A Study of Terrain Feature Matching for Lunar Landing Navigation

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We propose a new navigation method, which is based on terrain feature matching between an image obtained by the lander camera and an image synthesized based on lunar digital elevation model (DEM) information. Our synthesized image of the Moon is precise and is obtained by using the high-resolution DEM for the lunar surface and the solar position during the landing time. This high quality synthesized image could help us achieve our aim, which is to develop a versatile precise navigation system. The local terrain pattern feature of the lunar image was employed to landmark navigation. The rendered images have 3D position information of the selenographic coordinates, so we can directly calculate the position and pose of the camera, i.e., lunar lander by computer vision geometry. The matching is based on the similarity of the feature vector and employed robust methods. In this paper the outline of our approach is explained along with some results and the accuracy of the lander position and pose estimations obtained via computer simulation are shown.

Key Words: Lunar Landing Navigation, Texture Feature Matching, Rendering Image of the Moon

1. Introduction

A precise and safe lunar lander navigation during orbit and descent has been studied for future lunar landing projects. High definition images of the lunar surface and terrain elevation information obtained by recent lunar orbiters, the SELENE and the Lunar Reconnaissance Orbiter (LRO), are efficiently used for assessing lunar landing site selection. In order to pinpoint the target site, which is scientifically determined, the position and direction of the orbiting or landing lander are essential. Conventional lander position estimation methods, such as the one based on an inertial induction device, produce estimation errors of about several km. Hence, to achieve precise landing with an error margin within 100 m, more accurate position estimation methods are necessary. Terrain relative navigation (TRN), in which the landmark feature points of the obtained images are search with the corresponding features of the terrain map information, is considered to be effective for precise position estimation. In recent years, there have been many related studies dedicated to this method 1) 2) 3).

Some terrain navigation approaches, based on the images obtained by the imaging sensor onboard the lander, have been proposed. In crater matching navigation, the craters detected from images are cross-checked from the crater list along with its distribution pattern. In another approach, the obtained image is directly matched with the predicted CG images. We proposed a new terrain feature matching navigation; in this method, the image texture intensity features, such as SIFT, SURF or KAZE, of the obtained images and the prepared CG images are matching ques. The high resolution digital elevation model (DEM) can be used to create highly detailed CG images of the landing site. Due to these high-quality CG images, we can achieve our aim of a versatile precise navigation system. To be more specific, the image shading features of the onboard-image and CG-image are regarded as landmarks on the lunar surface. Then, the landmarks are matched with each other. Our terrain feature matching navigation can be applied even under unfavorable conditions, such as non-crater region and very low sun altitude, i.e., polar regions and during early morning and late evening time.

In this paper, we describe an outline of our terrain feature matching navigation and present some experimental results.

2. Outline of Terrain Feature Matching

In this section, an overview of our proposed method is discussed. This method consists of two phases; a preprocessing phase and an on-the-fly phase. Figure 1 shows the flowchart of our method. The preprocessing phase for rendering CG-images requires information about the 3-D terrain elevation, lander position and direction, camera parameters, and the solar position. The textural features, such as SIFT, SURF, or KAZE, are extracted from the CG-images. These features are stored as the landmarks for a reference navigation map with a feature vector and its 3-D position of lunar coordinate system. The on-the-fly phase is when the lander is orbiting and descending to the landing point. During the on-the-fly phase phase, when the lander is orbiting and descending to the landing point, the terrain features are first extracted from the image obtained by the onboard camera. Then, the features that best match the features of the on-the-fly phase are obtained from the reference map.

Finally, the position and direction of the lander is calculated from the features of the reference map. Because the features retain their 3-D positional information, the position and direction of the lander, i.e., onboard camera, can be geometrically calculated by the standard camera calibration technique 4).

