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Robotics Technology for Asteroid Sample Return Mission MUSES-C

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Abstract

The MUSES-C mission is the world's first sample and return attempt to/from the near Earth asteroid. In deep space, it is hard to navigate, guide, and control a spacecraft on a real-time basis remotely from the earth mainly due to the communication delay. So autonomy 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 describes various kinds of robotics technologies applied for MUSES-C mission. A global mapping method, an autonomous descent scheme, and a novel sample-collection method are proposed and presented in detail. The validity and the effectiveness of the proposed methods are confirmed and evaluated by numerical simulations and some experiments.

1 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 asteroid have received a lot of attention in the world. NEAR spacecraft[1] was successfully put into the orbit of asteroid 433 Eros in February in 2000. After precise remote-sensing observations, NEAR spacecraft succeeded in hard-landing on the surface of EROS in February in 2001. In Japan, ISAS(Institute of Space and Astronautical Science) plans to launch an asteroid sample and return spacecraft MUSES-C[2] toward a near Earth asteroid 1998SF36 in 2002.

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 the spacecraft for deep space exploration. On the other hand, because the shape, the rotational motion, and the surface terrain of the asteroid are not known in advance, robotics technology is used for the spacecraft to approach, rendezvous with, and land on the asteroid safely. In MUSES-C mission, the spacecraft will make a dynamic touch down the surface of the target asteroid and then collect samples automatically by using novel sampler system. This paper presents the autonomous functions and robotics technology used in MUSES-C sample return mission.

This paper is structured as follows. Section 2 describes the purpose and the scenario of MUSES-C mission. In Section 3, a new global mapping scheme based on image data is proposed. Section 4 discusses the strategy for autonomous approach and landing. Autonomous descent scheme based on laser range finder and vision system is proposed. In Section 5, a novel sample collection mechanism is proposed. For sample collection, the touch-down tests are performed by using the robotics hardware simulator with nine degrees of freedom. Finally, Section 6 is for discussions, conclusions, and future work of the research.

2 MUSES-C Mission

2.1 Outline of MUSES-C Mission

ISAS will launch the spacecraft, MUSES-C toward the asteroid in 2002. This project[3] 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 target body of the MUSES-C spacecraft is a near Earth asteroid 1998SF36. The launch is scheduled in November of 2002 and the arrival at 1998SF36 at the beginning of September of 2005. Leaving the asteroid at the middle of January of 2006, the spacecraft returns to the Earth in June of 2007. The mission duration from launch to the Earth return is about 4.5 years. In this nominal plan, the MUSES-C spacecraft stays for about four months around the asteroid and both mapping and sampling operations have to be carried out during that short period. The MUSES-C project also has a backup plan for which launch takes pace half a year later. Figure 1 shows the illustration of MUSES-C mission.

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.

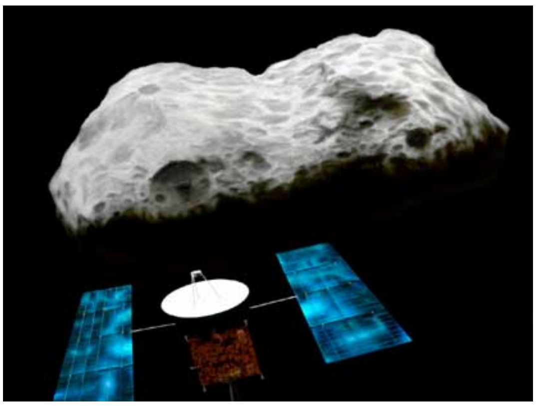


Figure 1 : MUSES-C Mission

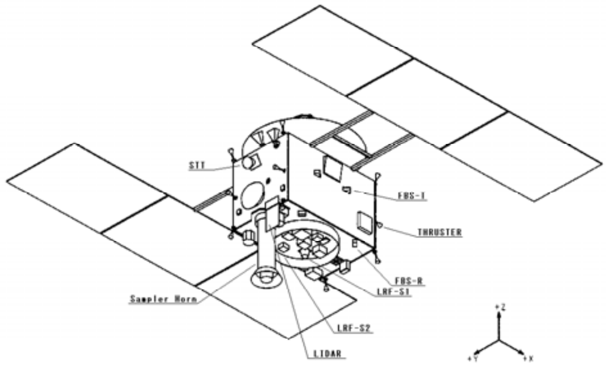


Figure 2 : MUSES-C Spacecraft

2.2 MUSES-C Spacecraft

In deep space, it is difficult to operate 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 descent and touch-down to the asteroid. For this purpose, MUSES-C has some optical sensors and onboard image processing system[4].

