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3-D CRATER ANALYSIS OF LDEF IMPACT FEATURES FROM STEREO IMAGERY

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SUMMARY

We report here preliminary results from attempts to derive depth and diameter information from digitized stereo images of impact features on LDEF. Contrary to our prior assumption, we find that impact craters in the T6 Al alloy are not paraboloid in cross section, but rather are better described by a 6th-order polynomial curve. We explore the implications of this discovery.

INTRODUCTION

In expectation of the LDEF return, the requirement for a system to analyze the hyper-velocity impact craters on the space-exposed surfaces of the spacecraft was determined. Ideally, this analysis system would be able to define in three dimensions the surface structure of each crater to a high degree of precision. As a minimum, the system should be able to determine the true depth and diameter of each crater. The 'true' depth is defined as the deepest point in the crater as measured from the level of the ambient surface, and the 'true' diameter is the inside diameter of the crater when measured at the level of the ambient surface (see Figure 1).

A number of constraints were placed upon this system design. The budgetary limitations were fairly severe, and the time frame for technique investigations was short. It was essential that the analysis system use a technique that was non-destructive and remote (i.e., no contact with the material surface permitted). In addition, the system must use a technique that could be incorporated into a portable system to be used at Kennedy Space Center during the deintegration of the LDEF spacecraft.

It was decided to use binocular imagery to analyze the crater morphologies. It was fairly inexpensive to achieve, and made use of some existing hardware to collect the information. A portable system configuration consisted of a portable PC equipped with a color video digitizing board and a color video multiplexer, a binocular microscope, a pair of video cameras, and a pair of optical disk drives with removable media. This system configuration would collect pairs of color digital images and store them to the optical media for later analysis. It was also decided to write software that would automatically register the image pairs on a pixel by pixel basis using a traditional cross-correlation technique. The parallax information in each pixel registration would provide depth data for each pixel, and thereby provide a full three-dimensional representation of the crater surface.

During the three month deintegration of LDEF, the Meteoroid and Debris Special Investigation Group (M&D SIG) generated approximately 5000 digital color stereo image pairs of impact-related features from all space-exposed surfaces. An earlier paper (1) describes the theory and practice of determining this 3-dimensional feature information from stereo imagery.

RECENT WORK

The attempts to analyze the KSC imagery using traditional cross-correlation were unsuccessful due to several problems inherent in the data. There was a significant difference in the photometric responses between the two cameras due to a lack of photometric calibration. In an analog world, this problem could be easily rectified by compensating for the different gains and offsets. In the digitized images, however, the data has already been quantized and truncated making it impossible to recover much of the information. There was also a problem with a lack of detail in many of the images due to depth of field limitations and lack of focal calibrations between cameras. Most of the craters digitized displayed a high degree of specular reflectivity, which is incompatible with cross-correlation techniques. Specular reflections are strongly viewing angle dependent, which means that high contrast details seen from one camera are likely to be very low contrast, or even invisible from the other camera. These problems, combined with a poor initial understanding of the task complexity, caused the planned approach of automated registration via cross-correlation to be unsuccessful.

Due to the problems encountered in attempting to implement the fully automated software, the decision was made to get an interactive (man-hour intensive) method working, and then come back later and continue the development of a fully automated capability as time permitted. The interactive approach was to allow an analyst to select a series of tie-points from an image pair, and use the three-dimensional information of the tie-points to perform a least-squares parametric fit to define the crater's geometry. (A tie-point is a pair of points, one from each of the two images, which represent the same point on a surface, i.e., a tie-point 'ties' the two images together at a single point.) The initial approach required that a few basic assumptions be made. The assumptions were that 1) the craters are basically paraboloid, 2) the craters are central-symmetric to an axis which is perpendicular to the ambient plane, and 3) there was liable to be some inherent error in the tie-point selections.

The interactive data collection software was set up so that the analyst would select tie-points in three sets, one each for the ambient surface, the crater interior, and the lip of the crater. (Note: the lip tie-points were collected just for statistical information. No attempt was made to parametrically define the lip geometry.) The first step in the analysis was to first calculate the distance from the focal plane for each tie-point in all three data sets. The analysis software would then calculate a least-squares fit for the ambient plane and compensate for rotations and offsets of the crater surface with respect to the camera's focal plane in all three data sets. A least squares fit of a paraboloid to the interior crater points was then performed. The intersection of the ambient plane with the paraboloid then determined the ideal crater depth, and the width of the paraboloid at the intersection with the ambient plane defined the ideal crater diameter.

