An Automatic Detection Algorithm for Small Craters Based on Morphology

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Abstract. Study of impact craters on planetary surfaces has revealed secrets of the evolution of planets. Identifying craters on planetary surfaces has become fundamental in planetary researches, whereas time-consuming, e.g. months to years to collect crater database. Small craters, including a large number of secondary craters, have shown its importance in researches of planetary sciences, whose database requires construction. Whereas, few studies concentrate on detection of small craters. In this paper, the writer adopts morphology-based algorithm to detect and localize the crater candidates effectively. The methodology has shown its effectiveness by detecting 869 small crater candidates in a region covering 37500 × 56250 m² on the Martian surface, with a precision of 79.29 %. Among those true positive detections, 91.25 % are craters with a diameter less than 1 km (not included). Compared with existing automatic detection methods on planetary impact craters, the method proposed in this paper performs better on detection of small craters, and it fills the blank of detection of craters with a diameter less than 200 m. Focusing on detection of small craters, it can provide a tool for quickly generating datasets for planetary scientific research in a targeted manner.

1. Introduction
Preliminary studies have shown that impact craters can be important in revealing the secrets of planets and planetary satellites. Planetary craters can be roughly divided into several types by diameters: super large (more than 2000 km), giant (1000–2000 km), large (200–1000 km), medium (60–200 km), small (10–60 km) and very small craters (less than 10 km) [1]. In order to make the expression concise, in this paper, we generalize craters with a diameter less than 60 km collectively, as small craters.
Few methods of automatic detection of small craters are proposed, versus a series of automatic detection on larger craters. In consequence of the vast number, the want of automatic detection on numerous small craters comes into being [2] [3]. Compared with small craters, larger craters are not only in a much smaller number, but can also be detected by human vision without serious scrutiny and can be easily indexed manually. A small crater with diameter of 200 m in the HRSC image, with resolution 12.5 MPP [4] [5], will only occupy 16 pixels. The small image size of a small crater could be a disadvantage in detection, whereas unavoidable, since the size of a small crater itself is limited, and the resolution is limited by the instruments and orbits of satellites that are designed in planetary exploration missions, although we try to get the remote sensing images with best resolution. The difficulties in detecting small craters may lead to the lack of automatic detection methods.
There are craters with very small diameters on the planetary surfaces. A significant composition of these craters are secondary craters. Secondary craters, which are impact craters created by ejecta thrown out...
from a larger crater (primary crater), have a diameter less than 5% of its parent primary crater \[6\] \[7\] \[8\]. For example, a primary crater with a diameter of 4 km will produce oceans of secondary craters with a maximum diameter of 200 m. Secondary craters are important in the researches of planetary sciences. In the study of the mixing of lunar regolith, Costello et al. (2018) regard the inclusion of secondary craters in their research as a most important update \[8\]. In order to generate the reworking rate in Apollo cores, the secondary craters are necessarily included in analysis \[9\]. However, in very small diameters, numerous secondary craters are rather tough to be detected automatically.

To identify impact craters scientifically, the criteria for identifying an impact crater, especially separating it from volcanic origins include: ejecta blankets, rayed ejecta pattern, elevated rims, depth-diameter ratios; large energy required for excavation process; production of breccia, shock-metamorphosed material and impact-melted glasses \[10\]. Principle crater features in remote sensing images of the target planet should be taken into account, e.g. solar elevation and illumination behavior. Interferences encountered when identifying craters include similar geographical features (e.g. small volcanic constructs or valleys), the overlap of craters and multi-ring structures, and erosion of crater rims that may eliminate disk shape of craters.

Presently in the research field of Planetary Sciences, small craters on the planetary surfaces are indexed by human labor with the assistance of computer tools, consuming months to years to collect data (typically the centroid and radium) of millions of craters. For example, with the assistance of a popular computer tool, \textit{ArcGIS}, it requires three steps to collect the information of a single crater. The steps are shown in Figure 1: (a) detect a crater by human eyes; (b) index three points on the circumference of the crater rim; (c) the computer will generalize the location information, \((x, y)\) in the coordinate, as well as the radium of the circle that fits the crater rim.