Rendezvous and touch down to the asteroid, whose size, shape, surface condition are unknown, requires intelligent and advanced navigation, guidance and control system. Figure 2 shows the outline of the MUSES-C spacecraft. The spacecraft has two kinds of optical navigation cameras. The narrow angle camera (ONC-T) is used for mapping and multiple scientific observations of the asteroid from the Home Position. The wide angle cameras (ONC-W1 and ONC-W2) are both used for onboard navigation, though W2 is used only when high-phase angle observation. Control electronics for ONCs (ONC-E) equipped with a RISC processor and a Gate Array image processor has some image processing functions such as image compression, center-finding of bright object, correlation tracking, feature terrain extraction, etc. Measurement of the altitude is performed with LIDAR (Light radio Detecting And Ranging). LIDAR covers the measurement range from 50[m] to 50[km]. For sampling the surface materials, cancellation of the relative horizontal speed is essential while touch down. To accomplish this requirement, the spacecraft drops a Target Marker (TM) that can act as a navigation aid by posing as an artificial landmark on the surface. The position of TM is estimated by using ONC. Since it is not so easy to detect TM from several tens of meters altitude, TM is equipped with reflexive reflector and ONC has a flash lamp (FLA) whose radiation is synchronized with camera exposure. Laser Range Finder (LRF) is used at a lower altitude. LRF has four beams that are canted with 30 [deg] and can measure the range from 7[m] to 120[m]. LRF can provide the height and attitude information with respect to the surface. Four sets of Fan Beam Sensors (FBS) are equipped onboard as alarm sensors to detect some potential obstacles that may hit the solar cell panels.

3 Global Mapping

The MUSES-C spacecraft can rendezvous the asteroid by range and range rate method and conventional optical navigation method. 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] from the sun side and the terminator side are scheduled in MUSES-C mission. The spacecraft keeps the home position during global mapping.

In order to successfully approach and touch-down on the asteroid, it is needed to both accurately estimate relative motion between the asteroid and the spacecraft and accurate 3-D model of the asteroid. This paper proposes a new global mapping scheme. The spacecraft will take asteroid images from various viewpoints at a distance of approximately 20[km]. Motion estimation is performed based on feature points GCP(Global Control Points). A 3-D model will be built using motion stereo method.

3.1 Motion Stereo Technique

The camera (ONC) attached to the spacecraft, takes asteroid images from different viewpoints. It is noted that the spacecraft keeps a home position, and multi-viewpoint images are obtained using asteroid rotation. Then, the asteroid images are transmitted to the earth, and the computation for global mapping is performed on the ground station.

In the first step, the relative movement of the spacecraft to the asteroid is estimated using a shape from motion technique. In the second step, images taken from adjacent camera positions are paired, and individual pairs are used to calculate the asteroid shape using a motion stereo technique. The technique first establishes pixel correspondences between each image pair using a correlation-based matching, which divides each image of the pair into blocks and calculates the correlation of pixel values among these blocks. The correlation equation used is as follows,

$$\text{correlation} = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \cdot \sum_i (y_i - \bar{y})^2}} \quad (1),$$

where

x_i : the value of a pixel i in a block, and

y_i : the value of a pixel i in another block.

$$\bar{x} = \sum_i x_i \Big/ n, \quad \bar{y} = \sum_i y_i \Big/ n$$

n : the number of pixels in a block.

For each pixel correspondence, camera position data can be used to calculate the 3-D position of one point (sample point) on the object surface. The corresponding pixel values provide an intensity value for each point. By repeating these calculations for all observed correspondences, it is possible to obtain a full set of sample points with their respective intensities. Then, the global map of the target asteroid is constructed by connecting the sample points with triangle patches.

