A Contour-Based Method for Small Impact Crater Identification (Postprint)

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Abstract

Automatic crater identification is one of the important research hotspots in planetary exploration missions. Due to limitations in data precision and algorithms, previous methods have often focused on identifying larger-scale craters. Based on the Chang' e-2 digital elevation model (DEM) data, which currently offers the highest precision and most comprehensive coverage internationally, we propose a method for automatically identifying small craters using contour lines. First, the contour characteristics of small crater models are analyzed to determine characteristic parameters and establish an index system; second, contour information from the experimental area is extracted and screened to identify contours meeting the characteristic parameters; finally, the Hough transform is used to fit crater boundaries and extract position and size information. Analysis of small crater identification results in the experimental region demonstrates that the method can configure different parameters for craters of various scales, enabling batch identification and extraction with an overall accuracy exceeding 90%, thereby proving its effectiveness for automatic small crater identification and extraction. This method addresses the limitation of existing automatic identification methods that predominantly target larger-scale craters; the identification results can supplement small-scale craters in existing lunar crater databases, providing a foundation for establishing a comprehensive lunar crater database in the future.

Full Text

A Method for Automatic Recognition of Small Impact Craters Based on Contour Lines

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Abstract

Automatic crater recognition represents a significant research focus in planetary exploration missions. Due to limitations in data precision and algorithmic constraints, previous methods have predominantly targeted larger-scale craters. Leveraging the Chang'e-2 Digital Elevation Model (DEM)—currently the highest-precision and most comprehensive global lunar topographic dataset available internationally—this paper proposes a novel method for automatic recognition of small craters based on contour line analysis. The methodology comprises three key stages: first, analyzing the contour line characteristics of small crater models to establish a robust indicator system with defined parameters; second, extracting contour information from experimental regions and screening for contours that match the characteristic parameters; and finally, employing Hough transform to fit crater boundaries and extract positional and dimensional information. Analysis of small crater recognition results from experimental regions demonstrates that this method enables parameter customization for different crater scales, facilitating batch-wise extraction with a comprehensive recognition accuracy exceeding 90%. These results validate the effectiveness of the proposed approach for automatic small crater identification. This method addresses the prevailing limitation of existing automated techniques that focus primarily on larger craters, and its recognition results can supplement small-scale craters in current lunar crater databases, laying the groundwork for future development of a comprehensive global lunar crater database.

Keywords: crater recognition; Chang' e-2 DEM; topography analysis; contour

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Impact craters are extensively distributed across planetary surfaces, representing the most prominent topographic features and serving as windows into planetary interior materials [1]. Due to the Moon' s lack of atmosphere, lunar craters remain well-preserved, making them crucial for studying lunar morphology, relative geological age, rock structure, and lunar origin. Crater recognition research has evolved from early telescope-based observation and manual delineation of crater morphology, through visual identification using remote sensing imagery, to recent computer-automated recognition. With the massive acquisition of lunar imagery and topographic data, automated crater identification has emerged as a new research hotspot. Numerous scholars have proposed various methodologies and established crater databases at multiple scales [2], [3], [4], [5], [6], [7]. Based on analysis and synthesis of existing approaches, crater recognition methods can be broadly categorized into four types: manual visual interpretation, morphology-based fitting, machine learning, and geospatial information analysis.

Manual visual interpretation utilizes imagery and topographic data to establish interpretive indicators for crater identification, employing manual interactive recognition of each crater within computer environments. While this approach currently offers the highest accuracy, it is extremely time-consuming and labor-intensive, making it unsuitable for global lunar surveys or small-scale crater identification. Morphology-based fitting methods leverage the circular geometric characteristics of craters in imagery. Following image segmentation, shape-fitting algorithms such as Hough transform and conic curve fitting are employed to extract crater boundaries. For instance, reference [8] utilized a combined Hough transform algorithm, reference [9] adopted a fuzzy Hough transform, reference [10] proposed a chord midpoint Hough transform algorithm, and reference [11] employed least squares ellipse fitting for crater extraction. Machine learning approaches include BP neural networks with training samples [12], decision tree algorithms [13], and object-oriented methods [14] for crater recognition. Geospatial information analysis methods have utilized slope as a recognition element [15], while references [16-17] employed 500m-resolution Chang' e-1 DEM data with morphology-based fitting for crater extraction. Reference [18] utilized slope data, texture information, and profile curvature as recognition criteria, adopting a water-flooding method for Martian crater identification.

