DEM matching image navigation by motion stereo
for the future lunar and planetary explorers

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Abstract
We propose an image navigation method for the orbital phase and the powered descent phase of the future lunar and planetary explorers. DEMs are made onboard by using time-series stereoscopic pair images of the lunar or planetary surface taken by the optical camera(s) installed on the explorer. The explorer decides its location by matching the onboard DEMs to the reference DEMs acquired in advance.

Despite initial navigation errors, or bias errors of the inertial measurement unit, we can obtain the position accuracy equivalent to the image resolution by using this navigation method. We show that this navigation method can be executed by existing or near-future onboard computers and that it has good properties in navigation performance and robustness.

1. Introduction
It is expected that the terrain-following navigation method, matching data observed by the explorer to the terrain data acquired in advance, will be applied to the future lunar or planetary explorers, under the circumstance that a high navigation accuracy is required as pinpoint landing.1,2)

We propose a DEM matching image navigation method.3) DEM (Digital Elevation Model)s are made onboard by using time-series stereoscopic images of the lunar or planetary surface taken by the optical camera(s) installed on the explorer. The explorer decides its location by matching the onboard DEMs to the reference DEMs acquired in advance.

As a result of our research, we show that this navigation method can be executed by existing or near-future onboard computers and that it has good properties in operability and robustness.

2. Outline of the navigation method
On the DEM matching image navigation by motion stereo ("DEM navigation"), we calculate three dimensional positions of each pixels in the nadir-looking image by stereo 3D measurement with the use of a forward-looking image and a nadir-looking image, and transform them to a "onboard DEM". At the same time, we store the terrain data of the lunar or planetary surface acquired in advance on the memory system of the explorer, and transform them to "reference DEM" in the same map coordinate system as the onboard DEM. Then we match the DEMs, and get the horizontal position as the disparity of DEMs, and vertical position as the
average elevation difference at the optimal matching position. In case of the moon, the estimated position acquired in the ground station is applied to the initial navigation position, and the attitude is acquired by the star sensor. In the interval of DEM matching outputs, the inertial measurement unit (IMU) propagates the state vectors, however there is no need for updating the DEM matching output until the IMU errors grow significantly large. There shows the concept of DEM navigation in Fig.1., and the general process flow of it in Fig.2.

This navigation method is applied to the orbital phase and the powered descent phase of lunar or planetary explorers. From the viewpoint of fuel consumption and control capacity, it is desired to reduce errors by executing this navigation on the orbit before starting the descent guidance.

We can obtain navigation accuracy equivalent to the image resolution, when we make the DEM resolution the same size as the image resolution. The position acquired by DEM matching includes not only position errors caused by the initial navigation values or IMU errors, but also the contribution of the attitude errors, however, the reduced distance on the lunar or planetary surface acquired by the multiplication of the attitude errors and the explorer altitude is significantly smaller than position errors, so we can achieve enough accuracy only by DEM matching as a parallel displacement. There is a method that calculates position errors and attitude errors at the same time, but it has very high computational loads, so we don't apply it to our navigation method.

Although reference DEMs have bias position errors and bias attitude errors, if we define the target orbit or the target landing point on the same terrain data as the reference DEMs, the bias errors will be canceled.

When the update interval is sufficiently short, there is a possibility to estimate the explorer velocity, but which is assumed to be difficult in the near-future technology level, so it is desirable to use the other method as a radio altimeter and velocimeter to get the velocity, when the high accuracy is required in the ground speed at a low altitude in landing phase.

It is impossible to match DEMs when there are no topographic relieves, however, there is no liquid ocean on the surface of the moon and the many solid celestial bodies, and there are topographic relieves caused by craters in flat regions like "mare of moon". So it is possible to execute DEM navigation in almost every regions on the lunar and solid planetary surface.

If the powered descent is executed by continuous maneuver, image blurring caused by the vibration may occur. We must wait the quantitative judgment, however, it is desired to make descending maneuver ON/OFF control, and to take pictures when the maneuvers turn off.