The accuracy by the motion stereo technique depends mainly on an asteroid surface texture. If there is no distinctive texture, it tends to produce erroneous matching results. A shape from limb technique can be used to improve the matching results. Figure 3 shows the principle of a shape from limb technique. According to this technique, an asteroid image is divided into two regions; an asteroid region and a background region. From the asteroid region, it is possible to calculate the 3-D object area that contains the asteroid. From the background region, it is possible to calculate the restricted 3-D area that does not have any intersection with the asteroid. A number of 3-D object areas are obtained from multi-view images, and the circumscribed polygons can be produced, that contain the asteroid by making intersections of all the 3-D object areas.

The accuracy of matching can be improved by using the circumscribed polygons. In the matching process, the search areas of corresponding pixels are restricted so that the calculated position of a sample point is located inside the circumscribed polygons. Hence, the matching errors that expand the map can be almost reduced. However, the error that shrinks the map cannot be avoided with this technique.

The strong point of the shape from limb technique is that it can produce stable results with any surface conditions. On the other hand, the concave areas cannot be corrected by this technique.

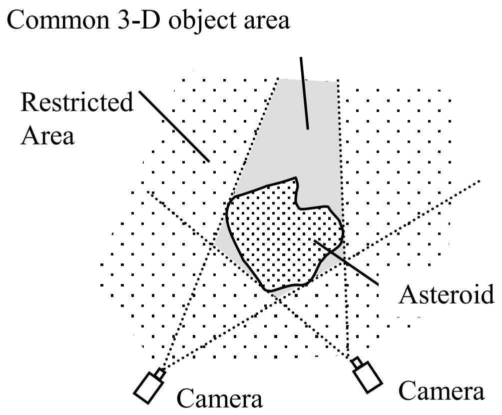


Figure 3 : Principle of Shape from Limb

3.2 Hapke Reflection Model

The accuracy of the stereo matching depends on the asteroid surface reflection. If the reflection is independent of the incidence and emergence angles, the matching process can produce accurate pixel correspondences, but the actual intensity varies with the incidence and emission angle change caused by asteroid rotation.

In order to evaluate the effect of the reflection model on the matching accuracy, some experiments were performed by using computer graphics images generated with the Hapke reflection model. The Hapke model[6] is considered to the most precise reflection model of asteroids. A Lambertian reflection model was also used in the comparison. In the experiments, the albedo is uniform over the asteroid surface. In the Lambertian reflection model, the intensity of a point I is calculated by the following equation.

$$I = k \cos(\text{incidence angle}) \qquad (2),$$

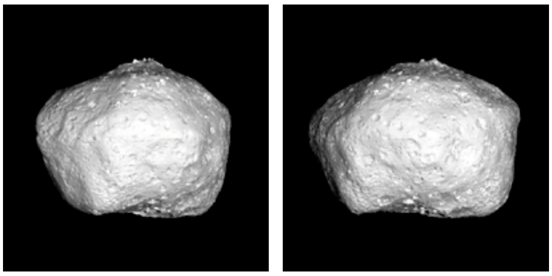
where k is constant coefficient. This equation indicates that the intensity is only determined by the incidence angle. Compared to Lambertian reflection, the Hapke model has two charateristics. (The detail of Hapke reflection is described in Ref.[6].)

(1) The intensity curve has a keen peak where the angles of incidence and emission are almost the same. The phemonmenon is called the “opposition effect”.
(2) Except for the area influenced by the opposition effect, the intensity change with the incidence angle change is relatively small.

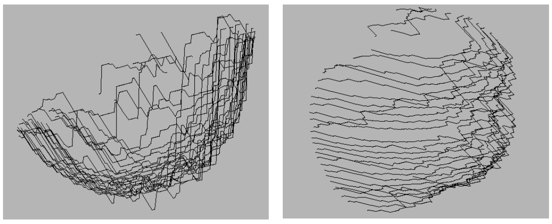
3.3 Simulation Results

Asteroid images were generated by computer graphics techniques with both the Lambertian and Hapke reflection models. A polygon asteroid model, 1 [km] in diameter, was used. The distance between the camera and the model center was 20 [km]. The field of view(FOV) of the camera is 4 [deg] in horizontal and vertical, and the image resolution is 500 [pixels] by 500 [pixels]. The phase angle is 10 [deg]. By rotating the asteroid at 30 [deg], stereo images were generated.

