Estimation of Motion and Shape of Asteroid Based on Image Sequences

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Abstract

In order to successfully approach and land on an asteroid, it is necessary to both accurately estimate relative asteroid/spacecraft motion and generate an accurate 3-D model of the asteroid. To do this, we propose a new method of equipping a CCD camera on the future spacecraft MUSES-C. The spacecraft will take asteroid images from different viewpoints at a distance of approximately 20 Km. After the relative asteroid/spacecraft motion has been estimated using feature points (or Global Control Points; GCPs) tracked on the obtained images, a 3-D model of the asteroid is created using a motion stereo method. The obtained shape data is then used to select landing positions on the asteroid surface.

This paper describes the proposed method and reports the results of experiments evaluating its potential effectiveness.

***Key words**:* Asteroid Exploration, Motion Estimation, Shape Reconstruction, Motion Stereo Method.

Introduction

As the number of missions exploring the moon and planets have increased, the navigation technology of a spacecraft in deep space has become more important than ever. In recent years, the probing and sampling returning of asteroids has received much attention in Japan, Europe, and the United States. In deep space, it is difficult to navigate, guide, and control a spacecraft remotely from the earth on a real-time basis mainly due to the communication delay. Thus, autonomous navigation and guidance is required for the final approach to an unknown body. For approaching and landing safely, it is necessary to obtain detailed information on the shape and motion of the target body in advance. In space, the motion estimation of a target body is very difficult because the relative position is unknown.

This paper proposes a strategy for estimating the motion and shape of an unknown body for the asteroid exploration spacecraft MUSES-C[1]. First, we discuss the estimation of asteroid/spacecraft motion by tracking feature areas such as craters on image sequences. Second, we also proposes a motion stereo method to reconstruct a 3-D model of an asteroid. From the reconstructed model, the landing sites on an asteroid's surface are selected.

Navigation Sensors

The navigation sensors currently slated to be used on the MUSES-C spacecraft include a telephoto lens camera (ONC-T: Optical Navigation Camera-Tele), a wide-angle lens camera (ONC-W: Optical Navigation Camera-Wide), and two range finders, LIDAR (LIght raDAR) and LRF (Laser Range Finder).

The LIDAR is used at a range from 50 Km to 50 m, while the LRF is for distances less than 50 m. The LRF is equipped with three offset beams providing distance measurements in three directions to estimate the altitude of the spacecraft relative to the surface.

Other common navigational instruments, such as a star sensor and a sun sensor, will also be provided on the spacecraft.

Motion Estimation by GCP Tracking

Relative motion of the asteroid and the space craft

In estimating the relative motion of the spacecraft and the asteroid, we may consider that the asteroid is spinning at constant rate along a fixed axis, and translating at a constant velocity.

Asteroid motion observed from the spacecraft is estimated by tracking feature points on the asteroid surface with ONC-T; spacecraft attitude is to be determined with the star sensor and the sun sensor. Here, let us introduce the inertial coordinates whose origin is ONC-T. Hereafter, we refer to these as "camera coordinates". We refer to the number of observations (the number of obtained images) as K, and to the number of GCPs as N.

Case A: Acceleration

Let us first consider a general case in which the spacecraft is accelerating. The following table lists the unknown variables relevant to this case (see Fig.1):

p_i : position of the i-th GCP at time t_1

$d_i(t_k)$ **:** distance between the coordinate origin and the i-th GCP at time t_k