In order to test the accuracy of the interactive analysis software, three craters were selected which were large enough to perform fairly accurate manual depth and diameter measurements. The manual measurements were performed resulting in measured depths of 147, 455, and 933 microns and diameters of 279, 1254, and 2426 microns. Binocular images of each crater were digitized, and the interactive data collection of tie-points was completed. The tie-point data was analyzed using the parametric fit software, and the outputs were compared to the manual measurements. There was an expected error in the manual measurements of approximately 2%, but for this accuracy test, the manual measurements were accepted as 'true.' The results were somewhat disappointing. The average error in the estimated crater depth was 15.5%, and the average error in the diameter estimate was -11.9%. Both of these errors were significantly larger than was considered acceptable.

In attempting to determine the source of the encountered errors, three possible causes were isolated and tested. The possibilities were defined as 1) software 'bugs,' 2) an algorithm which was overly sensitive to input errors, and 3) a false basic assumption regarding paraboloid crater geometry. The error sources were tested in the order listed above, as this was deemed to be the order of their likelihood.

In order to test the software integrity, several 'perfect' paraboloid craters were computer generated, and corresponding tie-points were generated. The analysis resulted in 0% error. The tie-point collection, and initial depth calculations were also tested separately using holes drilled in aluminum as test cases. These two tests combined demonstrated that the software was performing as expected.

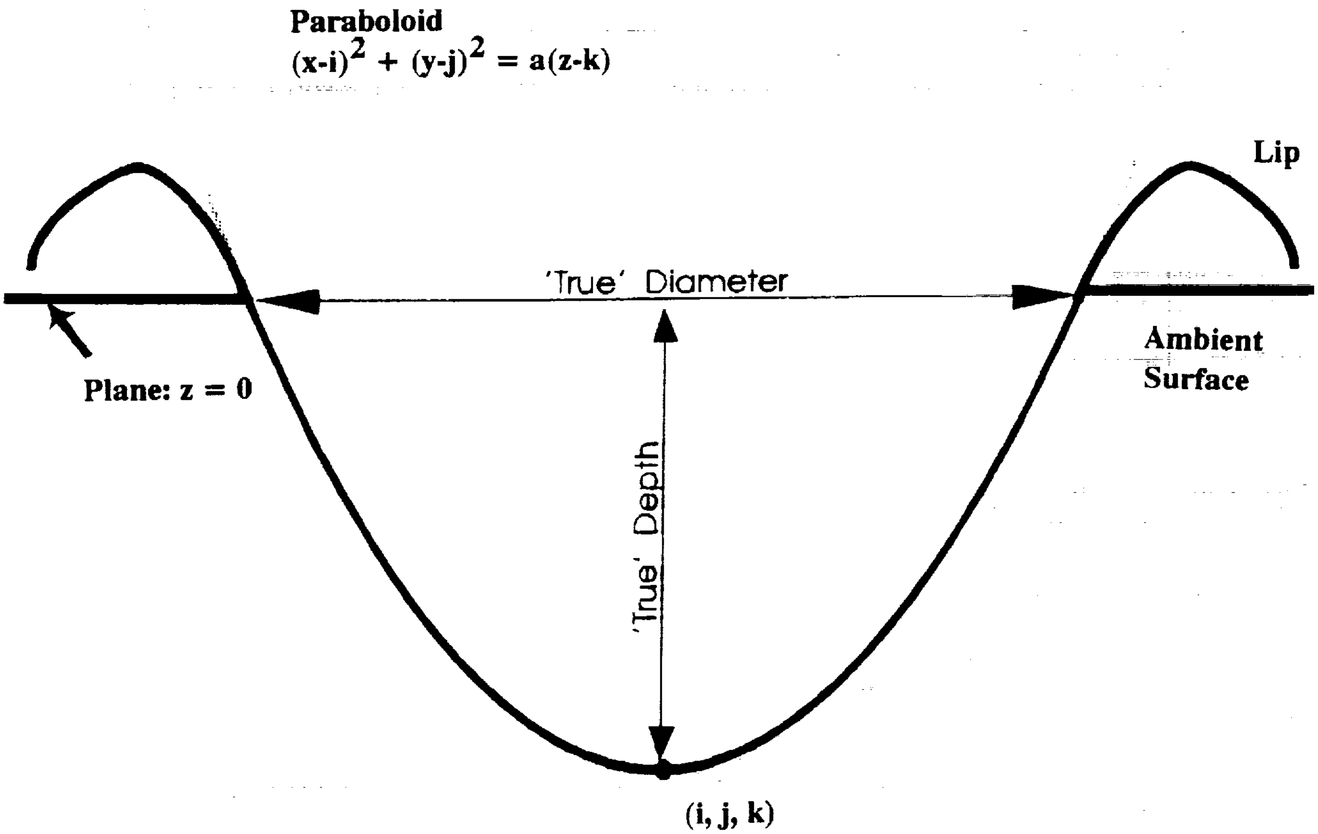
To test the algorithm's sensitivity to input errors, the previously generated 'perfect' craters were again used. A Monte Carlo technique was applied to generate randomized errors in the tie-point data prior to being input to the analysis software. The magnitude of the induced errors was greater than or equal to the maximum expected input errors. Numerous runs were performed in batch mode with statistical analysis of the resulting outputs. This analysis resulted in an average error in the depth estimate of 2.5%, and an average error in the diameter estimate of 7.5%. These errors were larger than desired, but still not large enough to account for the errors encountered in the analysis of the real craters.