![Figure 1. Collect information for a single crater manually](image)

There exists several but limited works focus on the detection of small craters. Series of works aim at detection of craters with a diameter between 200 m and 5 km, based on shape and Haar-like texture features, are proposed by Bandeira et al. \[5\] \[11\] \[12\]. In their latest experiment, 1563 out of 1937 craters in a diameter between 200 m and 5 km as ground truth in the target research area are detected, with a precision of 85.1 % (Figure 6). However, this methodology is only effective to craters larger than 200 m, which leaves the detection methods of craters in a diameter less than 200 m still blank. A recent study of detection of small craters in the charge-coupled device (CCD) images of the Chang’E Lunar Orbiters is reported to detect crater with a diameter less than 200 m, and the smallest diameter of the detected crater is 20 m, applying a coarse-to-fine strategy \[13\]. In a \(2793 \times 2841\) (pixel \times pixel) Chang’E-2 CCD image with a resolution of 1.4 MPP, 232 out of 276 craters are detected, with a precision of 84.06 %, among which 96.12 % have a diameter less than 230 m. Note that lunar remote sensing images generally has a higher resolution and fidelity compared to other planetary images, due to the equipment capturing those images, which should be taken into consideration. For other planetary craters, there are few automatic detection methods of craters with a diameter less than 200 m.

This work, aimed at developing a practical tool for automatic small crater labelling and recording, under the consideration of practical needs in researches in the field of planetary sciences, reduces the labor and cost of time of manual visual analysis and interpretation. The algorithm steps are shown in Figure 2. The experiments will be conduct on Martian craters remote sensing images, whose image features are in accord with most of the planetary surfaces images captured by satellites in recent years.
Figure 2. Main algorithm steps for detection of small craters

2. Removal of Unselected Features

2.1. Removal of Noises and Small Background Features

With MATLAB, the method of morphology in image processing is used to denoise the image background, and to clear the small background features that can be generally ignored by human vision, e.g. tiny rocks. By comparing different methods of denoising, the results show that the method of morphological reconstruction (based on disk structure) has the highest performance, as shown in Figure 3: (a) original image; (b) result after opening and closing operation; (c) result of morphological reconstruction and a series of image processing process; (d) the noises and small background features which are eliminated. The disk structure element for method of morphology in image processing is in harmony with the disk shape of the craters. It can be seen that for the methods based on morphological reconstruction, the rim structure of the crater is preserved well, the highlight and shadow crescent-like features caused by solar height angle are obviously preserved, and the noises and small background features are effectively eliminated.

Figure 3. Removal of noises and small background features

2.2. Removal of Large Background Features

Applying frequency filters in the frequency domain, using FFT to convert; we can select effectively the highlight and shadow pairs, which will be described in detail in section 3. However, before the combination of highlight and shadow pairs, and reconstruction of disk-like crater features, we should remove clearly the large background features, which could have negative impact on the detection of crater candidates.

The result of connectivity domain process without large background removal is shown in Figure 4. Comparing with the initial image and the crater positions, the precision can be predicted, which is expected to be low. Therefore, removal of large background is very important. In this work, the large background features are eliminated by processing of connectivity domain. By setting the limitation on eccentricity and solidity, to select the crescent-like shapes only, the large background features are declined effectively, as shown in Figure 5: (a) highlight region; (b) shadow region.
3. Crescent-like Highlight and Shadow Regions
Solar elevation angle is also called solar zenith angle, which is the angle between the horizon and the center of the Sun's disc, when the sight of light is not perpendicular to the horizon [14]. In most of Martian data, including HRSC data, the craters have highlight and shadow regions caused by this angle. After removal of large background features, converting the processed images (highlight region and shadow region) to binary image, the resultant images show clear crescent-like features (Figure 5). The shadow image is originated from the complement of original hyperspectral image after removal of noises and small background features.

