Autonomous Landing System for MUSES-C Sample Return Mission

Takashi Kubota, Shujiro Sawai, Toshihiko Misu,
Tatsuaki Hashimoto, Jun'ichiro Kawaguchi, Akira Fujiwara

The Institute of Space and Astronautical Science,
3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, JAPAN.
TEL: +81-42-759-8304, FAX: +81-42-759-8304
E-Mail: kubota@cnenet.isas.ac.jp

Abstract

This paper describes an autonomous landing system for MUSES-C sample return mission. In deep space, it is difficult to navigate, guide, and control a spacecraft on a real-time basis remotely from the earth mainly due to the communication delay. So autonomous navigation and guidance is required for final approach and landing to an unknown body. It is important to navigate and guide a spacecraft to the landing point without hitting rocks or big stones. In the final descent phase, cancellation of the horizontal speed relative to the surface of the landing site is essential. This paper proposes an autonomous landing method based on optical sensors. The validity of the proposed method is confirmed by graphical simulations. This paper also proposes a sample collector method to collect the surface materials.

1. Introduction

As increasingly many missions are developed to explore the moon or planets, the navigation technology of a spacecraft in deep space is getting more important than ever. In recent years, the probe and sample return of asteroid has received much attention in Japan as well as in Europe and the United States. The Institute of Space and Astronautical Science (ISAS) will launch the engineering test spacecraft, MUSES-C[1] toward a near earth asteroid NEREUS in 2002.

In deep space, it is difficult to navigate, guide, and control a spacecraft on a real-time basis remotely from the earth mainly due to the communication delay. So autonomous navigation and guidance is required for final approach to an unknown body. Many researchers have studied rendezvous methods in interplanetary and approach phases. However, there are few publications on autonomous landing methods in the final approach phase. For landing on an unknown body safely, it is necessary to obtain the terrain information of a planetary surface around a landing point. It is also important to navigate and guide a spacecraft to the landing point without hitting rocks or big stones. In the final descent phase, cancellation of the horizontal speed relative to the surface of the landing site is essential. This paper proposes a method for a spacecraft to land on the asteroid surface autonomously. This paper presents an autonomous landing scheme by integrating several navigation sensors. For the purpose of guiding a spacecraft to the landing point, the MUSES-C spacecraft is supposed to drop a visual target marker that can play a navigation aid as an artificial landmark on the surface. This landmark drastically reduces the computer burdens. This paper also proposes a sampling mechanism to collect the surface materials.

This paper is structured as follows. Section 2 describes the purpose and the mission scenario of MUSES-C mission. In Section 3, the strategy for autonomous approach and landing is proposed. Section 4 describes navigation sensors used in MUSES-C mission. In Section 5, a navigation method using visual sensor is proposed. A method to extract visual feature is explained Section 6 presents a sampling mechanism. Finally, Section 7 is for discussions, conclusions, and future work of the research.

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2. MUSES-C Mission

ISAS will launch the spacecraft, MUSES-C[2] toward the asteroid NEREUS in 2002. This project is aiming at demonstrating four key technologies required for the future sample and return missions from extra-terrestrial bodies. Those technologies are : 1) solar electrical propulsion with ion thrusters in an interplanetary space, as a primary propulsive means, 2) autonomous optical guidance and navigation, 3) automated sampling mechanism, and 4) direct hyperbolic reentry of the recovery capsule to the ground.

The nominal target of the MUSES-C[3] spacecraft is a near earth asteroid NEREUS(4660). The launch is scheduled in January of 2002 and the arrival at Nereus at the beginning of April of 2003. Leaving the asteroid at the end of May of 2003, the spacecraft returns to the Earth in January of 2006. The mission duration from launch to the Earth return is about four years. In this nominal plan, the MUSES-C spacecraft stays for about two months at the asteroid and both mapping and sampling operations have to be carried out during that short period. The project also has a backup target 1989ML(10302) for which the launch and recovery take place half a year later respectively. In the backup plan, the mission period is about six months.

