroid is a very small object whose gravity field is too little for any sampler to dig and drill the surface. Nevertheless, the spacecraft has to cope even with the hard surface such as rocks, while it is requested to function for soft surface like sands as well. Therefore, Hayabusa spacecraft has a novel sample collection system as shown in Fig.10. The proposed method is the combination of the shooting projectile and the fragment catcher. The basic idea is retrieving fragments from the surface ejected by the projectile shot. And a key in the mechanism is the use of the catcher whose inlet surface covers the shot area that is concealed from the main body of the spacecraft, so that the fragments and dusts cannot hit the spacecraft at all. The spacecraft extends a mast whose tip end is equipped with a gun shooting a projectile of 10[g] at the speed of 300[m/sec]. A tiny hole that opens above a flange relieves the high-pressured gas after the shot. It has deceleration device inside that absorbs the fragments /projectile kinetic energy.

VI. Touchdown Dynamics

Hayabusa spacecraft is modeled by a chain of free-floating links in a tree configuration consisting of articulated bodies as shown in Fig.11. Flexible elements such as solar panels and sample horn can be treated as segmented virtual rigid links connected with elastic hinges. When Hayabusa touchdowns the surface, here it is assumed that the contact happens only at the endpoint of the sampler horn. The dynamic motion of Hayabusa spacecraft is described with the presence of the external forces.

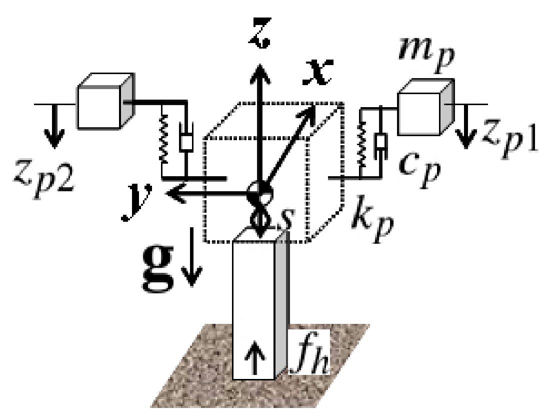


Fig. 11. Hayabusa Spacecraft Model

A. Dynamics Model

Dynamics motion of Hayabusa spacecraft is described as follows.

$$
\begin{aligned}
&M\ddot{x} = f_{t_x} \\
&M\ddot{y} = f_{t_y} \\
&M(\ddot{z} - g) + k_p(z - x_{p1}) + c_p(\dot{z} - \dot{x}_{p1}) + \\
&\qquad k_p(z - x_{p2}) + c_p(\dot{z} - \dot{x}_{p2}) = f_{t_z} + f_h
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
&I_x\ddot{\varphi} = f_{tt_x} \\
&I_y\ddot{\theta} = f_{tt_y} \\
&I_z\ddot{\psi} = f_{tt_z} + s f_h
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
&m_p\left(\ddot{z}_{p1} - g\right) + k_p(z_{p1} - z) + c_p(\dot{z}_{p1} - \dot{z}) = 0 \\
&m_p\left(\ddot{z}_{p2} - g\right) + k_p(z_{p2} - z) + c_p(\dot{z}_{p2} - \dot{z}) = 0
\end{aligned} \tag{3}
$$

where,

M	: mass of the main body
Ix,Iy,Iz	: moment of inertia
x,y,z	: position
φ,θ,ψ	: attitude
ft, ftt	: thruster inputs.

B. Solar Pnael Model

The structural vibration of the solar panels is excited by RCS attitude control, causing the attitude rate fluctuation whose frequency and amplitude are the functions of structural flexibility of the panels and coupling factor between the panels and spacecraft body. The flexibility parameters and coupling factors are estimated before launch using the computer simulation based on the mathematical model of the spacecraft and panels. The on-orbit data is extracted from IRU rate telemetry that is downloaded at a sampling rate of 32 [Hz]. The vibration frequency around x axis almost matches with each other. The vibration about y and z axis, however, do not coincide with simulation model data. The reason for this difference is now under investigation. Unmodeled non-linear behavior of hinges is one of the predicted candidates of the difference cause.

VII. Flight Results

A. Touchdown #1

The first landing for sampling was tried on November 20th in 2005. The guidance and the navigation were all performed in order as planned. Figure 12 shows the flight profile in the final descent phase taken from TD#1 event. 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 (black dotted line) of ONC observations. The residual indicates the difference of estimated marker direction and actual direction. The residuals were kept around zero, indicating that onboard navigation filter worked as designed. 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 align the local surface. The attitude profile, expressed by Z-Y-X euler angles, also indicates that attitude maneuver was properly executed to align the spacecraft to local surface.

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 16 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.

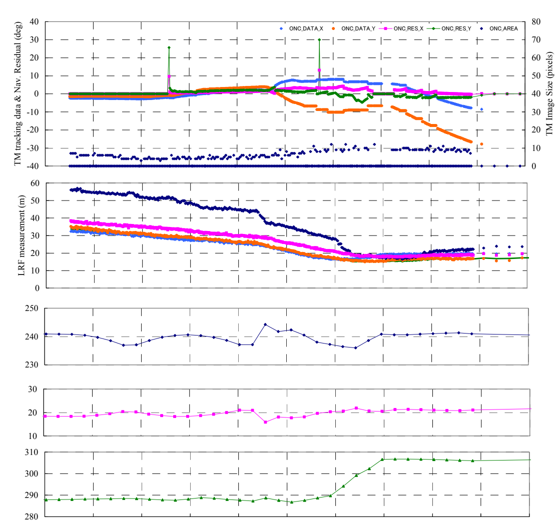


Fig. 12. Flight Profile in Final Descent Phase (TD#1)