Summarizing the advantages and disadvantages of previous research methods and their limitations, this study employs the world' s most comprehensive and highest-precision Chang' e-2 digital terrain data to propose a contour line-based topographic analysis method specifically targeting small crater recognition and extraction, addressing the deficiency in both quantity and accuracy of small craters in existing databases.

In February 2008, the State Council approved the Phase II lunar exploration program, whose primary objectives included achieving lunar soft landing and conducting in-situ 探测 and automatic 巡视勘察. Chang' e-2, serving as the technical precursor satellite for Phase II, had as its primary scientific mission the detailed survey of the entire Moon and the Chang' e-3 landing region, with fine-scale mapping of global lunar topography. The Chang' e-2 satellite was successfully launched on October 1, 2010, at 18:59:57 Beijing time from the Xichang Satellite Launch Center. On October 24 at 16:49, the two-line-array CCD stereo camera onboard Chang' e-2 was first activated, successfully acquiring forward- and backward-looking image data. By May 20, 2011, the CCD stereo camera had completed its mission, acquiring a total of 607 orbits of image data. During production of the global lunar imagery, 384 orbits of data imaged at 100km orbital altitude were selected (including 344 orbits covering ±70° latitude and 40 polar orbits) for production of global digital elevation model products. The data processing workflow included data preparation, survey area organization, tie point preparation, global adjustment, primary product generation, standard product production, and global mosaic. Incorporating Chang' e-2 satellite orbit and attitude measurement data with five lunar absolute control points, global adjustment was performed. After four years of data processing, 7m, 20m, and 50m resolution DEM data were successfully produced. The Chang' e-2 DEM data surpasses international 同类产品 in spatial resolution, data consistency, and mosaic completeness. This study selects the 7m-resolution DEM data for small crater identification and extraction.

2.1 Crater Model Analysis

Based on fundamental morphology, impact craters can be classified into three categories: simple craters (bowl-shaped small craters), complex craters (larger craters with central peaks), and multi-ring basins [19]. An ideal complex crater model primarily comprises five morphological elements: crater rim (rh), crater wall (w), crater floor (f), impact melt (m), and central peak or ring (p). Ejecta deposits consist of crater rim (rh), hummocky deposits (rr), and ray deposits (rc). Impact melt (m) overlays other morphological elements. Simple bowl-shaped craters (c) typically occur atop hummocky deposits (rr). Crater recognition constitutes a feature extraction task that analyzes imagery or topographic data to identify crater rims (rh) and extract crater diameter (D), center position, and elevation information.

[Figure 1: see original paper] Ideal complex crater model (Don Wilhelms, 1987)
[Figure 2: see original paper] Cross-sectional profiles of simple and complex craters

Contour lines are closed curves connecting adjacent points of equal elevation on topographic maps, representing the most commonly used form for expressing topographic morphology and relief. Contour lines can be extracted from digital elevation models, scientifically reflecting fundamental lunar surface features including elevation, slope, aspect, and terrain trends. The Chang' e-2 DEM data features exceptionally high spatial resolution, enabling continuous representation of lunar surface elevation in two-dimensional geographic space. This data facilitates convenient and detailed extraction of lunar crater topographic contours, enabling expression, analysis, and processing of crater morphology.