It was decided then to test the basic assumption of the crater geometry. In order to test this assumption, five impact craters were generated in T6 aluminum alloy, which is the most common exposed material on the LDEF. These craters were large enough to be easily cross-sectioned; the sizes ranged from 3.1 to 7.0 mm in depth and 7.0 to 19.8 mm in diameter. Each crater was then carefully cross-sectioned through its center. Digital monocular images of the cross section of each crater were generated, and a high resolution two-dimensional digitization of the interior surface structure of each crater was then performed. The digitizations contained 66 to 111 data points each to attempt to minimize the errors. A series of two-dimensional polynomials were then fitted to the digitized points. Second order (Eq. 1), fourth order (Eq. 2), and sixth order (Eq. 3) polynomial curve fits were each performed. No odd order polynomials were used because the assumption that a crater is central symmetric was still in effect. A first order term (bx) was left in the fit equations in order to compensate for any axial rotations incurred during the initial digitization.

$$y = a + bx + cx^2 \qquad \text{(Equation 1)}$$
$$y = a + bx + cx^2 + dx^4 \qquad \text{(Equation 2)}$$
$$y = a + bx + cx^2 + dx^4 + ex^6 \qquad \text{(Equation 3)}$$

The results of these curve fits compared to the raw data were somewhat surprising. The 2nd order curve fits were consistently deeper and wider than the actual craters. The 4th order curve fits were consistently shallower and wider than the actual craters. The 6th order curve fits, however, resulted in inconsistent errors in depth and diameter. Figure 2 shows images of the three cross-sectioned craters with the superimposed 2-D curve fits. Figure 3 depicts the total amount of error encountered in the curve fits, and Table 1 summarizes the percent errors in depth and diameter estimates for each of the five test shots from each type of curve fit. The consistency of the magnitude and especially sign of the errors in the second and fourth order curve fits suggests that these errors are not due to random factors, but instead are due to the unsuitability of these equations for defining the crater geometry.

Idealized Crater Geometry



Cross Sectional View

Figure 1 Initial idealized crater geometry assumed for this investigation, employing a paraboloid cross-section. True depth and diameter are indicated.

