Hybrid Method for Detection of Lunar Craters Based on Topography Reconstruction from Optical Images

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Abstract — Many applications in lunar and planetary science require robust crater detection algorithms (CDAs). In this paper, we present a novel hybrid CDA which utilizes the topography reconstructed from optical images and our previously developed topography-based CDA. The proposed CDA is applied to two Chandrayaan-1 M 3 optical images and one selected region of Lunar Reconnaissance Orbiter WAC global optical image mosaic. The overall approach consists of: (1) reconstruction of topography from optical images; (2) corrections of brightness and contrast of used optical images (this step is required for manual verification of crater-candidates before inclusion into the resulting catalogue); and (3) processing by topography-based CDA. In addition, the integrated topography-based CDA has been used for the review of the initial topography reconstruction algorithm, and consecutive improvements. With such an approach, we demonstrate that our topography-based CDA, additionally improved using new crater shape-based interpolation method, can be used: (1) with topography refined from optical images; and (2) during subsequent improvements of the topography reconstruction algorithm. Experimental evaluation of the proposed CDA is done by manual verification of crater-candidates and registration in the previous LU60645GT catalogue. The evaluation has shown that the proposed CDA was used successfully for cataloguing of 3570 Lunar craters, which are almost all visible craters from the three selected regions. The accompanying result is the new LU64215GT catalogue of 64 215 Lunar craters, which is currently the most complete catalogue of Lunar craters.

I. INTRODUCTION

With each new lunar and planetary mission, the volume of acquired data increases significantly [1]. The expectations that crater detection algorithms (CDAs) will play an important role in methods of processing and interpreting large amounts of data are justified by the fact that impact craters belong to the most intensely studied geological features.

An overview of 112 CDA-related publications from numerous authors is given in two recent papers [2][3]. From these publications, it can be concluded that almost all CDAs are based on either digital elevation maps (DEMs) (e.g. [4], [5], and [6]) or optical images (e.g. [7], [8], [9], and [10]). The possibility of using DEM-based (topography-based) CDA for optical images has been proposed in [11], but is still in an early stage of development. The recently released Chandrayaan-1 Moon Mineralogy Mapper (M 3 ) dataset and Lunar Orbiter Laser Altimeter (LOLA) data, as well as the Lunar Reconnaissance Orbiter (LRO) Wide Angle Camera (WAC) global image mosaic, are an opportunity for the construction of a DEM of high lateral resolution. The basic principle is the reconstruction of height and gradient from shading [12], where in the subsequent step the refined DEM can be used by a DEM-based CDA with the purpose of cataloguing of craters.

During the work on the largest publicly available catalogue of Martian craters MA130301GT [3], among others we: (1) used the previously developed DEM-based CDA [6]; (2) developed an advanced algorithm for matching craters between different catalogues; (3) developed an semiautomatic methodology for evaluation of crater-candidates and registration in the ground-truth (GT) catalogue; and (4) developed an algorithm for brightness and contrast corrections of global image mosaics. A new crater shape-based interpolation method has been additionally developed in the meantime, which considerably improves the existing DEM-based CDA [6] regarding the detection of very small craters [13]. The results of the application of this new interpolation-based CDA are [14]: (1) even more complete MA132843GT catalogue of Martian craters; (2) the first CDA that demonstrated processing of global Lunar DEM; (3) the most complete catalogue LU60645GT of Lunar craters; and (4) the method for re-projection of the used datasets and crater coordinates. The interpolation-based CDA can be either Canny based, as in [6], or Shen-Castan based, as in [3]. The objective of this work is the reconstruction of topography from optical images and cataloguing of Lunar craters using the above CDAs and related research. The initial results in this direction have been reported recently [15][16]. In this work, a considerably improved overall methodology will be presented, wherein we further improved the method for DEM construction. The new hybrid CDA was applied to two selected regions of the Chandrayaan-1 M 3 dataset and one region of the LRO WAC global image mosaic. The accompanying result is the new LU64215GT catalogue.

II. METHODS AND DATASETS

The schematic flow diagram of the new hybrid CDA, shown in Fig. 1 (left), wherein generation of tiles for selected optical images defines the placement into the global dataset for
each image, includes: (1) reconstruction of topography for each image and import of the constructed DEM into the global DEM dataset; (2) brightness and contrast corrections of each image and import of the fixed optical image into the global image mosaic; and (3) utilization of the constructed global DEM dataset with the previously developed DEM-based CDA [6][13][14]. The constructed global image mosaic is utilized during manual verification and registration of craters in the GT catalogue. The new hybrid CDA, individual steps of the overall approach and used datasets are described in more detail in the following subsections.