The spacecraft is launched via the ISAS medium class launch vehicle M-V. The mass of the spacecraft is about 500[kg] including chemical and ion engine propellant of 130[kg] The planned solar cell is a tri-junction cell and the solar panel generates approximately 1.8[kW]. During the flight, the distance from the earth is shorter than 2 AU.

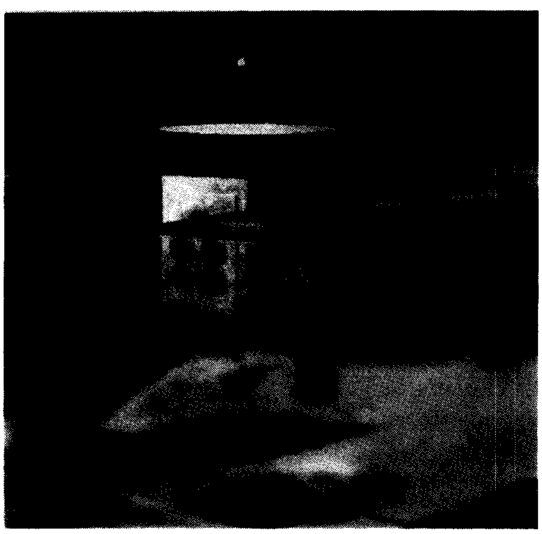

Fig.1 MUSES-C Mission

3. Autonomous Landing System

The MUSES-C spacecraft can rendezvous the asteroid by range and range rate method and conventional optical navigation method[4]. However long communication delay prevents ground based remote control in the proximity region around the asteroid. So autonomous landing system is important for mission success. At a range 20[km] from the asteroid, global mapping of the asteroid is performed to determine the topography of the surface and to search candidates of landing sites of scientific interest. The precise spin axis orientation and rotation rate and phase are also determined. The three-dimensional shape model of the asteroid is constructed for the approach and descent phase. Global mapping[5][6] from the Sun side and terminator side are scheduled in MUSES-C mission. The spacecraft keeps the home position before descent for sampling.

The strategy for autonomous landing consists of the following phases as shown in Fig.4.

1. Descent Phase

Optical navigation is used when the whole of the asteroid can be visible on the image. However difficulty shows up, when the spacecraft approaches close to the surface and the image spreads over the field of view. Feature areas are extracted and tracked on the images. If some of feature areas are unsuitable, new appropriate feature areas extracted automatically.

2. Final Descent Phase[7]

In the event of sampling, cancellation of the relative horizontal sped is essential to the touchdown. For the purpose of securing this high-lighted event, the spacecraft is supposed to drop a visual target marker that can act as a navigation aid. The position of a spacecraft with respect to the target marker is estimated by processing both flash-on and flash-off image data. The spacecraft is navigated and guided to the landing point based on landmark image. Introducing artificial landmarks drastically reduces the computer burdens.

3. Touch Down Phase[8]

As the spacecraft descends, there are some possibilities to collide with the surface. So it is needed to keep the attitude of the spacecraft parallel to the touch-down surface, while hovering at some altitude. Final Go or NO-Go decision for sampling is made at that time. Then the spacecraft starts the free-fall and touch down the asteroid surface to collect samples. During the free-fall of the spacecraft, some potential obstacles are checked.

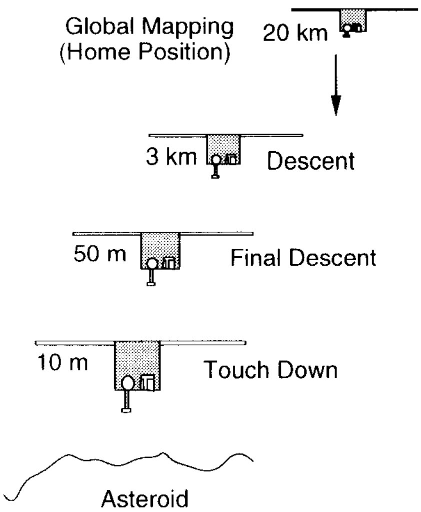

Fig.2 Autonomous Landing Strategy

4. Navigation Sensors

Rendezvous and touch down for the asteroid, whose size, shape, surface condition are unknown, requires intelligent and advanced navigation, guidance and control. A method is proposed to combine several navigation sensors, which makes it possible for a spacecraft to approach and touch down on the asteroid surface safely.