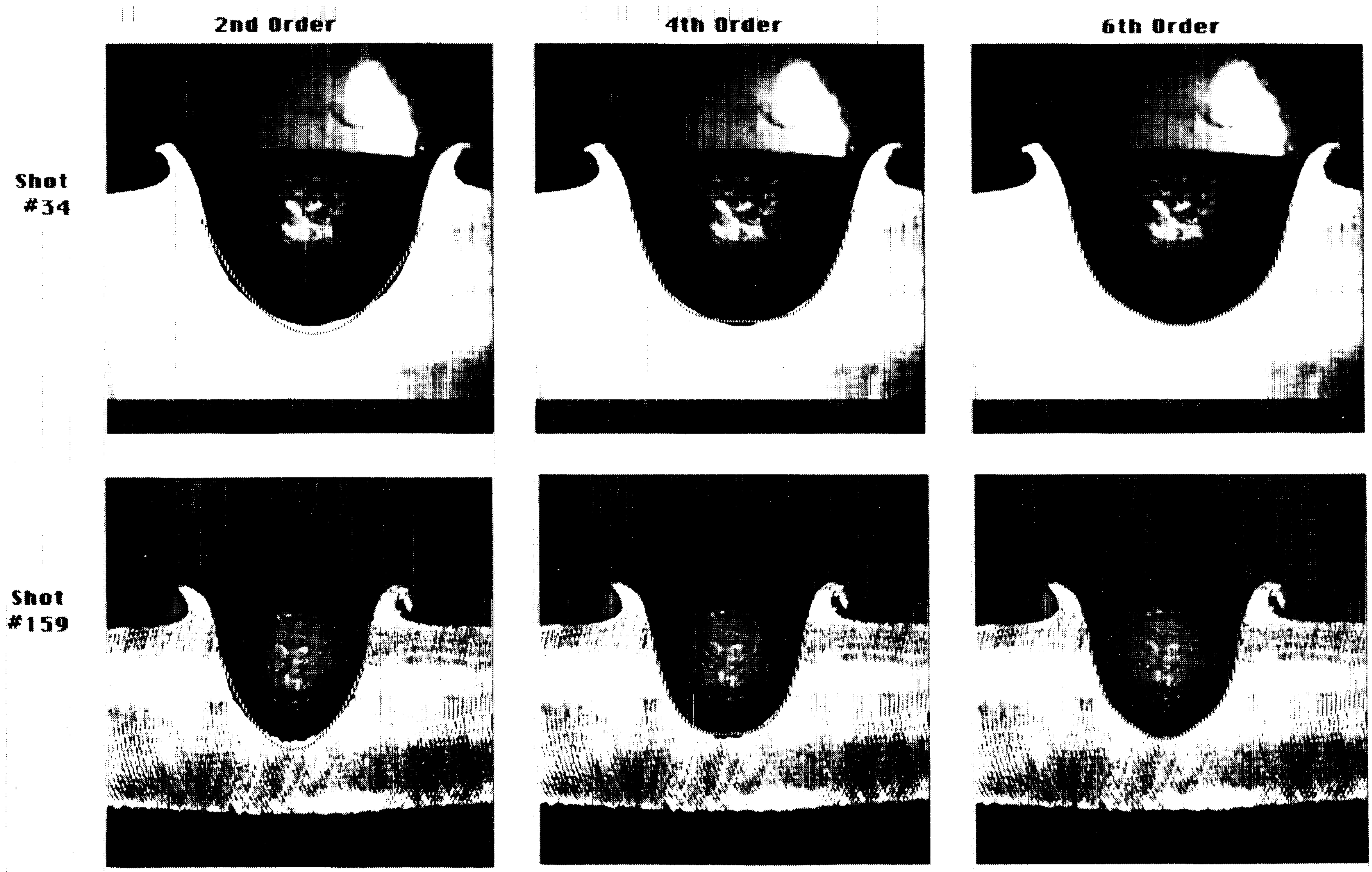


Figure 2 Comparison of polynomial 2-D curve fits for large cross-sectioned test craters in T6 aluminum. For two different craters (#s 34 and 159) fits to 2nd-, 4th- and 6th-order curves are indicated by stippled curves.