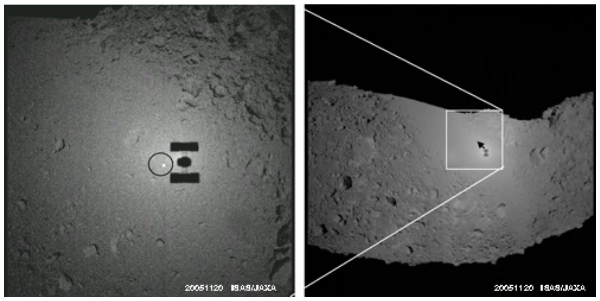


Fig. 13. Navigation Image in Final Descent Phase

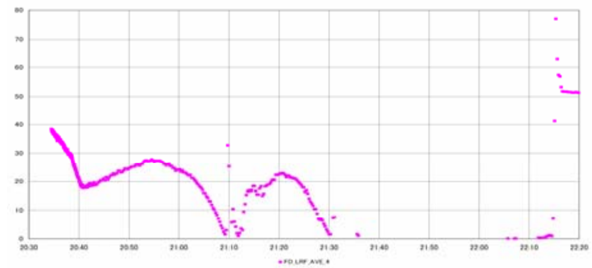


Fig. 14. Altitude data calculated by LRF

B. *Analysis on Touchdown Dynamics*

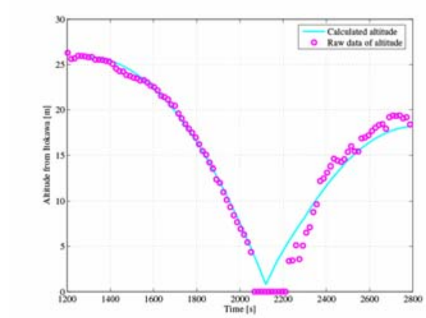
Figure 14 shows the altitude measured by LRF. Based on the altitude data, dynamics motion on sample horn and Hayabusa spacecraft is analyzed in mainly the direction of z-axis. The disturbances such as thruster projection, asteroid gravity, solar pressure are taken into consideration. It is estimated that the solar pressure is $-1.261*10^{-7}$ [m/s2], thruster input is $2.899*10^{-7}$ [m/s2]. As a result, the surface gravity in the direction of x-axis is $7.4*10^{-5}$ [m/s2].

Figure 15 shows the estimated horn behavior. It is estimated that the period during touchdown is 2.35 [s]. Figure 16 shows the behavior of solar panel vibration.

VIII. Conclusion

This paper has presented the AOCS and GNC schemes in the final descent and touchdown phase for Hayabusa spacecraft. Touchdown sequence and sampler horn system have been presented. This paper also has presented touchdown dynamics considering the spacecraft, solar panels, and sampler horn. At the first step, initial analysis has been conducted for the flight data on Touchdown #1. Detailed analysis is under going.

(a) Altitude data



(b) Eestimated force data

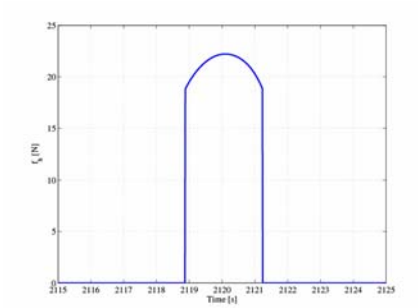


Fig. 15. Behavior of Spacecraft and Sampler Horn

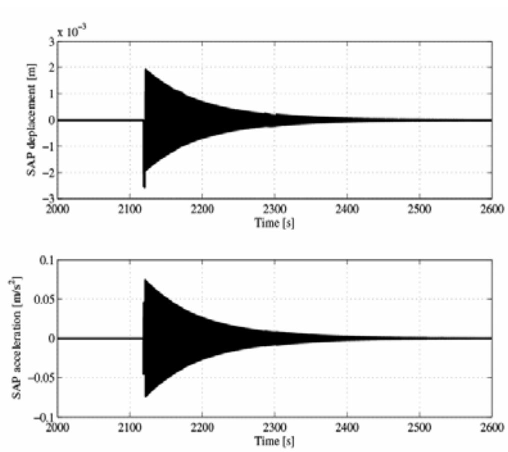


Fig. 16. Behavior of Solar Panel

References

[1] R.Farquhar, NEAR Shoemaker at Eros : Rendezvous, Orbital Operations, and a Soft Landing, Advances in the Astronautical Sciences, Astrodynamics 2001, Vol.109, pp.953-972. 2001.

[2] J.Kawaguchi, K.Uesugi, A.Fujiwara, The MUSES-C Mission for the Sample Return - Its Technology Development Status and Readiness, IAA Int. Conf. on Low-Cost Planetary Missions, No.IAA-L-0306, 2000.

[3] K.Wittmann, B.Feuerbacher, S.Ulamec, H.Rosenbauer, JP.Bibring, D.Moura, et al., Rosetta Lander in situ Characterization of a Comet Nucleus, Acta Astronautica Journal, vol.45, pp.389-395, 1999.

[4] T.Hashimoto, T.Kubota, J.Kawaguchi, M.Uo, K.Baba, T.Yamashita: Autonomous Descent and Touch-down via Optical Sensors: Advances in the Astronautical Sciences, Vol. 108, pp469-480, Univelt Inc., 2001

[5] M.Uo, K.Shirakawa, T.Hashimoto, T.Kubota, J.Kawaguchi, "Hayabusa's Touching-down to Itokawa - Autonomous Guidance and Navigation - , AAS2006, AAS-06-214, 2006.

[6] T.Yamashita, M.Uo, T.Hashimoto, Nonlinear Spacecraft, IFAC Automatic Control in Aerospace, pp.327-332, 2001.