![Fig.1. Concept of DEM navigation.](image1)

![Fig.2. General process flow of DEM navigation.](image2)
3. Navigation devices

3.1. Optical navigation camera

(1) Number of camera

In case of one navigation camera, there are two methods, whether or not to actively control the pitch attitude of the camera.

There occur additional costs and risks in the active attitude control method.

In case of no active attitude control, when the off-nadir angle of the camera is small, the elevation estimation accuracy gets worse because of narrow parallax on short observation interval. On the other hand, along-track-wise duplicative region in stereo pair images becomes narrow on long observation interval. When the off-nadir angle of the camera is big, the parallax becomes narrow for the observation interval, and the matching accuracy gets worse because geometric distortion in images becomes larger considering the curvature of the moon or planets. For example, in case of nadir looking camera with 30 degrees field of view and parallax is 15 degrees, along-track-wise duplication of the stereo image is the half of them. On the other hand, in order to keep the parallax 15 degrees, the camera field of view must be larger than 15 degrees.

On the other hand, in case of two navigation cameras, we can choose any parallax to obtain the highest 3D measurement accuracy. In addition, there is no need for active attitude control, we control the camera attitude only to be trained in the almost constant direction toward the center of the body.

If one camera breaks down in the two camera method, we can switch to the one camera method and achieve 1FO (one failure operable). However, in order to achieve 1FO in the one camera method, we need two cameras.

(2) Parallax of stereo pair images

When base height ratio (B/H ratio) is big, although the sensitivity of elevation errors to matching errors becomes lower, the matching accuracy becomes lower because of the geometric distortion of images caused by the topographic relieves. In addition, time intervals between stereo pair of images observing the same point of the surface becomes longer, so the relative position and attitude data accuracy becomes worse. As seen in the example of the lunar orbiter "SELENE" and earth observation satellites, it is assumed to be appropriate that the parallax of the stereo pair images is 15 to 30 degrees.

(3) Field of view

When there are small topographic relives in the images observed by the navigation camera, DEM matching accuracy becomes worse. Additionally, in order to make the duplicated region of stereo pair images larger in one camera method, it is desirable that the filed of view of the camera(s) is wide. However, we must be attentive to the lens distortion of wide angle camera.

And, it is desirable that the filed of view at the end of powered descent phase includes the horizontal movable range in the vertical descent phase.

(4) Spatial resolution

Because the surface resolution of the navigation camera is proportional to the explorer altitude, the lower explorer altitude becomes, the higher DEM matching accuracy becomes. So in the powered descent phase, it is enough that the resolution of images becomes equivalent to required navigation accuracy at the end of the phase when the explorer altitude becomes lowest. In this regard, the resolution of the source terrain data of reference DEM must be higher than required navigation accuracy.

For example, when "SELENE" Terrain Camera data of 10 meter per pixel resolution is applied to reference DEM, if the instantaneous field of view (IFOV) is 2 milliradians, the surface resolution of the image at the altitude of 5 km becomes 10 meter per pixel.

3.2. Inertial measurement unit

In DEM navigation, an IMU propagates state vectors of the explorer. In addition, the relative position and attitude of the camera between the forward-looking image and the nadir-looking image are acquired by the IMU. For example of lunar orbit, although position errors caused by IMU propagation is equivalent to the orbit determination errors (about a few kilometers) as initial navigation errors, there is no problem to execute DEM navigation. However, the relative position and attitude errors between the stereo pair images make the accuracy of onboard DEM worse, so it is desirable to minimize them.

About IMU errors (1 sigma) proposed at SELENE-B symposium, the accelerometer bias error is 60 micro-G and the gyro bias error is 0.02 degrees per hour. On this IMU, if an allowable error for the position caused by the accelerometer bias and for the reduced distance on the lunar surface caused by the gyro bias is 10 meters, the meantime to grow up to that size for the accelerometer
bias is about 180 seconds, and that for the gyro bias at the altitude of 100 kilometers is about 1000 seconds.