Table 1 Errors in Depth and Diameter Estimates For the Five Test Shots From Each Type of Curve Fit

	Depth Error (%)			Diameter Error (%)		
Shot #	2nd Order	4th Order	6th Order	2nd Order	4th Order	6th Order
34	5.57	-3.92	-2.43	9.80	2.07	1.11
148	7.14	-3.63	-1.89	6.29	0.70	-0.06
159	6.79	-3.97	-1.33	9.30	1.88	0.76
160	6.57	-3.39	1.44	8.46	1.47	-0.10
163	8.70	-3.61	1.57	7.69	1.26	0.04

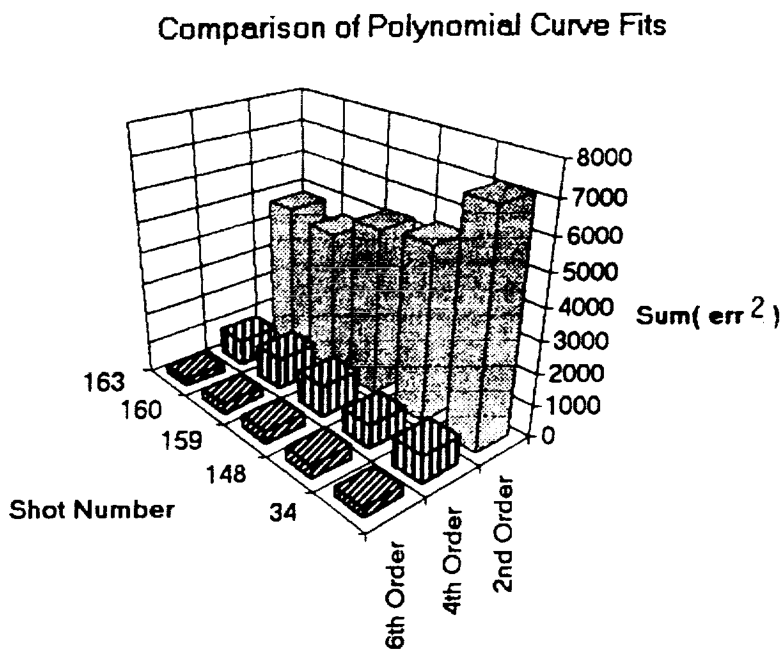


Figure 3 Summary of polynomial curve fits for all 5 large test craters. The vertical axis indicates the sum of square of the errors for diameter and depth.

When comparing the results of the cross-section study to the 3-D paraboloid fits on the three original test craters, a rather puzzling discrepancy arises: the 2-D parabolas were consistently deeper and wider than the actual craters, but the 3-D paraboloids were consistently deeper and *narrower* than the actual craters. The explanation for this discrepancy has not yet been determined. It is possible that findings of the cross-section study hold true only for the size range which was tested (7 - 20 mm, much larger than the LDEF impact craters), or perhaps the overall crater geometry is more a factor of the particle velocity upon impact. What seems more likely though is that the majority of the problem is due to input errors. The initial three (small) test craters had only 12, 9, and 7 tiepoints, while the five cross-sectioned craters had 66 to 111 data points. The effect that a single pixel of uncertainty has in the vertical is inversely proportional to two times the tangent of the angle of separation between the two cameras. In the cases being looked at here, that proportion is approximately four to one. This means that a single data point has about four times the uncertainty in the 3-D paraboloid analysis as a similar point in the 2-D polynomial curve fits. Also, the initial test crater images suffered from the same focus and depth of field problems, which increases the amount of error in the data point selection.

CONCLUSIONS AND FUTURE WORK

The conclusions based on the work done thus far is that the assumption that impact craters are basically paraboloids is false, at least for the size ranges tested by cross-section. The current algorithm's sensitivity to input errors is also a major concern. Future testing needs to address the issue of algorithm sensitivity versus the number of input data points, as this was not addressed during the initial sensitivity testing. Further cross-section tests are planned for smaller craters to determine if the initial results of the cross-section tests are size related. Investigations will be made into methods for minimizing the effect of input errors to the 3-D analysis. It may also be possible to derive a correction factor from the data which would enable the continued usage of the paraboloid fit to determine a crater's depth and diameter. We also hope to write a semi-automated tie-point selection routine which will use existing manually selected tie-points as 'seeds' to enable a much greater number of input data points. If this venture is successful, we may be able to perform a 6th order 3-D polynomial curve fit to the craters for a much more reliable crater definition.

REFERENCE

(1) See T.H., Allbrooks M.K., Atkinson D.R., Sapp C.A., Simon C.G. and Zolensky M.E. (1992) Meteoroid and Debris Special Investigation Group: Data Acquisition Procedures. LDEF - 69 Months in Space, NASA CP-3134, p.459-475.