Figure 3 shows the current developing navigation sensors for MUSES-C mission. These instruments are used for the purpose of not only the navigation of the spacecraft but also scientific observation. 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. Measurement of the altitude is performed with LIDER (Light radio Detecting And Ranging). LIDAR covers the measurement range from 50[m] to 50[km].

In the final approach phase to the asteroid, the spacecraft orbit motion is synchronized with respect to the surface using image data. For sampling the surface materials, cancellation of the relative horizontal speed is essential to the touch down. To accomplish this, the spacecraft will drop a Target Marker that can act as a navigation aid by posing as an artificial landmark on the surface. The position of the target marker is estimated by ONC-W.

Laser Range Finder (LRF) is used at a lower altitude. LRF provides the height and attitude information with respect to the surface. A method is proposed, to estimate the height and attitude information of a spacecraft relative to the landing surface based on the range data. LRF has four beams that can measure the range from 7[m] to120[m].

Fan Beam Sensor (FBS) is onboard as an alarm sensor to detect some potential obstacles that may hit the solar cell panels. This paper presents an autonomous landing scheme by integrating the visual information and the range information. The effectiveness and the validity of the proposed landing method are confirmed by graphical simulations.

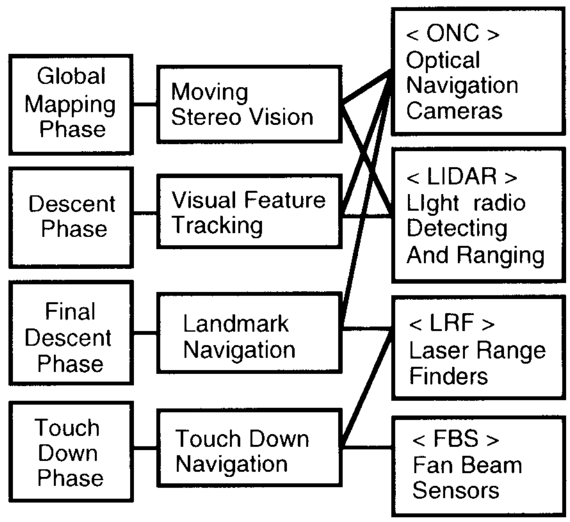

Fig.3 Navigation Sensors

5. Image Based Navigation

In descent phase, geographic features such as craters would be visible in images and be very useful in optical navigation. This paper proposes a new optical GNC system[9][10] which tracks small features such as craters, rocks valleys etc. on the target surface as feature points (FPs). In case that the landing site has visually characteristic features, it would be easy to guide the spacecraft to the landing site. However, not always exist such features on the landing site. In many cases, the landing site is chosen from flat areas so as to have the spacecraft touch down and land safely. So unluckily such an area would have almost no distinctive features. The proposed method uses distinctive features, which are not identical with those of the landing sites as FPs in order to avoid this problem.

The proposed scheme consists of two modes : tracking mode and updating mode. A landing point is designated on the camera image from the earth. Then visual feature areas are extracted as FP on an image and range to the landing site is measured by LIDAR. The location of the landing site with respect to the spacecraft is calculated as shown in Fig.4. In the tracking mode, the spacecraft tracks the FP on images based on template matching algorithms. The merit of the proposed scheme is that the landing site itself does not need to have any characteristic features. Therefore the spacecraft can land flat and safe area. As the spacecraft descends, however, some of FP would become unsuitable for tracking because of split from the field of view, extension etc. If such a situation occurs, new appropriate FPs are extracted automatically to reconstruct a renewed coordinate.