In this regard, we must pay attention to the contribution of the initial velocity estimation errors for position errors see 5.1(3).

3.3. Required disk capacity for reference DEM

There is no need to have terrain data of whole sphere for reference DEM, however, it is enough to have the span of down-range to execute DEM navigation and the width of cross-range corresponding to the camera field of view and various errors. In addition, if we can set the update interval of image navigation long on the basis that the accuracy of IMU or that of initial navigation values are high, there is no need to have terrain data for all span of down-range continuously, but it is enough to have only neighboring regions around points to match DEMs.

As formats of terrain data for reference DEM, it is possible to be (1) 3-dimensional coordinate system of the Cartesian coordinate or latitude-longitude-altitude, or (2) 2-dimensional coordinate system as DEMs in some kind of map coordinate. We can reduce the data volume one-third in (2) compared to that in (1), however, there is possibility that we must transform DEMs coordinate system.

Applying DEM navigation to lunar landing, by simple calculations, the required disk capacity for reference DEM varies from about 1 MB to 200MB, depending on the descending method, the region of terrain data and data record format.

4. Profile of descending trajectory

There are two ways to execute powered descent. One is that the explorer reduces its periapsis by deceleration maneuver on the orbit, after coasting from a few dozen of degrees to 180 degrees in the elongation, and then reduces its speed by continuous maneuver ("Hohman descent"). The other is that the explorer reduces its speed by continuous maneuver from its orbit directly ("direct descent"). On the former we can save the amount of propellant consumption, meanwhile, on the latter we can reduce the span of the descent sequence.

In terms of DEM navigation, Hohman descent has advantages in two points described below. Firstly, in Hohman descent, the time interval of observations between stereo pair images is shorter because of the low altitude, so the relative position and attitude errors is smaller, because the ground speed toward the lunar or planetary surface is almost same in both descending methods except the end stage of powered descent. Secondly, when descending in the same distance, the descending angle is shallow in Hohman descent because the altitude has got lower in advance, so the difference of resolution between the forward-looking image and the nadir-looking image is smaller, consequently image matching accuracy becomes higher than that of direct descent. In case of lunar landing, comparing direct descent from the altitude of 100 kilometers orbit with Hohman descent after reducing the altitude to 15 kilometers, except the almost last term of descending, the interval of stereo pair images observed is about 20 or 40 seconds in direct descent, and is less than 3 seconds in Hohman descent.

5. Analyses by using simulated images

5.1. DEM navigation at the altitude of 50 km

We added tiny topographic reliefs generated by the fractal method, and simulated craters generated by obeying the shape model and distribution model of lunar craters to the low resolution terrain data, and rendered by obeying the lunar surface reflectance model, then made simulated images of lunar surface at the explorer altitude of 50km.

The IFOV of navigation camera is 2 milliradians (i.e. surface resolution at 50 kilometers is 100 meters per pixel), the image size is 256 pixels by 256 pixels, and the image is grayscale of 8 bits per data. We set off-nadir angle of forward looking image to 15 degrees. As the MTF of the navigation camera, we added contribution of neighbor 5 pixels by 5 pixels values to each pixels.

DEMs are expressed in 100 meters per pixel of orthographic map projection coordinate, whose standard latitude and longitude are determined as the center position of nadir-looking image by initial navigation value. We applied the terrain data as rendering object of simulated image to reference DEM.

(1) Navigation performance at solar elevation 45 deg

We made a pair of stereo images of the navigation camera at the condition that solar elevation is 45 degrees and quantization scaling value is 255/0.3, and then evaluated DEM navigation performance.