A. Hybrid Crater Detection Algorithm

1) Topography Reconstruction

a) General Approach

The image-based DEM construction is an extension to the shape from shading (SIS) approach by Horn [12]. The original error functional is extended to incorporate an existing low-resolution DEM by adding a term describing the deviation of the low-frequency component of the constructed DEM from the low-frequency component of the restricting DEM as explained in [15] and [17]. The new error term is globally convex and acts as a pulling force towards the restricting DEM to ensure convergence. We found that the SIS approach underestimates slopes and therefore crater depths when initialized with a flat surface. To overcome this problem, a single-image photoinclination (PHCL) approach and Horn's scheme to recover height from a gradient field [12] are used in [15] as an initialization to the DEM construction algorithm. To solve the ill-posed problem, the component of the initial surface gradient perpendicular to the direction of incident light is set to zero because it has only minor influence on the reflectance for oblique illumination. The resulting DEM shows overestimated slopes on sunlit crater rims, which has a negative effect on crater detection. Therefore, we will show in this study that it is advantageous to omit the PHCL step and initialize the algorithm with the 1/512° LOLA DEM, as for the purpose of crater detection the circularity of craters is more important than the actual depths.

b) Reflectance Models

The most important choice for the surface reconstruction algorithm is the choice of the reflectance model. For our
approach we use two different models: the Lunar-Lambert model and Hapke's model with isotropic multiple scattering approximation (IMSA). The Lunar Lambert model is a weighted sum of a Lambertian reflectance term and the Lommel-Seeliger term. The weight is based on the angle between the sun position vector and the camera position vector. The parameters that have been determined by [18] as least squares fit to Hapke's model are used within this study.

The IMSA model is a physical model derived by Hapke [19]. It takes into account physical properties of the surface and therefore has more parameters than the simpler Lunar-Lambert model and is computationally more intense. It is more accurate if exact knowledge of the illumination geometry can be assumed. The parameters of the IMSA model for the lunar surface are adopted from [20].

The hyperspectral M³ dataset (see II.C.2) contains pixel-specific values for the illumination direction and the viewing direction. This allows the usage of the accurate IMSA model. The WAC global mosaic (see II.C.3) carries no accurate information about the pixelwise illumination conditions. Therefore the simple Lunar-Lambert model is used because it is robust against parameter uncertainties. The resulting DEM is not highly accurate and there are artifacts due to deviations from the assumed illumination geometry, but this is of minor relevance for the purpose of crater detection.

2) Corrections of Brightness and Contrast

Global image mosaics are not uniform in brightness, wherein some parts of the image are very bright while others are very dark. This is one of the major problems of the existing methods for brightness-contrast corrections. These methods usually compute optimized parameters for the overall image, which causes the problem that the brightest parts are still too bright while the darkest parts are still too dark after processing. On the contrary, our method computes the optimal parameters for a moving window, ensuring: (1) localization of optimal parameters for the method; (2) smooth change of these parameters and the result of processing.

3) DEM-Based Crater Detection Algorithm

The DEM-based CDA from the previous work [6] utilizes fuzzy Canny/Shen-Castan edge detection, followed by fuzzy Radon-Hough transform and extraction of numerous features including depth-diameter ratio, central peak volume, rim volume, and crater circularity in topography and parameter-space. The interpolation-based CDA used in this work is based on the previously described CDA, and in addition relies on a specially developed crater shape-based interpolation method [13][14]. This interpolation method considerably improves the previous CDA regarding the detection of very small craters.

B. Evaluation, Review and Iterative Improvements

1) Manual Evaluation of Crater-Candidates

After the CDA processed the refined DEM and proposed the crater-candidates, the following procedure is performed: (1) automated verification using GT catalogue available in this step, in order to extract the craters that are not in the GT catalogued yet; (2) manual evaluation of the remaining crater candidates in order to decide which ones are correct detections and need to be added to the GT. In the case when a crater-candidate is a correct detection, coordinates and diameter are corrected where required before inclusion into GT catalogue.

2) Review of Topography Reconstruction Algorithm

Whenever in the used optical image some clearly shown crater is detected by the CDA from the refined DEM with low assigned probability, it is a good candidate for the manual review of how the topography reconstruction algorithm works in such a case. The purpose is to outline inaccuracies in order to improve the reconstruction algorithm. A selected region of the refined DEM can be exported as a CSV file and imported in various applications for analysis, e.g. Excel. Once the DEM has been constructed using the improved DEM construction algorithm, the whole procedure can be repeated as long as no satisfying results are obtained.

C. Used Dataset

1) LRO Lunar Orbiter Laser Altimeter Dataset

The LOLA instrument on board the LRO provides time-of-flight measurements and therefore yields the accurate topography of the Moon. Due to the principle of laser altimetry, only single points are measured and the global mosaic is interpolated in-between. The resolution of the released 1/512° global mosaic is about 60 m per pixel but the lateral resolution seems to be drastically lower.