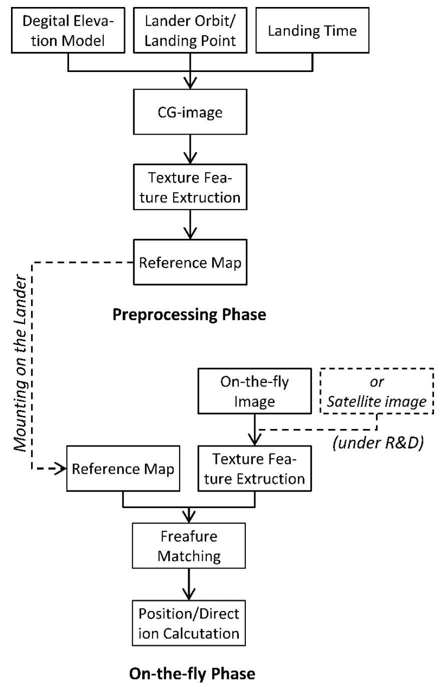


Figure 1: Flowchart of Terrain Feature Matching for Lunar Landing Navigation

2.1. High quality Lunar Surface CG-image

High resolution 3D DEM images for the lunar surface observed by SELENE and LRO is used for our study. The exact position of the Moon and the Sun for a specific time in the future can be calculated by the universal orbital database. Once the landing point is determined, it is possible to simulate the orbital and descending trajectory from the assumed specifications of the lander. We can create CG-images because we have all the relevant information; 3D models (Lunar DEM), illumination (solar position), and camera information (lander camera specifications and position and direction on its orbit).

These CG-images based on assumed information have geometric and photometric differences from actual images, which are obtained by the onboard camera during orbiting and descent. The geometric difference is caused due to an estimation error in the camera position and direction, and the photometric difference is caused due to the omission of lunar surface reflection model. These differences do not cause mismatching, since textural features are independent of these.

The geometric difference is similar to disparities of stereo vision, and it becomes the source of distance information. In the photometric difference, the DEM does not have a surface reflection model and very detailed 3D information. Hence, the CG-image does not have the high-frequency component. In our SIFT-features matching, the low frequency component of the image is used for matching ques. In addition, our proposed method can verify the certainty of the CG-images by using multiple orbital images obtained in the past missions. These orbital images are accompanied by supplementary information, i.e., time, position (latitude, longitude, altitude) and direction, camera specifications and etc.

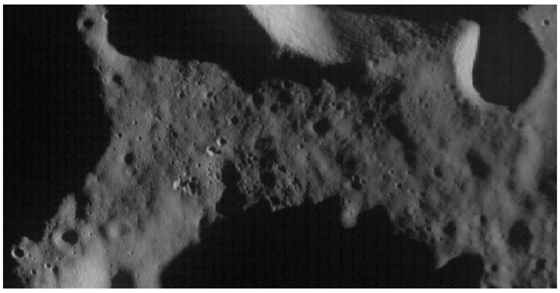
(a) On-the-fly image (satellite image) (b) CG-image

Figure 2: The On-the-fly Image and the CG-image

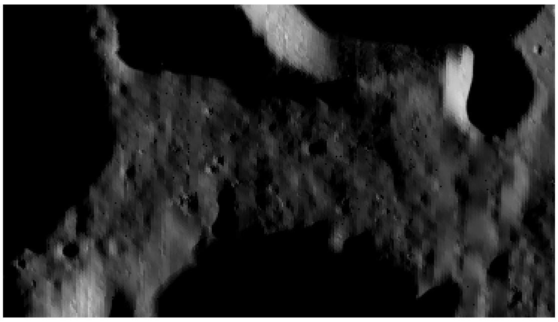
The actual image and the CG-image are shown in Figure 2. The actual image (Figure 2(a)) is taken by LOR-Camera Wide Angle Camera (LROC-WAC) at 0-degree longitude and 60-degrees south latitude in December 2012. The product ID of this orbital image is “60S0E 2009/12/24 12:43:53 m116297807me” 5). The CG image (Figure 2(b)) is obtained from the DEM of LOR Lunar Orbiter Laser Altimeter (LOLA) with a resolution of 400 meters per pixel. The solar and lunar positions are calculated based on the taken time. The camera position and vertical and horizontal field of view of the CG-image are set in order to fit the actual image. Tow images, the actual image and CG-image have differences, the geometric distortions caused by different camera positions and directions (and the camera model) and the surface details. The CG-camera model is the pinhole camera model. The actual image camera on the lander should be the pinhole camera model too. The actual image of the orbital artificial satellite is obtained from a line scanning camera model. This difference is less affected by the verification experiments in this study.

Figure 3 shows an example of the surface details differences. Figure 3 represents magnified views of the upper-right part of Figure 2. Figure 3 (b) does not include details of terrain, such as small craters and small rocks, because these small surface objects are not included in the

DEM information. However, in the matching phase of our navigation, the lack of detail is not a significant, because our method evaluates using textural features, and is not dependent on the high- frequency component.