ω **:** rotation rate

n **:** rotation axis orientation

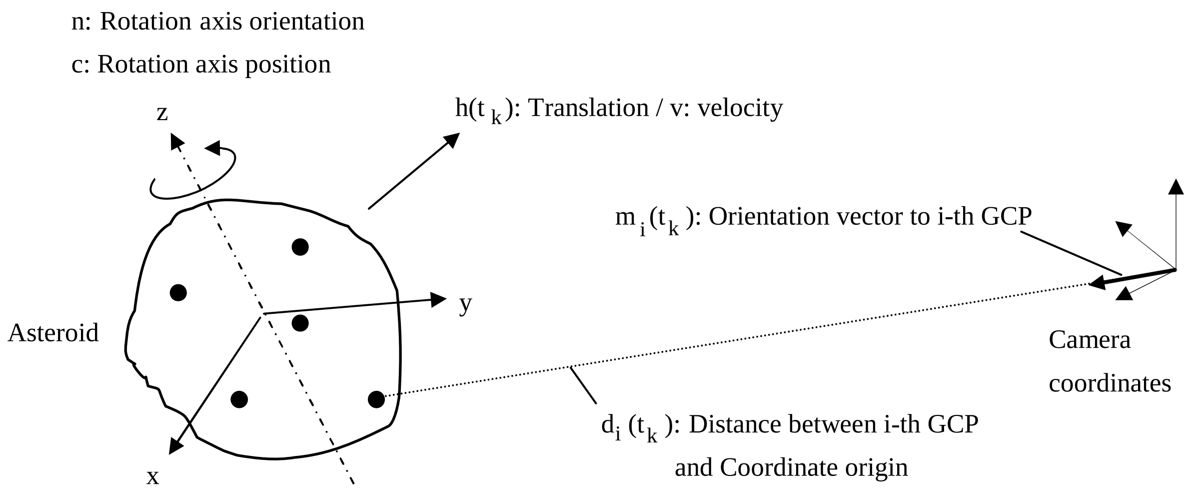


Fig.1 Asteroid coordinates (x,y,z) and variables for asteroid motion estimation for Case A and Case B.

$h(t_k)$ **:** asteroid translation at time t_k

$(i = 1, \cdots N, k = 1, \cdots K)$

Additionally, $m_i(t_k)$, the orientation vector from the coordinate origin to the i-th GCP at time t_k, is a relevant known variable that can be calculated from i-th GCP position on the ONC-T image obtained at time t_k. The following equation expresses the relationships among these variables, and can be used to calculate asteroid motion in terms of camera coordinates:

$$R(t_k)\, p_i + h(t_k) = d_i(t_k)\, m_i(t_k) \qquad (1)$$

$(i = 1, \cdots N, k = 1, \cdots K)$

where $R(t_k)$ is the rotation matrix of the asteroid at time t_k, and contains unknown variables, ω and n. (We should remember that a GCP observation alone will not provide the necessary scale parameter for applying this equation; such a parameter must be provided by LIDAR or some other sensor.)

In order to produce a unique solution to this equation,
the number of specific equation applications with which we are provided must be greater than or equal to the number of unknown variables.

Table 1 lists the variables and their respective numbers . From this table, we can calculate the sum of unknown variables as $KN + 3N + 3K$ and the sum of equation applications as $3KN + 1$ ("+1" is added to reflect the scale parameter). Accordingly, if $KN + 3N + 3K \le 3KN + 1$, then Equation (1) will have a unique solution. In extremely rare situations, this table may not be necessarily applicable. For example, if all GCPs are placed at the spin axis, the asteroid spin rate cannot be uniquely determined.

Case B: Non-acceleration

Let us now consider when the spacecraft is moving at a constant velocity. In this case, instead of variable

$h(t_k)$ (asteroid translation), two new variables are introduced, rotation axis position c at time t_1 and translation velocity v.
The following equation expresses the relationships among these variables.

$$R(t_k)(p_i - c) + c + v\,t_k = d_i(t_k)\,m_i(t_k) \qquad (2)$$

$$(i = 1, \cdots N, k = 1, \cdots K) .$$

Table 2 lists the variables and their respective numbers. From this table, we can calculate the sum of unknown variables as $KN + 3N + 8$ and the sum of equation applications as $3KN + 1$. Accordingly, if $KN + 3N + 8 \le 3KN + 1$, then Equation (2) will have a unique solution. Thus, as was true with Case A, this table may not be necessarily applicable in extremely rare situations.

Table 1. Variables for Case A.

Variables		Num. of each
Position of i-th GCP	p_i	3N
Rotation axis orientation	n	2
Rotation rate	ω	1
Translation	$h(t_k)$	3(K-1)
Distance from ONC-T to i-th GCP	$d_i(t_k)$	KN
Orientation vector	$m_i(t_k)$	3KN

Table 2. Variables for Case B.