[Figure 3: see original paper] Contour diagram

Morphological analysis of contour lines reveals that impact craters exhibit the following characteristic spatial features: (1) crater rim contours are typically approximately circular or elliptical; (2) multiple nested similar contours typically exist inside crater rim contours, mostly concentric circles or ellipses with relatively small spacing, while outer contours have irregular shapes with larger spacing, clearly distinguishing them from the rim; and (3) crater floors have lower elevation while rim edges have higher elevation, with cross-sectional profiles that can be fitted by concave downward parabolic curves. Consequently, lunar craters can be analyzed and identified through contour line characteristics and their interrelationships. As illustrated in the crater cross-sectional morphology in Figure 4 [Figure 4: see original paper], contour lines represent the isometric spatial form of craters. Therefore, by selecting appropriate contour intervals, the closed near-circular contours of crater rims can approximate real boundaries, enabling accurate identification and extraction of crater geographic location, size, and depth information.

[Figure 4: see original paper] Crater contour diagram

2.2 Indicator System and Parameter Determination

Crater contours typically exhibit nested ring-like patterns. The preliminary approach for discriminating crater features involves using circularity, rectangularity, and aspect ratio parameters to retain qualifying contours, then analyzing inter-contour relationships to aggregate nested contours and identify outermost contours. Subsequently, profile curvature is used to eliminate positive terrain features such as domes, retaining only negative terrain crater regions. Finally, Hough transform fits crater boundaries to obtain center positions and sizes. The indicator system and parameters thus include circularity, rectangularity, aspect ratio, and profile curvature concavity.

(1) **Circularity** is a crucial concept in image processing for feature extraction and description, reflecting the complexity of measured boundaries. The formula is:

$$e = \frac{4\pi A_0}{P^2}$$

where A_0 represents area, P represents perimeter, and e is the ratio of 4π times area to the square of perimeter. This feature reaches its maximum value of 1 for circular regions, with contours having values closer to 1 being more suitable as crater rims.

(2) **Rectangularity** is a commonly used rectangular fitting factor for target objects, with the formula:

$$e_1 = \frac{A_0}{A_R}$$

where A_0 represents area and A_R represents minimum bounding rectangle area. e_1 indicates the degree to which an object fills its minimum bounding rectangle. For rectangular objects, e_1 reaches its maximum value of 1; for circular objects, e_1 equals 0.79; and for elongated objects, e_1 decreases. Rectangular fitting factor values range between 0 and 1.

(3) **Aspect ratio** is defined as:

$$e_2 = \frac{W}{L}$$

where W represents the width and L represents the length of the minimum bounding rectangle. Circular regions have an aspect ratio of 1, and this parameter effectively eliminates elongated irregular contours.

(4) **Profile curvature concavity**: Since other elevated lunar features such as domes also produce near-circular closed contours, the processing method involves determining whether the DEM profile curve at potential crater locations exhibits a concave downward morphology. If concave, the feature is identified as a crater; conversely, if convex, it is not a crater. Real craters are determined based on the elevation relationship between inner and outer contours.

Only contours satisfying these indicators are retained, with the outermost contour among groups of closed contours having three or more nested relationships designated as the final crater boundary.

2.3 Crater Boundary Fitting

For retained contours satisfying the conditions, Hough transform is employed to fit boundaries and obtain center points and radius sizes. The Hough transform algorithm is a common method in image processing for recognizing geometric shapes and their features. The fundamental concept is: for any edge point $I(x, y)$ in binary image I, if it lies on a circle with center (a, b) and radius r, it satisfies:

$$(x-a)^2 + (y-b)^2 = r^2$$

From this equation, each edge point $I(x, y)$ maps to a quadratic surface in parameter space (a, b, r). The parametric form of equation (4) is:

