Construction of an Age Map of the Region Around the Young Lunar Crater Hell Q

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Abstract — The determination of the age of planetary surfaces basically depends on the areal density of detected craters. The analysis of the impact crater size frequency distribution (CSFD) is a classical approach that supports the age estimation process for planetary surfaces. Usually, manual crater counting and size evaluation is leading to an estimate of the CSFD, which is consequently considered as a time-consuming process especially for large surface areas provided with a high image resolution. The availability of global image mosaics at high resolution implies a need for automated crater detection algorithms. In this work, a template-based crater detection algorithm is applied to analyze image data under known illumination conditions. The results are used to produce the CSFD for a region around the young lunar crater Hell Q, where the threshold value of the applied automatic crater detection algorithm is calibrated based on a 16 km² region with known manual crater count data. As an advanced step, the accordingly configured crater detection algorithm is then applied to a much larger surface region of about 70 km² surrounding the selected calibration area, and a spatially resolved map of the surface age is calculated for overlapping rectangular areas, each covering 2 x 1.5 km². The obtained age values range from 1-2 Ma for the immediate vicinity of Hell Q to about 60 Ma at about 10 km distance from Hell Q.

Keywords - Crater statistics; automatic crater detection; crater detection algorithm; absolute model age; age mapping; Hell Q

I. INTRODUCTION

Estimation of the geologic age of planetary surfaces is of high interest in planetary research. The surface age estimation relies basically on counting impact craters and measuring their diameters. The availability of large amounts of high-resolution planetary images that cover different solar system objects provides the possibility to study them deeply and construct crater catalogues that contains large numbers of manually detected small craters [1] [2].

Apparently, impact craters are the results of previous impacts that happened in different intervals of time on planetary surfaces [3]. Impact craters exist in large abundances and are widespread on the Moon, Mars and Mercury due to lack of an atmosphere and conditions suitable for life [4]. The age of a planetary surface increases with increasing impact crater density, i.e. surfaces with a low number of impact craters are usually younger than densely cratered surface parts. Estimations of the crater size-frequency distribution (CSFD) are a basic tool for assessing the ages of surface regions. The derivation of the absolute model age (AMA) of a surface requires obtaining the number of craters and their diameters [5] [6] [7] [8] [9] [10] [11].

In this context, manual counting and measuring of craters is a time-consuming process, while automatic crater detection may lead to increased false positive detections. A comparison between automatic crater detection algorithms and manual crater counts has been implemented before (e.g. [1]); the results of the automatic detection algorithm differed, especially for craters of small size.

In this paper, an automatic crater detection algorithm (CDA) is applied to a high-resolution image of the lunar crater Hell Q of about 4 km diameter and its ejecta blanket. Except for Hell Q, the image exhibits only craters of small sizes, less than a few tens of meters in diameter [12]. An absolute model age (AMA) is obtained based on the resulting automated crater counts. By examining the whole surface area of the available high-resolution image a map of the surface age is created based on the automatically obtained crater counts.

II. AUTOMATIC ALGORITHMS FOR CRATER DETECTION

In general, the field of crater detection is an interesting and important topic in planetary science, which traditionally relies on the manual inspection of orbital images [7]. In the domain of remote sensing, automatic crater detection algorithms are an attractive approach for researchers that reduce the time required to analyze large amounts of planetary image data and provide the locations and sizes of craters in images automatically [13] [14] [15].

Small craters are much more frequent than large craters, but these small craters are often not easily visible in global image data sets. A variety of different CDAs have been constructed and developed by researchers who recognized the importance of the impact craters distribution and its strong effect on remote geologic studies of planetary surfaces (e.g. [1]). An issue of special importance has been to increase the level of detection performance for planetary images with reduced clarity of impact craters by creating new CDAs or by refining existing techniques [1]. Since more than a decade ago, a multitude of new approaches for automatic crater detection has been developed (see [14] for a detailed overview). The developed CDAs are usually divided into two classes, where one group of algorithms detects craters in...
images while another group relies on digital elevation models (DEMs) for crater detection [14] [16].