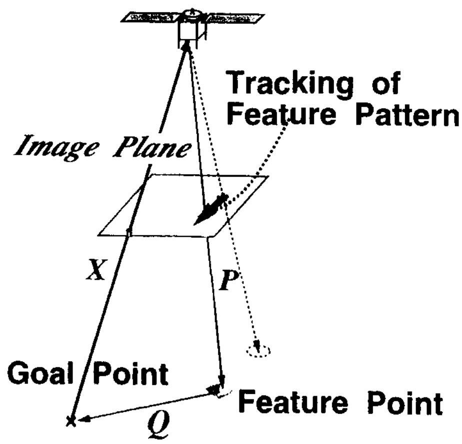

Fig.4 Image Based Navigation

5.2 Feature Extraction Scheme

As the spacecraft is at the mercy of the visual tracking, the block matching should be robust enough not to be defeated by noise. In addition, matching templates have to be chosen automatically, because real-time support from the earth is hardly available in deep space mission. The authors propose a simple and fast on-board scheme for extracting templates[11][12].

To make the tracking robust and accurate, each template used for the matching should have the following features :

1. shading pattern the wavelength of which is comparable with pre-selected size of template.
2. distinctive in the sense of contrast.

Such templates are extracted by the following procedure :

1. Enhance specific spatial wavelength of the original image by 2D band-pass filter.
2. Calculate local variance of filtered image to evaluate contrast.
3. Extract high local-variance areas as templates.

(1) Band pass filter
In the proposed scheme, BPF consists of the three image processing techniques : averaging, sub-sampling, and Laplacian filtering.

(2) Variance map
To evaluate roughness of the BPF image, the distribution of local variance is calculated. The procedure is as follows.
1. Calculate statistical variance within a window the size of which is equal to the template that is to be extracted.
2. Scan the window so as to cover the entire image.

(3) Templates extraction
Templates used for the tracking are extracted in order of local variance. Since the high local-variance points cluster in many cases, the extraction of another template is inhibited near to the already extracted ones.

5.3 Simulation Results

Figure 5 and Figure 6 show an example of original image and template extraction respectively. Four 32*32 [pel] windows are extracted from 256*256 [pel] original image in this case. The sub-sampling interval is chosen 4*4. Fig.6(a) is the smoothed and sub-sampled image of the original one. It is shown that detailed structures are omitted. In Fig.6(b), smooth shading of Fig.6(a) is suppressed by Laplacian filter to enhance comparable features with the templates (32*32). The local variance is calculated as shown in Fig.6(c). Bright areas have high-variance region as shown in Fig.6(d). This simulation result shows that the templates have appropriate features.