The standard deviation value of elevation errors of onboard DEM is 28.3 meters, and image matching
Accuracy is about 0.07 pixels considering B/H ratio. Matching onboard DEM and reference DEM, the correlation coefficient at the zero disparity position as the correct position becomes 0.996 of very high value, and the distribution of the correlation coefficient shows good correlation having only one peak.

In Fig. 3., we show the distribution of DEM matching correlation coefficient.

![Distribution of DEM matching correlation coefficient](image)

**Fig. 3. Distribution of DEM matching correlation coefficient.**

### (2) 3D measurement accuracy in various observation conditions

Adding to the image of (1), we made the simulated images of solar elevation 15, 30, 60, 75 degrees, 15 degrees of solar elevation and 255/0.1 of quantization scaling value, and 45 degrees of solar elevation without MTF. Then we evaluated 3D measurement accuracy of each images. We show the simulated images of the navigation camera in Fig. 4. In this figure we show only nadir-looking images except for the image of solar elevation of 75 degrees. In the image of solar elevation of 75 degrees, there occurs "hot spot" by the opposition effect.

We show the standard deviation values of onboard DEM elevation error in Table 1. As seen in Table 1., the higher solar elevation becomes, the higher 3D measurement accuracy becomes except for the case of solar elevation of 75 degrees. However there is no significant difference between 45 degrees and 60 degrees. In the case of solar elevation of 75 degrees, the accuracy becomes worse because of the hot spot. And, the bigger quantization scaling value becomes, the higher 3D measurement accuracy becomes. For example in the polar region with low surface reflectance, we can get higher accuracy by increasing the gain. The higher accuracy without MTF reveals that the optical performance influences 3D measurement accuracy.

<table>
<thead>
<tr>
<th>solar elevation (deg)</th>
<th>quantization scale</th>
<th>MTF</th>
<th>pixel value range of nadir image (DN)</th>
<th>standard deviation of elevation error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>255/0.3</td>
<td>Yes</td>
<td>0 - 79</td>
<td>45.0</td>
</tr>
<tr>
<td>30</td>
<td>255/0.3</td>
<td>Yes</td>
<td>0 - 121</td>
<td>37.2</td>
</tr>
<tr>
<td>45</td>
<td>255/0.3</td>
<td>Yes</td>
<td>45 - 161</td>
<td>28.3</td>
</tr>
<tr>
<td>60</td>
<td>255/0.3</td>
<td>Yes</td>
<td>91 - 228</td>
<td>26.6</td>
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<tr>
<td>75</td>
<td>255/0.5</td>
<td>Yes</td>
<td>71 - 204</td>
<td>201.6</td>
</tr>
<tr>
<td>15</td>
<td>255/0.1</td>
<td>Yes</td>
<td>0 - 236</td>
<td>33.7</td>
</tr>
<tr>
<td>45</td>
<td>255/0.3</td>
<td>No</td>
<td>31 - 177</td>
<td>23.1</td>
</tr>
</tbody>
</table>

### (3) Monte Carlo simulation

Using the stereo pair images of (1), we executed Monte Carlo simulations by adding the position and attitude errors of camera observing the forward-looking images.

We set horizontal velocity errors of down-range direction and cross-range direction as 5 meters per second, vertical velocity errors of altitude direction as 2 meters per second, and gyro bias errors as 0.02 degrees per hour. We multiplied 3 seconds (considering Hohman descent) or 30 seconds (considering direct descent) by those errors, and we generated the Gaussian random numbers considering these products as the standard deviation of position and attitude errors, then we executes one hundred thousand cases of navigation calculations. In this regard, the accelerometer bias error is small enough in such a short duration (see 3.2), so we neglected that.