Many existing CDAs are limited to the detection and counting of craters without retrieving more detailed information [17] [18]. The developing step after such CDAs is the automatic classification and extraction of further contextual information in addition to the crater detection itself [19]. The CDA implemented in [19] divides the craters into groups with different floor shapes. It was used to distinguish between different crater degradation states and for the detection of simple lunar craters of small diameter [19]. Furthermore, crater detection should have a high priority for additional mapping due to the important role of the CSFD as a remote sensing tool for surface age estimation [20].

Some image-based CDAs rely on techniques that process the test image to detect characteristics similar to the circular or elliptical shapes of crater rims, followed by a matching process between the resulting candidates and the manually detected craters [1]. Machine learning approaches applied in other CDAs are trained on image data labeled before by a human expert, followed by applying the resulting system to new image data [21].

In this paper, the CDA described in [22] is applied to the Lunar Reconnaissance Orbiter Narrow Angle Camera (LRO NAC) image M126961088LE (http://wms.lroc.asu.edu/lroc/view_lroc/LRO-L-LROC-2-EDR-V1.0/M126961088LE) showing the small crater Hell Q and its surroundings. This CDA is a template matching based system which is able to detect craters of less than about 10 pixels diameter in lunar images without the need for DEM data. The image-based algorithm will be applied to a part of the image, which will be divided into three equally sized areas for the purpose of evaluation and calibration of the optimal detection threshold. Consequently, the statistical analysis of the automatically estimated CSFD is the main element for the AMA estimation. Furthermore, a spatially resolved AMA map of Hell Q and the neighboring surface will be constructed.

III. IMAGE-BASED CRATERS DETECTION ALGORITHM

The template-based detection algorithm introduced in [22] is applied to the image data for analysis. The algorithm relies on six generated 3D crater models, which were generated depending on the analysis of track data of the Lunar Orbiter Laser Altimeter (LOLA) instrument [23] covering 23 small craters of about 8 km diameter located near lunar crater Plato [22].

These craters were related to three basic shapes: the simple bowl shape, flat-floored shape and central-mounded complex shape. Three representative profiles of these three shapes are shown in Fig. 1. These profiles were split in half, and by rotating the half-profiles a set of six 3D crater temples were created (Fig. 2), which were in turn used to synthesize six artificially illuminated image templates using the Hapke model [24] [25] given the known illumination conditions under which the image was acquired. These six templates were rescaled to a size range of 5-200 image pixels in order to allow for the detection of craters across a broad range of diameters. As a matching criterion, the normalized cross-correlation coefficient between the templates on the one hand and the analyzed image part on the other hand is used.

A fusion process for the crater candidates is applied after the template matching stage that will choose only the most significant detection result in the presence of multiple detections at the same position and/or with slight diameter differences.

![Figure 1. The three basic crater shapes derived from LOLA track data.](image)

![Figure 2. The six 3D crater models. Models 1 and 2 represent the small central mounded shape, flat-floored craters correspond to models 3 and 4, and models 5 and 6 represent simple bowl-shaped craters.](image)
IV. THE REGION OF INTEREST: HELL Q

The roughly 4 km sized crater Hell Q is located at 33.0° S and 4.4° W in the eastern part of the large walled plain Deslandres [12], roughly 300 km northwest of the well-known large crater Tycho. In [12], the Hell Q region is regarded for an AMA estimation based on very small craters with diameters between 5 m and 41 m, where potential secondary craters are excluded by detecting non-uniform spatial distributions using a statistical test. According to [12], the ejecta blanket of Hell Q exhibits a lower density of small impact craters than an impact melt pond of Tycho. Consequently, the age of Hell Q is lower than the age of Tycho [26].