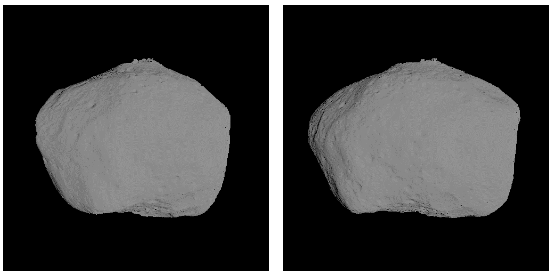
To investigate the validity of the proposed global mapping method, graphical simulations are performed. Figure 4 (1) and (3) show the generated images. The opposition effect did not occur in images (3), but the caters cannot be clearly seen in the images (3) that can be seen clearly in the images (1). This means that the intensity variation, which can be used as clues for matching, is slight in the Hapke images. By the proposed method, however, a more precise model (4) could be constructed from images with the Hapke reflection model than from those with the Lambertian reflection model (1). In these experiments, the shape from limb technique is not used in order to clarify the effect of the reflection model on the matching accuracy.



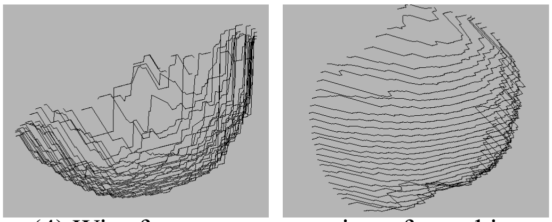
(1) Stereo images with Lambertian reflection



(2) Wire frame representation of matching



(3) Stereo images with the Hapke reflection



(4) Wire frame representation of matching

Figure 4 : Images and Matching Results
(Phase Angle : 10[deg])

4 Autonomous Landing Method

4.1 Descent and Landing Strategy

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 guide a spacecraft to the landing point without hitting rocks or big stones. In the touch down phase, cancellation of the horizontal speed relative to the surface of the landing site is essential. This paper proposes a new method for a spacecraft to land on the surface of an unknown planet autonomously, using optical cameras and laser altimeter. The proposed strategy for autonomous descent and touch-down consists of the following phases. The autonomous descent and landing sequence is illustrated in Fig.5.

(1) Descent Phase
While the whole of the asteroid image is in the FOV of ONC-W1, 3D navigation scheme[7] based on center-finding of the asteroid is used. After a part of the asteroid goes out of the FOV (about 1 km altitude), the spacecraft will nominally descent with only vertical velocity control because it can not detect the direction of the asteroid center. Therefore, navigation accuracy depends upon the initial position and velocity, which are determined in the Home Position.

For an experiment, NGC(Navigation, Guidance, and Control) system has also natural terrain tracking function. That is, characteristic features like craters on the surface are extracted from images and tracked autonomously. If some tracked features are recognized to be unsuitable for tracking, new appropriate features are extracted automatically. Line-of-sight vectors to the extracted features provide relative position to the surface. Since the locations of the features are unknown in the asteroid-fixed coordinate system, the spacecraft measures only the deviation of the vectors, that is, it can obtain relative velocity to the surface.

(2) Final Descent Phase
The sampling method in MUSES-C is so-called touch-and-go way. That means the spacecraft shoots a small bullet to the surface just after the touch-down is detected, collects ejected fragments with sampler horn, and lifts off before one of solar cell panels hits the surface. Therefore, the control of the vertical velocity and the cancellation of the horizontal speed are essential for both successful sampling and spacecraft safety. To meet these requirements, TM is released from the spacecraft at the altitude of about 100[m]. At the altitude of about 50[m], ONC-W1 tries to capture TM, that would be placed near the target landing point. To ensure the visibility of TM, the surface of TM is covered with reflexive reflector and ONC provides the differential image taken by flash-on and flash-

off.

After TM is successfully captured, the relative navigation logic is initiated to obtain the position with respect to TM and the local horizon, which is calculated based on the asteroid model. 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 LRF measurements. The spacecraft is guided to the landing point and stays there until the relative velocity is stabilized within a limit. Introduction of the artificial landmark drastically reduces the computational load and uncertainty of image processing, even though the function of natural terrain tracking[8] remains as an experiment and backup.