Fig.5 Original Image

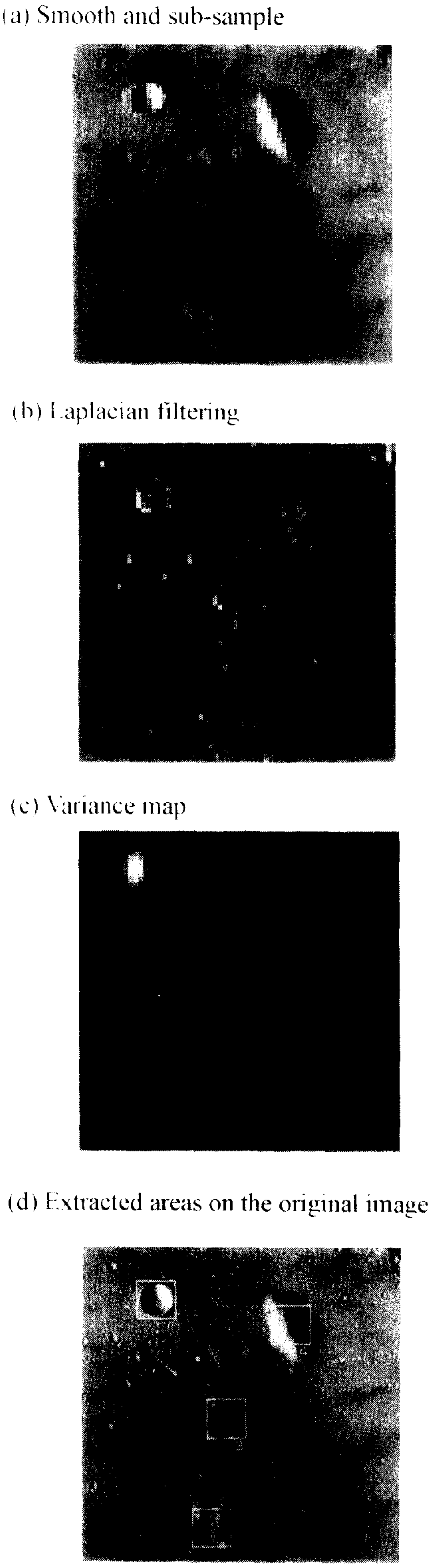

Fig.6 Simulation Results

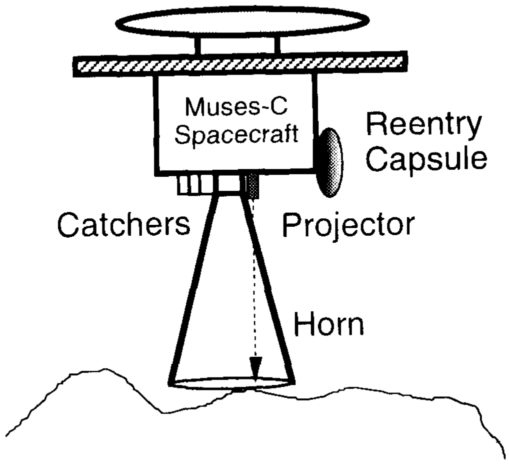

Fig.7 Sample Collector System

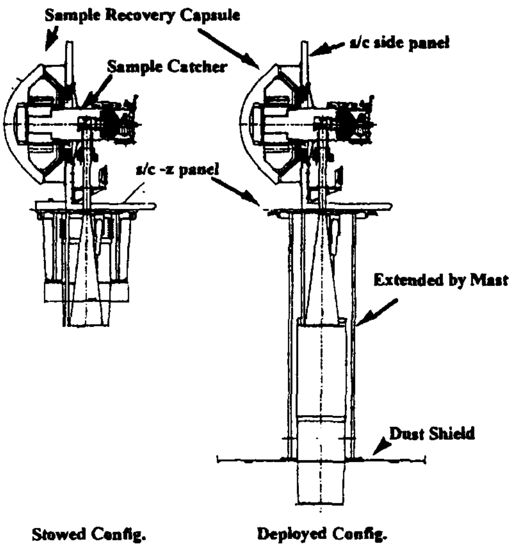

Fig.8 Sampler Horn

6. Sample Collector System

A sample collection technique is what the MUSES-C 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, the authors propose a sample collection scheme[13] by the combination of the Shooting Projectile and the Fragment Catcher as shown in Fig.7. The basic idea is retrieving fragments from surface ejected by the projectile shot. The key in the mechanism is the use of the catcher whose inlet surface covers the shot area that is concealed from the spacecraft main body, 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 grams at the speed of 300m/sec. Fig.8 draws how the extensible horn is stowed and deployed. Some low-gravity experimental results shows that several grams of fragments were successfully captured.

7. Conclusions

This paper has presented an autonomous navigation method to land on the asteroid surface in MUSES-C mission. A landing scheme by integrating several navigation sensors has been proposed. In descent phase, image based navigation has been also proposed. A method to extract visual feature areas has been explained. The validity of the proposed method has been verified by computer graphical simulations. This paper also has proposed a sampling mechanism to collect the surface materials. The validity of the proposed method has been confirmed by some experiments under the low gravity environment.

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