As seen in Table 2. of simulation results, in case of observation interval of 3 seconds, navigation errors are small as the standard deviation of horizontal position errors is 23 meters, and that of altitude is 53 meters. From these results, the relative position and attitude errors of the navigation camera does not matter in the point of the navigation accuracy. On the other hand, in case of observation interval of 30 seconds, the altitude error increases to 530 meters, however, the horizontal errors are less than 100 meters in both directions. It reveals the robustness of the DEM navigation in horizontal position because one image of stereo pair is nadir-looking.
(4) Processing speed and memory requirement

It takes 0.09 seconds to execute DEM navigation shown in (1)~(3) once by Intel Core2 E6700 CPU 2.66GHz (Visual C++/Windows) of 20 thousands MIPS, and 0.18 seconds by Intel Xeon 3.0GHz (GCC/Linux) of 9 thousands MIPS (except for file-reading time).

Whereas, TOSHIBA TX49/H is about 30 MIPS and HR5000 is 320 MIPS, those CPUs are used for space vehicles of JAXA, so it will take about 50 to 60 seconds by TX49/H and 5 to 6 seconds by HR5000. These duration is enough smaller than the duration that IMU propagation errors grow up to only 10 meters as shown in 3.2, so it is possible to say that DEM navigation can be executed by these CPUs.

In addition, required memory capacity for DEM navigation is about 0.7 MB, so the navigation program can be implemented in existing or near-future onboard computers.

Here, in case of the fixed field of view, the processing time and required memory capacity are inversely proportional to the square of image resolution. So that means, caused by the image resolution getting lower, the degree of navigation accuracy getting worse is smaller than that of processing time getting shorter and of memory capacity getting smaller. Then we can choose the camera resolution depending on the required navigation accuracy and the performance of navigation computer.

Table 2. Results of Monte Carlo simulations.

<table>
<thead>
<tr>
<th>&lt; time interval between stereo pair images = 3 sec &gt;</th>
<th>&lt; time interval between stereo pair images = 30 sec &gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔDR(m)</td>
<td>ΔCR(m)</td>
</tr>
<tr>
<td>avg.</td>
<td>5.7</td>
</tr>
<tr>
<td>std. dev.</td>
<td>22.7</td>
</tr>
<tr>
<td>min.</td>
<td>0.0</td>
</tr>
<tr>
<td>max.</td>
<td>100.0</td>
</tr>
</tbody>
</table>

ΔDR : navigation error toward down-range direction, ΔCR : navigation error toward cross-range direction, Δh : navigation error of altitude
5.2. **Application : Surface inclination judgment by the last motion stereo in powered descent**

We tried to judge steeply sloping area from terrain data acquired by motion stereo at the end point of powered descent.

The nadir-image and the forward-looking image are observed at the altitude of 3.5 kilometers and 4.5 kilometers respectively. Considering the use for landing obstacle judgment, we set the IFOV of the navigation camera 0.5 milliradians, and the image size 1024 pixels by 1024 pixels. Though this resolution of the camera is higher than that described in 5.1, we may scale down images when we use it for DEM navigation. We added simulated rocks obeying the distribution model\(^5\) to the terrain data. The resolution at the surface of the nadir-looking image is 1.75 meter per pixel, equivalent to the size of the lander, so it is adequate to judge steeply sloping area as landing obstacles by this image.

About the onboard DEM acquired by this simulated stereo pair of images, the average of the elevation error and the standard deviation of that are -0.2 meters and 1.0 meters respectively. And the judgment result is coincide well with that of reference DEM as the true value. We show the result of inclination judgment in Fig. 5.

![Fig.5. Result of inclination judgment](image)

6. **Conclusion**

We presented DEM matching image navigation by motion stereo as a terrain-following navigation method applied to explorers of known the moon or planets whose terrains are well known. This navigation method can be executed by existing or near-future onboard computers and has good properties in navigation performance and operability.

It is desirable to study the applicability to various terrain regions and optical conditions, and the performance with the guidance control systems.

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**References**

3) M. Hashimoto et. al. : DEM referring image navigation by motion stereo using two cameras for the lunar lander - As an application of "KAGUYA(SELENE)" Terrain Camera data -, Proceedings of the 34th remote sensing symposium, pp.47-50, 2008.