(3) Touch Down Phase

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. Then the spacecraft starts free-fall and touches down the asteroid surface to collect samples. During the free-fall of the spacecraft, some potential obstacles are checked with FBS. At the moment of the touch-down, the surface sampling sequence is initiated and the spacecraft lifts off from the asteroid surface immediately.

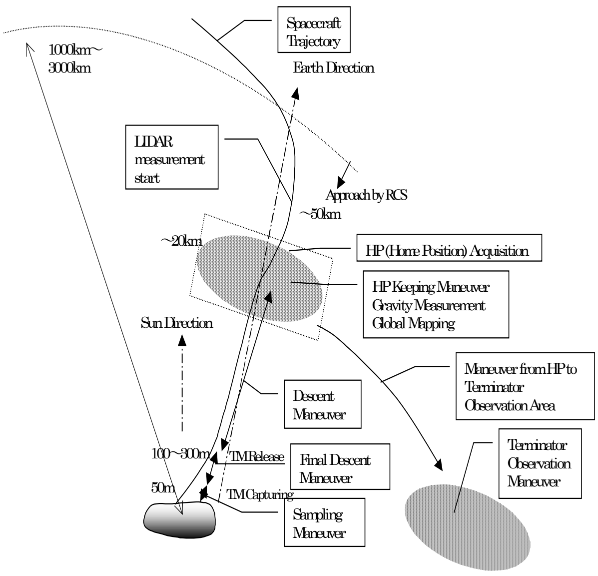


Figure 5 : Autonomous Landing Sequence

4.2 Image Based Navigation

The following image processing techniques are used for navigation in MUSES-C mission.

(1) Whole image Center Tracking (WCT)

In this mode, groups of adjoining pixels whose brightness beyond the specified threshold are extracted and the center address and the total number of the pixels of each group are calculated. Though less than nine groups are extracted as the specification, only one group, which has maximum number of pixels is usually used for center finding of the asteroid. When the image of the asteroid is divided into some portions with the illumination condition, AOCU uses some relatively large groups and estimates real center of the asteroid.

(2) Target Marker Tracking (TMT)

The function of this mode is basically the same as WCT mode except that TMT uses a differential image between flush-on and off. Different from the center finding of the whole asteroid image, the size of the extracted groups are expected to be a few pixels considering the distortion of the optics and the number of extracted groups must be one in order to track TM properly.

(3) Fixed Window Correlation tracking (FWC)

This mode is prepared for an experiment and a backup when TM is not captured. Some tracking windows are designated on an image and the windows are used for templates of the tracking. Each window on the next coming image is correlated with corresponding template and the deviation of horizontal and vertical pixels between images are calculated. FWC is used to measure the relative velocity against the surface.

(4) Auto Window Tracking (AWC)

AWC[9] is also prepared for an experiment and a backup and the function of the correlation tracking is same as FWC. AWC autonomously sets tracking windows, that is, at first, some edges are extracted on the image, and the areas which contain many edges are selected as characteristic terrain, and then tracking windows are set around the terrain. Though this algorithm is advanced and somehow complex, it seems more robust against terrain and illumination condition than FWC, because it uses windows, which can be easily tracked.

To satisfy the stringent requirement on position and velocity estimation, a navigation filter that utilizes Kalman filter technique 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.

4.3 Simulation Study

To confirm the effectiveness and robustness of the onboard logic, a lot of numerical simulations have been done. Figure 6 shows one of the surface images generated by graphical simulator. Figure 7 shows the simulation result of final descent phase and the spacecraft succeeded in touchdown.