Variables		Num. of each
Position of i-th GCP	p_i	3N
Rotation axis orientation	n	2
Rotation rate	ω	1
Rotation axis position	c	2
Velocity	v	3
Distance from ONC-T to i-th GCP	$d_i(t_k)$	KN
Orientation vector	$m_i(t_k)$	3KN

Shape Reconstruction by Motion Stereo Technique

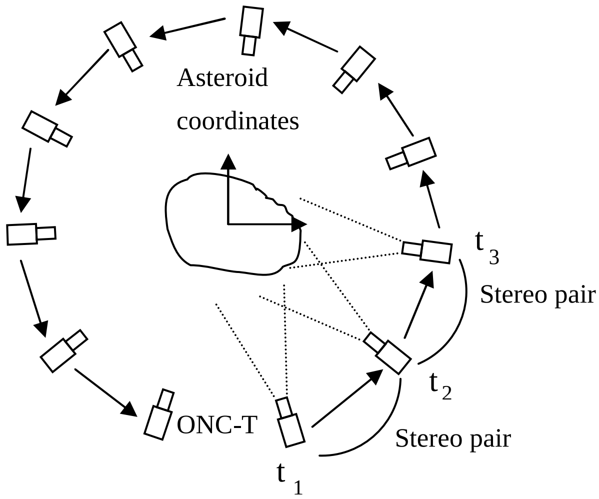


Fig.2 ONC-T positions represented on asteroid coordinates.

Stereo measurement

Here we introduce coordinates fixed to the asteroid, and then express ONC-T positions from time t_1 to t_K with the asteroid coordinates (see Fig.2). On the coordinates, ONC-T moves around the asteroid according to the asteroid rotation.

Images taken from adjacent ONC-T positions are paired, and individual pairs are used to calculate asteroid shape using a motion stereo technique[2,,3]. The method first establishes pixel correspondences between each image pair using a correlation-based matching technique, which divides each image of the pair into blocks and calculates the correlation of pixel values among these blocks.

For each pixel correspondence, we can use ONC-T position data 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, we are able to obtain a full set of sample points with their respective intensities. Connecting the sample points in triangles results in the creation of a surface model of the asteroid.

The mesh itself expresses the shape, and the intensity values at the vertices of the triangles express an intensity pattern, the "texture" of the asteroid surface. We refer to the mesh produced from one pair of stereo images as an "asteroid-portion model" because it represents just one section of the asteroid surface.

Integrating Asteroid Portion Models

To integrate such asteroid-portion models, we need to determine the relative positions among the portions. These positions can be calculated from ONC-T positions, but if the GCP tracking error results in significant inaccuracy, we can use a new technique to improve integration accuracy with texture matching technique[2,3] .

This technique uses texture data to find overlapping areas between two adjacent portion models using the criterion so that the texture pattern of the overlapping areas agrees. Once overlapping areas have been found, we can easily determine relative positions between the two portion models using the criterion so that the distance between overlapping areas is minimized. When all asteroid-portion models have been integrated in this way, the model is complete.

Error Analysis for Stereo Measurement

Two major factors produce error in stereo measurements. The first factor is matching error produced when trying to establish correspondences between stereo images. The accuracy of established correspondences depend on object texture: clearly defined distinctions in texture on an asteroid surface help produce extremely accurate correspondences, but poorly defined distinctions can easily result in erroneous correspondences. We have evaluated our correlation-based matching technique in this regard in the experiment described in the next section.

The second factor is quantization error, which is mainly determined by pixel resolution (20'' for ONC-T) from the camera-to-camera distance and from the cameras-to-object distance (Fig.3). The error decreases as the cameras-to-object distance decreases and the camera-to-camera distance increases.