4. Detection of Crater Candidates
4.1. Reconstruction of Disk-like Crater Features
Combine the highlight and shadow pairs to reconstruct crater disk-like features, with the assistant of open and close processes. The definition of open and close is shown in equation (1) and equation (2), where $f$ is the input image, $b$ is the structure element, $\circ$ indicates the operation of dilation, and $\oplus$ is the operation of erosion:

$$f \ast b = (f \circ b) \oplus b$$  \hspace{1cm} (1) \\
$$f \ast b = (f \oplus b) \circ b$$  \hspace{1cm} (2)

The open operation is a combination of erosion and dilation, which can be used to eliminate small objects; while the close operation firstly dilate and then erode the input image, which is efficient at excluding small black holes. The combination of open operations and close operations can improve the reconstruction of the disk shape of craters. The definition of dilation and erosion is listed in equation (3)
and equation (4), where \( f(x, y) \) is the input image, \( b(x, y) \) is the structure element, calculating the value of pixel at \((s, t)\), \( D_f \) and \( D_b \) indicate the domain of \( f \) and \( b \) respectively:

\[
(f \oplus b)(s, t) = \max \{ f(s - x, t - y) + b(x, y) \mid (s - x, t - y) \in D_f, (x, y) \in D_b \} \tag{3}
\]

\[
(f \circ b)(s, t) = \min \{ f(s + x, t + y) + b(x, y) \mid (s + x, t + y) \in D_f, (x, y) \in D_b \} \tag{4}
\]

The centroid and area of the disk connectivity domain are collected. The feature indexes of connectivity domains out of the defined interval for disk-like features are screened out.

4.2. Detection of Crater Candidates

According to the position and area of ROI recorded in a Matlab “struct”, the detected craters are circled in red, as shown Figure 6.

![Figure 6. Crater candidates detected on target research hyperspectral image](image)

The result shows that Martian craters are automatically detected effectively. To analyse the performance in detail, the smallest crater detected is in diameter of 100 m. Accordingly, the majority of \( FN \) (non-detection of real craters) are craters with diameter less than 100 m, and complex craters (more than one craters that are connected or included in larger craters). \( FP \) (detected craters that are not) concentrate at the edge of the middle part of the picture. This curved landform is a suspected lava channel terrain. The remained background features, which are not eliminated in former steps, may lead to these false detections. No significant improvement was found after adjusting the parameters and attempts of other methods, including median filter, watered, K-means clustering and Harr wavelet.

5. Performance Evaluation

5.1. Target Research Hyperspectral Image and Region of Interest

Performance of the detection algorithm is evaluated on a remote sensing hyperspectral image caught by High Resolution Stereo Camera (HRSC), with CCD arrays. The image could be download from NASA’s open resource of planetary images: PDS Geoscience Node. The target area is contained in the nadir panchromatic image \( h0905 \) under the HRSC category, with the size of 3000 by 4500 pixels. With the assistance of software Envi, which is designed for processing remote sensing images, the area for testing is selected and derived as shown in Figure 6, with resolution of 12.5 MPP, covering \( 37500 \times 56250 \text{ m}^2 \) on the Martian surface, containing massive, linear and other normal background features on the Martian surface, with certain mechanical and atmospheric noise.

There are 3050 craters in diameter between 40 m to 6600 m in total in the above target research hyperspectral image manually indexed [5] [11] [12], which provides a reliable instruction of the craters location, being assisted with the definition [1] and characteristics [10] of craters. Among the 3050 craters, 1937 craters are in a diameter between 200 m to 5 km. Therefore, the number of craters in a diameter less than 200 m should be no more than 1113, which require careful scrutiny to be detected by human
vision. The ROI of this work are small craters defined in section 1, with detection preferably effective to craters with a diameter < 1 km, in accord with the target of the work. Typically, the ROI should include craters with a diameter less than 200 m, to fill the blank of detection method left by existing works.

5.2. Performance Evaluation

By morphology-based algorithm, 869 crater candidates are detected in the target research area, and the craters information are recorded. The statistical result is \( TP = 689 \) and \( FP = 180 \), where \( TP \) indicates number of actual craters in the detected craters, while \( FP \) is the number of non-craters that are detected as craters. Precision \( p \) is calculated in equation (5). The detected as craters have a diameter between 100 m and 60 km: < 1 km (91.25 %); < 500 m (85.85 %); < 200 m (32.57 %).

\[
p = \frac{TP}{TP + FP} = 0.7929
\]

From the statistics, for one thing, the efficiency and precision of crater detection by image processing is comparable to the results in other related papers using conventional image processing only. In specific, the detection performs well for small craters with obvious rim features, or large depth/area ratio (high visibility). Additionally, the algorithm is available to detect craters with small diameters with the smallest one of 100 m, surrounded by background features, or with ambiguous rims (low visibility). Moreover, the algorithm is effective for complex craters (multiple craters connected together, or a crater contains other craters). In this case, we define the crater that fits the circled region (Figure 6) as the detected crater. For another, the majority of FP is related to the incomplete background feature removal.