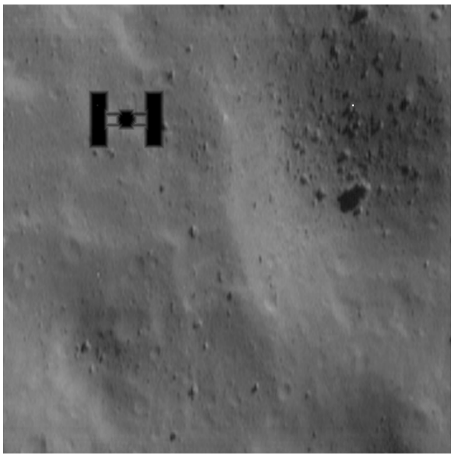


Figure 6 : Asteroid Surface Image by CG

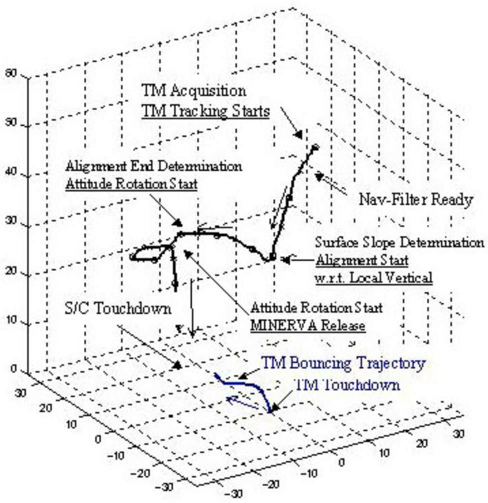


Figure 7 : Simulation Result

4.4 Target Marker

Artificial target marker is dropped down onto the asteroid surface to cancel the relative velocity. To use such an target marker, it is needed to develop a marker object with low restitution coefficient under the micro-gravity environment. To develop an object with low restitution coefficient, Japanese traditional "otedama" concept is introduced. "Otedama" is made of some amount of small beads inside a soft cover cloths. When "otedama" collides with other object, beads are expected to reduce the total collision energy. To investigate the collision mechanism of "otedama", the dropping tower micro-G experiments were performed at MGLAB in Gifu in Japan. Figure 8 shows the overview of "otedamas" in the experimental box. Experimental results show that restitution coefficient values of "otedamas" mark below 0.1.

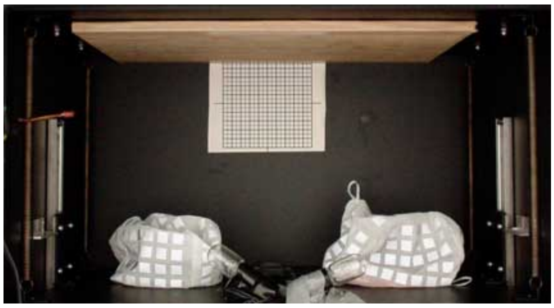


Figure 8 : Target Marker

5 Sample Acquisition 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, this paper proposes a novel sample collection system. 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 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[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.

Figure 9 shows the prototype model[10] of sampler horn. To verify the validity of the proposed touch-down and sampling sequence under the micro-gravity environment, some experiments[11] have been performed for touch-down of the asteroid surface using a 3-D robotics hardware simulator.

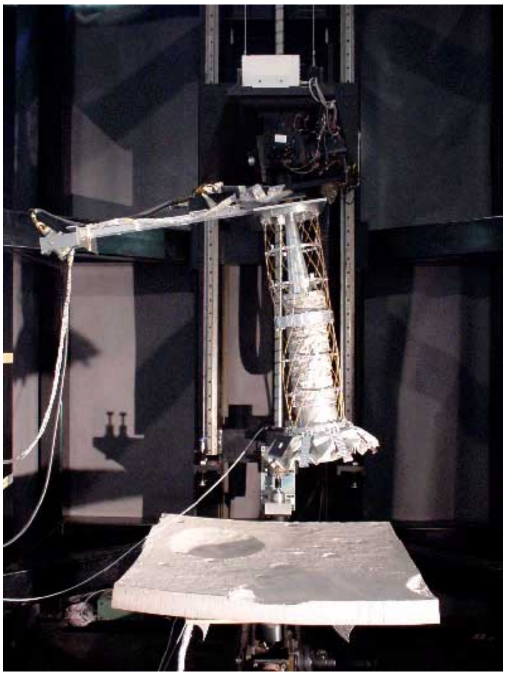


Figure 9 : Experimental Sampling System

6 Conclusion

This paper has presented autonomous functions and robotics technology used in MUSES-C mission. This paper proposed global mapping method based on motion stereo techniques. Then this paper has presented an autonomous descent scheme to land on the asteroid surface A landing scheme by integrating several navigation sensors has been proposed. In descent phase, a method to track visual target marker has been explained. The validity of the proposed method has been verified by graphical computer 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.

Acknowledgement

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