$$a = x - r\cos\theta$$

$$\theta \in [0, 2\pi)$$

Let the radius of the circle to be detected be $r \in [R_1, R_2]$. According to Hough transform, for any edge point $I(x, y)$, θ and r are traversed with step sizes $\Delta\theta$ and Δr through $[0, 2\pi)$ and $[R_1, R_2]$, respectively, to obtain subspaces of parameter space (a, b, r) and increment corresponding accumulator cells $AC(a, b, r)$ by 1. After traversing all points in the image, the accumulator array AC is obtained, where any point $AC(a, b, r)$ represents the number of edge points on circle (a, b, r). Circles with identical numbers of edge points but different radii have different probabilities of being true circles, with smaller radii having higher probability. Therefore, roundness is defined as:

$$p = \frac{n}{r}$$

where n represents the number of edge points on the circle, r represents the radius, and p represents roundness. The accumulator array AC elements are used to calculate roundness, yielding a three-dimensional roundness array C. Circular targets correspond to local peaks in the roundness array, where $C(a, b, r)$ represents local maxima.

3.1 Recognition Workflow

Experimental regions G227 and G228 were randomly selected from the Chang' e-2 7m global DEM data. Based on ENVI and IDL platforms, programs were developed according to the principles and methods described in Section 2. The workflow involves: first, extracting contours from Chang' e-2 DEM data using appropriate contour intervals; second, screening preliminary crater regions using circularity, rectangularity, aspect ratio, and profile curvature; and finally, extracting crater boundary information through Hough transform. The extracted information is imported into AirGIS to determine crater geographic locations and radii, with depth information calculated from elevation differences, generating a small crater database containing location, size, and depth attributes.

[Figure 5: see original paper] IDL program diagram

3.2 Recognition Results

Automatic recognition results based on DEM contour analysis are illustrated in Figure 6, with detailed statistics provided in Table 1 .

[Figure 6: see original paper] Crater detection result diagram

The proposed method identified 728 and 989 craters in regions G227 and G228, respectively. To evaluate the method' s accuracy, we employed the algorithm evaluation metrics proposed by Shufelt [8]: detection percentage $D = 100 \times TP/(TP + FN)$, branch factor $B = FP/TP$, and quality percentage $Q = 100 \times TP/(TP + FP + FN)$, where TP represents correctly identified craters, FN represents missed craters, and FP represents falsely identified craters. Currently, the best evaluation method remains comparison with manually identified results as reference.

Crater detection result statistics

The statistical results in Table 1 indicate that the proposed method achieved evaluation metrics D of 92.9% and 91.9% in the two experimental regions, with a mean of 92.4%; branch factor B values of 4.4% and 7.7%, with a mean of 6.1%; and quality percentage Q values of 89.2% and 81%, with a mean of 85.1%. These evaluation metrics demonstrate that the proposed method yields excellent detection results for small craters, with high correct recognition rates and low false positive rates, though a small portion of craters remain missed. The high accuracy benefits significantly from the high-precision Chang' e-2 data, resulting in relatively low omission rates and confirming the method' s feasibility and effectiveness.

3.3 Discussion

This paper presents a method for automatic recognition and extraction of small craters using contour lines derived from high-precision DEM data. Compared with traditional point-by-point slope index analysis, this approach transforms edge extraction into terrain line analysis, effectively avoiding interference from terrain wrinkles and debris fields while offering a simpler, more efficient recognition 流程 with faster processing speed. The method allows setting different contour intervals to recognize craters of different scales in batches and intervals, achieving high recognition accuracy with low false positive rates. The relatively low omission rate also benefits from Chang' e-2' s high-precision data, demonstrating the method' s feasibility and effectiveness.

However, it should be noted that for severely degraded craters with heavily damaged rims and gentle walls, contours cannot clearly express or accurately delineate crater morphology, preventing accurate recognition and causing omission errors. Nevertheless, comparison with co-located imagery data enables identification through manual interpretation. Therefore, future research directions should focus on recognizing severely degraded craters, which represents a weak link and unresolved challenge in all crater detection methods. In practical applications, this method' s recognition results can supplement small-scale craters in existing lunar crater databases, enriching current lunar crater databases.

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Note: Figure translations are in progress. See original paper for figures.