In the study in [26], which regards among others the craters Hell Q and Tycho, an age of 110-110 Ma is estimated for the crater Tycho and a value below this range for Hell Q. The young age of Hell Q is inferred from the fact that this crater is superposed on one of the rays formed by ejecta material of Tycho [26]. In [27] the structure of a small impact melt deposit on the floor of Hell Q is described. In the morphological and spectral study in [28] about the central peak region of Tycho, this crater is considered as a young impact crater of an approximate age of 110 Ma. In the works in [29] and [30] age values of Tycho of 100 Ma and 96 Ma, respectively, are given. Similarly, an age of about 100 Ma is estimated for Tycho in [31]. A slightly higher age of 138\(^{+24}_{-20}\) Ma has been determined for Tycho in [32].

The template matching based CDA applied in this study strongly depends on a detection threshold that controls the CDA sensitivity and efficiency. This threshold value is adjusted such that the automatically determined AMA corresponds as closely as possible to the value obtained by manual crater counting. For validation purposes, the 16.3 km\(^2\) reference region is divided into three adjacent areas of equal size, and the minimum absolute difference between the CDA-based and the manually determined AMA has been calculated for each of the three sub-areas. The detection threshold obtained for each area is then applied to the other two areas. Table 1 summarizes the resulting number of craters in each sub-area detected by the CDA and by manual counting respectively. Table 2 presents the AMA values derived from the CDA-based algorithm, which range from 1.25 Ma to 2.39 Ma. The arithmetic mean of the three obtained threshold values, corresponding to 0.677, can be considered as the “optimal” threshold. Applying this threshold value to the total 16.3 km\(^2\) reference area results in an AMA of 1.65\(^{+0.02}_{-0.02}\) Ma.
### Table I. Results of the threshold adaptation: number of craters.

<table>
<thead>
<tr>
<th>Tested on</th>
<th>Trained on</th>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
<th>Manual Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.668</td>
<td>0.677</td>
<td>0.686</td>
<td></td>
</tr>
<tr>
<td>Area 1</td>
<td></td>
<td>92 craters</td>
<td>79 craters</td>
<td>72 craters</td>
<td>247</td>
</tr>
<tr>
<td>Area 2</td>
<td></td>
<td>127 craters</td>
<td>108 craters</td>
<td>95 craters</td>
<td>228</td>
</tr>
<tr>
<td>Area 3</td>
<td></td>
<td>97 craters</td>
<td>84 craters</td>
<td>74 craters</td>
<td>203</td>
</tr>
</tbody>
</table>

### Table II. Results of the threshold adaptation: estimated AMAs.

<table>
<thead>
<tr>
<th>Tested on</th>
<th>Trained on</th>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
<th>Manual Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.668</td>
<td>0.677</td>
<td>0.686</td>
<td></td>
</tr>
<tr>
<td>Area 1</td>
<td></td>
<td>2.39 Ma</td>
<td>+0.064 -0.066 Ma</td>
<td>1.68 Ma</td>
<td>+0.092 -0.100 Ma</td>
</tr>
<tr>
<td>Area 2</td>
<td></td>
<td>1.97 Ma</td>
<td>+0.144 -0.177 Ma</td>
<td>1.60 Ma</td>
<td>+0.236 -0.236 Ma</td>
</tr>
<tr>
<td>Area 3</td>
<td></td>
<td>1.68 Ma</td>
<td>+0.086 -0.095 Ma</td>
<td>1.53 Ma</td>
<td>+0.101 -0.109 Ma</td>
</tr>
</tbody>
</table>

## V. Age Map of the Hell Q Region

The automatic construction of a surface age map is a new interesting task. To create such map, the template-based CDA has been applied to an orthorectified 1 m/pixel version of LRO NAC image M126961088LE with a wide sliding window of 2000 × 1500 pixels (2 × 1.5 km²) moving over the whole image at a step width of 10 pixels (10 m). Given the very small size of the craters and their limited number in our case study, the template-based CDA is able to identify a large fraction of the manually determined craters (a more detailed performance analysis of the CDA is currently in progress). Only a small fraction is missed due to neighboring or overlapping craters. In addition, there might occur a slight positional offset between template-based CDA and manually detected crater positions, but that does not affect the AMA estimation process as it only relies on the craters density per area and their diameters values.