2) Chandrayaan-1M³ Dataset

The Chandrayaan-1 Moon Mineralogy Mapper (M³) is a hyperspectral pushbroom camera providing 85 pixel-synchronous channels with center wavelengths between 461 nm and 2976 nm and widths of about 12 nm. In order to reconstruct the surface, the channels with center wavelengths beyond 2000 nm are ignored to avoid thermal radiance. The released datasets are accompanied by pixel-synchronous sun and camera position data. Therefore the M³ dataset is an ideal dataset for the construction of DEMs with high lateral resolution.

3) LRO Wide Angle Camera Dataset

Recently the global WAC dataset from the LRO has been released. It features a lateral resolution of 100 m per pixel. Therefore it offers the possibility of creating DEMs with high lateral resolution and a decrease of the size of detectable craters was expected. However, the global mosaic offers only approximate knowledge about the illumination and viewing direction. In order to construct a DEM of the surface we assumed the camera looking straight down on the surface. The illumination angle on the equator was set to the center of the corresponding specified interval. The equatorial illumination vector is rotated to match the corresponding latitude of the image. Wherever this assumption is not valid, it will create artifacts which mainly consist of over- and underestimation of slopes. Therefore the resulting DEM is not highly accurate but on the other hand absolute accuracy on crater depths is not important for crater detection. The large region extracted from the WAC dataset is divided into overlapping tiles of 1500 by 1500 pixels size. The final DEM is assembled from the individual tiles, using weighted sums in the overlapping areas.
Figure 2. Analysis of the DEM construction using the algorithm with initial PHCL (top-left); results of the algorithm for DEM construction without initial PHCL (top-right); previously catalogued craters (bottom-left); and newly catalogued craters (yellow) which cannot be detected with the algorithm with initial PHCL (bottom-right).
III. RESULTS

The processed output of our CDA for the DEM obtained using the initial algorithm is shown in Fig. 2 (bottom-left). There are numerous craters that can be detected and cataloged using the 1/512° DEM constructed from the Chandrayaan-1 M³ optical image and that cannot be detected using 1/512° LOLA data. The particular advantage of the refined DEM is in the areas where LOLA data are still not available, and where the elevation values are therefore interpolated. These areas are apparent on the LOLA shaded relief maps as vertical smooth tracks with missing measurements.

The analysis of the DEM construction is shown in Fig. 2 (top). According to the previously catalogued craters and the newly catalogued craters which cannot be detected with the initial algorithm, as shown in Fig. 2 (bottom-right), the improved algorithm provides much better results than the initial one. In both cases (the initial and the improved DEM construction algorithms) we analyzed crater-candidates only down to the same assigned probability threshold (0.12) in order to make the results comparable.

Eventually, as shown in Fig. 3, using the new DEM construction algorithm we processed the optical images for three regions (x₁ and x₂ are longitudes, y₁ and y₂ are latitudes of the corners, in the east/planetocentric coordinate system): (1) x₁=1.64, y₁=-23, x₂=3.06, and y₂=-27 (Chandrayaan-1 M³ region 1) (2) x₁=-2.399414, y₁=-4.200195, x₂=-1.698242, and y₂=-44.202148 (Chandrayaan-1 M³ region 2), and (3) x₁=0.000977, y₁=3.50293, x₂=45.506836, and y₂=-0.506836 (LRO WAC region 3).

The accompanying result to the new hybrid CDA is the new LU64215GT catalogue. Main phases of the work on this new catalogue of Lunar craters are shown in Fig. 4. In comparison with the previous LU60645GT catalogue, the result is considerably larger number of the craters within the selected
regions. This confirmed the practical applicability of the hybrid CDA approach.

IV. CONCLUSION

In this work, a DEM-based CDA has been used for systematic cataloguing of craters from topography reconstructed from optical images. This is an important contribution to the field of CDA-related research, because optical images cover most of the lunar and planetary bodies in considerably larger special resolution and quality than existing DEMs. As shown, the proposed hybrid CDA has been tested successfully. In addition, the initial version of the topography reconstruction algorithm has been improved, which has resulted in even better crater detection characteristics. In addition to the first Chandrayaan-1 M3 region used in the initial research, the overall approach has been demonstrated for the second, considerably larger Chandrayaan-1 M3 region and a third, also considerably larger, LRO WAC region. Processing of the LRO WAC region has been an additional challenge, because this is not an individual image like in the two Chandrayaan-1 M3 examples but a mosaic composed of multiple individual images. Despite these difficulties, the overall approach is successful in this case as well. Ongoing work involves the reconstruction of larger parts of the lunar surface covered by the M3 dataset and the LRO WAC global optical image mosaic. Future crater detection activities will additionally be based on DEMs of even higher resolution obtained from other spacecraft images.

REFERENCES