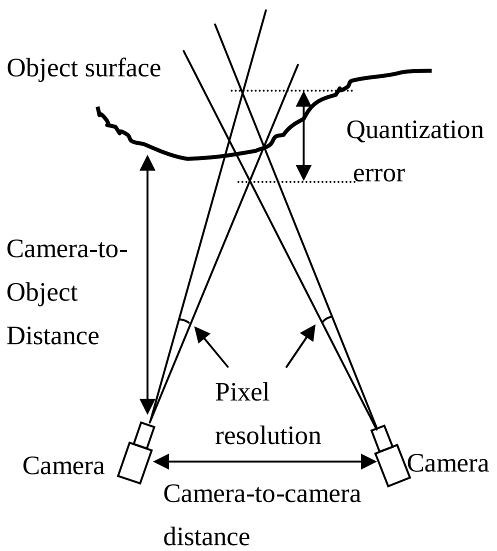


Fig.3 Quantization error in stereo measurement.

Now we consider the camera position which minimizes the quantization error when the distance between the cameras and object (the spacecraft altitude) and the camera resolution are fixed. We introduce polar coordinates to express the spacecraft position. The coordinate transformation equation is expressed as follows:

$$x = r\cos\varphi\cos\theta$$
$$y = r\cos\varphi\sin\theta \qquad (3)$$
$$z = r\sin\varphi$$

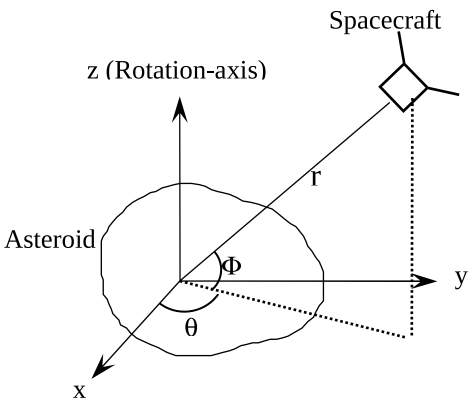


Fig.4 Polar coordinates (θ, Φ, r).

To analyze the quantization error, we consider a simple case when the spacecraft is moving on a circular orbit and is always aiming toward the circle center. When the spacecraft moves from (θ, ϕ, r) to $(\theta + \delta\ \theta, \phi, r)$ due to the asteroid rotation, the distance between two the camera positions is calculated with the next equation.

$$d = r\cos\phi\sqrt{2(1-\cos\delta\ \theta)} \qquad (4)$$

From this equation, we find that d goes the maximun when $\phi = 0$. This means that the position above the asteroid equator is the best position to maximize the camera-to-camera distance on any given rotation angle, and to minimize the quantization error.

On the contrary, a large camera-to-camera distance complicates establishing correspondences. Therefore, the optimum camera-to-camera distance should be determined from a tradeoff of both effects.

Experimental Results

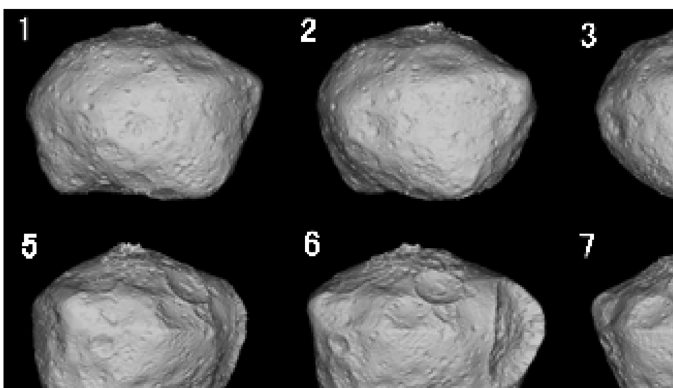
We performed a shape reconstruction experiment using computer graphics images. The main purpose of this experiment was to evaluate the efficiency of the correlation-based matching method for asteroid images.

Image generation with computer graphics

A polygon model of Phobos, 1 km in diameter, was used to generate computer graphic images. The camera was located above the equator to minimize the quantization error (as described in the previous section) [4]. The distance between the camera and the model center was 20 Km. The camera parameters such as focal length were the same as ONC-T.

The type of light was parallel projection to simulate sunlight, and its projection direction was parallel to the camera axis. There was no ambient light. The illumination model was Lambertian reflection. Since the model had no texture data, the brightness of each area of the model was determined by the angle between the light direction and the surface normal.