(a) On-the-fly image (satellite image)



(b) CG-image

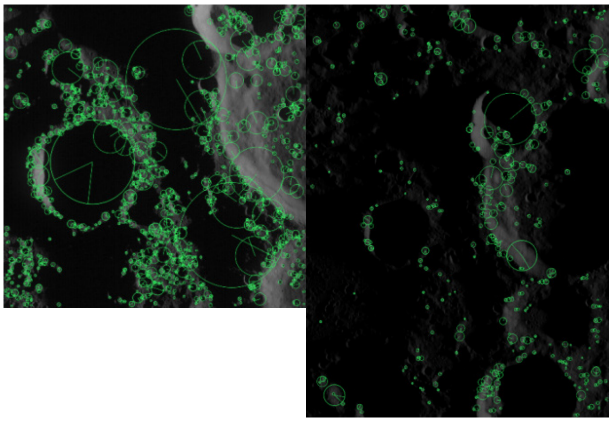
Figure 3: Magnified View

2.2. Texture Feature Matching and Position/Direction Estimation

First, the feature extraction of the on-the-fly actual image and the CG image are described. The CG-image have no detail of the lunar surface and geometric distortion. Considering that the CG-image have no detail and the geometric differences from the actual image, it is reasonable to adopt the texture feature, i.e. SIFT, SURF, KAZE and etc., as the matching ques. In this paper, we employee the SIFT-feature (Scale Invariant Feature Transform), which is very common texture feature in the computer vision area.

The results of feature extraction are shown in Figure 4. Figure 4 (a) is cut out the center of Figure 2 (a) (LORC-WAC) as the on-the-fly image into squares. The green circles indicate the extructed SIFT features points. The size of the circle shows the range to gather for partial features. The straight line in the circle indicates the direction of the features. The circles and directions are normalized the local area, that means the scale and rotation invariants are functioning each place.

Figure 4 (b) is cut out the center of Figure 3 (b) (CG-image) as the reference map. The reason why the cut-out area is slightly larger than Figure 4 (a) is that it is assumed that the searching area of the reference map (CG-image) is cut out from the GNC information. Similarly, the SIFT features are extracted and shown in green.



(a) On-the-fly image (satellite image) (b) CG-image

Figure 4: Extracting Local Terrain Textures

Next, the feature matching and the position/direction of the camera (= the lander) is explained below. Here the conventional method was adopted for feature matching. For each the SIFT feature vector of the on-the-fly image, the nearest vector is searched for the reference map (CG-image feature vector list), then these feature points with closest vector made a corresponding pair. The white line in Figure 5 indicates a corresponding pair, which means best similar feature vector pair. The green points with or without white line on images are the texture feature points. After the matching, some corresponding pairs are extracted. Parallel white line groups extending from top-left to low-right are correct corresponding pairs. You know that there are many incorrect matching pairs in Figure 5.

Using these pair, the correct pairs are selected by the planer fitting algorithm based on the homography estimated by the RANSAC (RANdom Sample Consensus) method. The green frame on right of Figure 5 is matched planer area. Figure 6 shows the distorted on-the-fly image on the CG-image.

Through a series of experiments in this section, we confirmed that the on-the-fly images and the CG image can be matched using the texture features. If the camera parameter has known, the position and direction of the camera (= the lander) can be calculated from the homography matrix. Strictly speaking, in this case, we cannot calculate the positon and direction of camera, because the orbital image as the on-the-fly image is not pinhole camera but line scan image.

In above this example, the planer fitting is employed for texture features matching. The altitude of camera of two images is very high, so the projected object, i.e. the lunar surface, can be could be approximated to a plane. If lander altitude was lower, the 8-points algorithm should be employed for feature matching and camera's positon and direction estimation. And the SLAM (Simultaneous Localization and Mapping) or SfM (Structure form Motion) technologies are very well studied and stable, therefore these methods is also effective. The bundle adjustment by nonlinear optimization is very effective for parameter estimation.

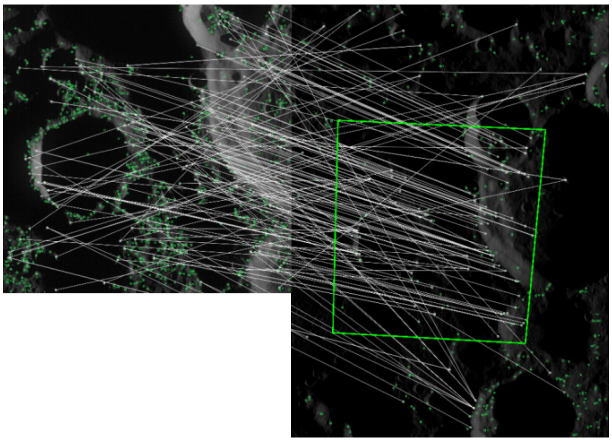


Figure 5: Matching Terrain Features of Figure 4.