5.3. Operating Environment

The operating environment is listed below for the convenience of repetition of the work. Under the machine condition of 1 CPU, 3.1 GHz, 8GB RAM, 5 mins are needed from input to output. The output includes the information document of craters, and the image dataset of craters.

6. Conclusion

The work is based on morphology-based image processing. It effectively get use of the features of remote sensing images, which are two-dimensional grey images, and the characteristics of craters: the disk shape and the highlight and shadow crescent-like pairs caused by the disk shape of the crater and the solar altitude. Focusing on detection of small craters, which has shown its importance in the research field of planetary sciences, this work saves a lot of time compared with manual small crater data collection. In terms of automatic detection of craters, this work performs well in detection of small craters, with a concentration of craters with a diameter < 1 km (91.25 % in the experiment), which is seldom reported, and fills the blank of detection of craters in a diameter less than 200 m.

In addition, the tool developed in this work has high user practicability. The users just need to input the image of target research area into the main document, and then the image will automatically go through the detection by series of morphology-based algorithm, and output the list of crater information and collected crater images.

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References

[1] Han, T. L., Meng, X. G., Shao, Z. G., and Zhu, D. G. 2007 Geomorphology and Geology of Mars (Beijing: Geological Publishing House)

[2] Tanaka, K. L. 1986 The stratigraphy of Mars Journal of Geophysical Research vol 91 (B13), pp 139–158

[3] Faure, G., and Mensing T. M. 2007 Introduction to Planetary Science-The Geological Perspective (Netherlands: Springer) pp 233-234
[4] Neukum, G. and Jaumann, R. 2004 HRSC: the High Resolution Stereo Camera of Mars Express
*Mars Express: the scientific payload* pp 17 - 35

[5] Ding, W., Stepinski, T. F., Bandeira, L., Vilalta, R., Wu, Y., Lu, Z., and Cao, T. 2010 Automatic
detection of craters in planetary images: an embedded framework using feature selection and
boosting *CIKM ’10 Proceedings of the 19th ACM international conference on Information and
knowledge management (Toronto)* pp 749-758

[6] Liu, H., Tian, X. L., and Xu, A. A. 2014 A New Auto-Extraction Algorithm of Multi-Size Lunar
Craters Based on the Chang’E Data *Applied Mechanics and Materials* vols 599-601, pp 1340-1345

[7] McEwan, A. S., and Bierhaus, E. B. 2006 The Importance of Secondary Cratering to Age
Constraints on Planetary Surfaces *Annual Review of Earth and Planetary Sciences* vol 34, pp
535–567

[8] Costello, E. S., Ghent, R. R., and Lucey, P. G. 2018 The mixing of lunar regolith: Vital updates
to a canonical model *Icarus* vol 314, pp 327-344

[9] Blanford, G. 1980 Cosmic ray production curves below reworking zones *Proceedings of the
Conference on Lunar and Planetary Science* vol 11, pp 1357-1368

[10] Taylor, S. R. 1982 *Planetary Science: A Lunar Perspective* (Lunar and Planetary Institute)

[11] Bandeira, L., Ding, W. and Stepinski, T. F. 2010 Automatic Detection of Sub-Km Craters Using
Shape and Texture Information *41st Lunar and Planetary Science Conference*

[12] Bandeira, L., Ding, W. and Stepinski, T. F. 2012 Detection of sub-kilometer craters in high
resolution planetary images using shape and texture features *Advances in Space Research* vol 49,
pp 64-74

[13] Kang, Z. Z., Wang, X. K., Hu, T., Yang, J. T. 2019 Coarse-to-Fine Extraction of Small-Scale
Lunar Impact Craters From the CCD Images of the Chang’E Lunar Orbiters *IEEE Transactions on
Geoscience and Remote Sensing* vol 57(1), pp 181-193

[14] Jin, S. G., Haghighipour, N., Ip, W. H. 2015 *Planetary Exploration and Science Recent Results
and Advances* (Berlin, Heidelberg: Springer)