The CSFDs were computed for the overlapping rectangular sub-areas of LRO NAC image M126961088LE using the “optimal” threshold value of 0.677. Using our Matlab implementation of the CSFD-based technique according to [7] [8] [9] [10], the sub-area specific AMA values were computed and translated into an age map (Fig. 3). The AMA values of the map range from between 0.1 and 15 Ma in the center of the region to about 55-70 Ma in the southern, northwestern and southeastern parts of the region.

The CDA-derived AMA map indicates that the crater Hell Q and its immediate surroundings are younger than the surface to the north and south, due to the very young age of Hell Q. The AMA values are gradually increasing from the crater towards the north and more abruptly at about 4 km distance south of the crater (Fig. 3). The region depicted in blue color in the age map of Fig. 3 presumably corresponds to the ejecta blanket of Hell Q.

The more or less gradual increase of the surface age with increasing distance from Hell Q may be due to a gradual thinning of the ejecta blanket of Hell Q with increasing distance from the crater. In the thinner parts of the ejecta blanket, craters on the older underlying surface “shine through” the ejecta and thus indicate a higher surface age. The observation that the AMA of the outer parts of the ejecta blanket of Hell Q is younger than 100 Ma, the approximate age of the crater Tycho, can be attributed to the superposition of Hell Q on one of the ejecta rays of Tycho as noted in [26].

The study area is considered as being partially affected by secondary crater contamination [12]. Some of the detected craters are distributed as clusters that might influence the inferred AMAs [12] (see e.g. [33] for a general description of the effect of secondary craters on CSFD-derived ages of planetary surfaces). In [12], each diameter interval of the histogram representing the CSFD is analyzed with respect to the uniform distribution of the respective craters, where a diameter interval with non-uniform crater distribution is detected using statistical F and G tests and is excluded from the CSFD [12]. Since this approach might remove uniformly distributed craters together with the clustered craters from the same diameter interval, leading to a removal of too many craters from the CSFD, a useful feature of future versions of our system will be a refined statistical analysis of the spatial crater distribution to separate clustered craters from uniformly distributed craters without the need for removing all craters of one or several diameter intervals.
VI. SUMMARY AND CONCLUSION

An image-based template matching CDA has been applied to the high-resolution LRO NAC image M126961088LE showing the region around the small lunar crater Hell Q. The applied CDA has yielded a reliable CSFD based on the detected craters and their estimated diameters, and the AMA of the surface has been derived. A calibration process based on reference manual crater counts for a sub-region of the total image was applied to obtain an appropriate detection threshold value. The resulting average AMA of the crater floor is consistent with the reference age obtained by manual crater counting in [12].

A construction of a spatially resolved map of the AMA has been obtained by applying the template-based CDA to overlapping sub-regions of the study area. The age map shows that the crater Hell Q is only 1-2 Ma old and thus clearly much younger than the neighboring surface. The estimated AMA increases continuously with increasing distance from Hell Q, which may be due to a gradual decrease in thickness of its ejecta blanket.

The described automatic age map construction technique allows for a comparison between surface parts or geological units in terms of their AMAs. It can be easily applied to any other surface areas once manual crater count data are available as a reference for a small sub-region.

As a step of future work, it might be useful to increase the detection rate for more uncommon crater types by providing the CDA with a larger number of templates representing a larger variety of crater shapes, especially degraded craters. Another future approach is to distinguish between primary and secondary craters according to their shape or spatial distribution and then to analyze the effect of the secondary craters on the AMA estimation.

ACKNOWLEDGMENTS

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REFERENCES