The model was rotated 30 degrees and twelve images were generated (see Fig.5). The rotation angle "30 degrees" was experimentally determined on the condition that the matching works well and the quantization error is small.



Shape reconstruction

As described in the previous section, a model was reconstructed from the twelve Phobos images. The window size of matching was 7 by 7 pixels. Fig.6 shows the original model and the reconstructed model of Phobos. Although the reconstructed model contains perturbations, it still resembles the original model sufficiently enough to consider that the stereo matching technique performed successfully on the asteroid images.

A few conspicuous errors are seen on the reconstructed model (see Fig.6). These errors occurred on the center of the portion models where the angle between the light direction and the surface normal was small. We assume that correlation-based matching technique tends to make correspondence errors where the such is small, as there are no clearly defined textural distinctions in these areas. If there are discernible textures on the target asteroid, correlation-based matching should perform better .

Summary

We have proposed a method for modeling asteroid motion and shape from ONC-T image sequences. We have formulated equations from which asteroid motion can be estimated, and determined the conditions under which they will have unique solutions. We have also introduced stereo measurement and texture matching techniques for model generation.

Fig.5 Phobos images (generated by computer graphics)

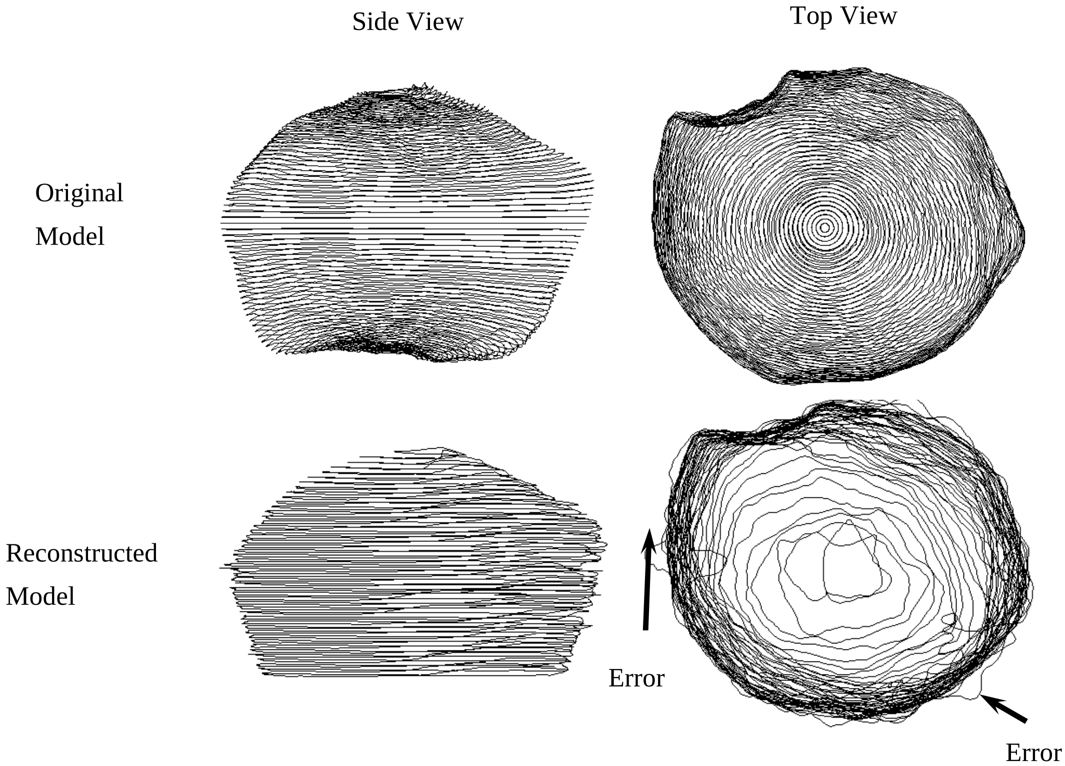


Fig. 6 Original model and Reconstructed model of Phobos.

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