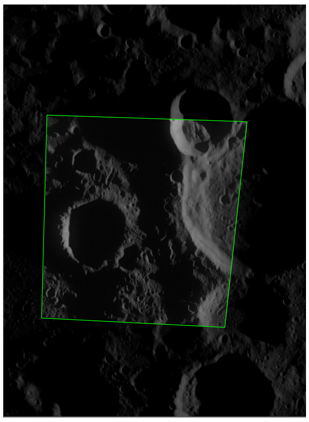


Figure 6: Overlapped Deformed On-the-fly Image on the CG-image

3. Simulation of Lander Position/Direction Estimation

In this section, assuming that the feature matching was successful, the positon and direction the lander was estimated by computer simulation. The sequential position and direction of the lander on a sample landing orbit, from the south latitude 50 degrees to the south pole along the latitude 0 degree, was calculated by our lunar landing simulator. Figure 7 shows the lander altitude from the average radius of the moon and its direction with respect to vertical direction. This landing distance is about 1,200 km and landing time takes about 22 minutes.

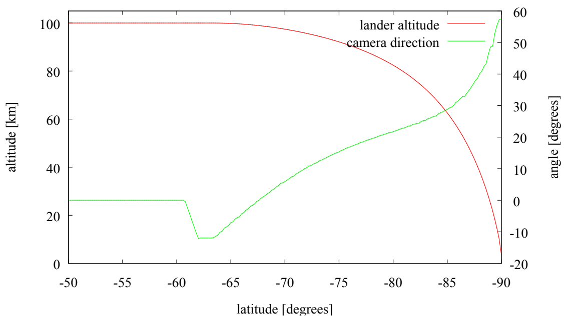
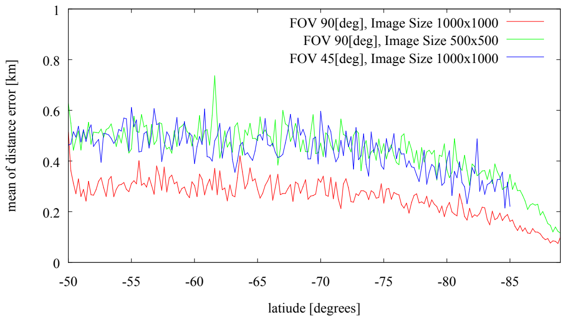
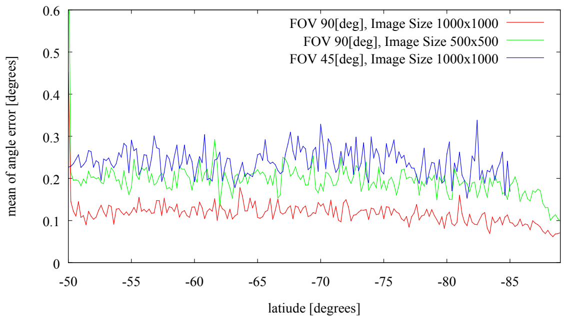


Figure 7: Lander Altitudes and Lander Directions

For each sample point, 30 feature points are randomly picked up from SIFT-key points of the CG-images, which are rendered by simulated lander orbital information. Every feature position is added Gaussian error with standard deviation 1.5 pixels. The average of the estimated position and direction is obtained from 30 trials. The position error is the distance between correct and average position, and the direction error is the angle of correct and average direction. The results of three different cases, (I) FOV (Field of View): 90 degrees & image size: 1000x1000 pixels, (ii) FOV: 90 & image size: 500x500, (iii) FOV: 45 & image size: 1000x1000, are shown in the Figure 8. The larger the image size and the wider FOV, the better results are estimated.



(a) Estimated Position Error



(b) Estimated Direction Error

Figure 8: Lander Position and Direction Simulated Results

4. Conclusions

The outline of our terrain feature matching navigation method is described along with some experimental results in this paper. This method consists of two phases; a preprocessing phase and an on-the-fly phase. In the preprocessing phase, the CG-images are created, and then the reference map are registrated the textural-feature vector with its 3D-information of the lunar coordinates. Next, during the on-the-fly phase, the terrain features of the on-the-fly images are matched to a reference map, and then the position and direction of the lander are calculated. Our method can be used under various conditions, such as in non-crater regions, in polar regions, which have very low solar altitudes, and during the early morning and late evening.

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