EXPERIENCE WITH SHAPE-FROM-SHADING FOR THE REFINEMENT OF SPATIAL DATA FOR MARS CARTOGRAPHY FROM MARS EXPRESS HRSC IMAGERY

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Abstract

The paper is an account of investigations into the use of shape-from-shading (SFS) for the improvement of spatial data obtained from photogrammetric processing of HRSC (‘High Resolution Stereo Scanner Camera’) imagery on ESA’s Mars Express Mission. As one of seven scientific instruments on the Mars Express Orbiter, HRSC has been gathering data mainly for geological, atmospheric, and cartographic studies since January 2004. The paper first describes a process denoted De-Re-Shading for modifying illumination induced shades in the image scenes. Kernel is an SFS-method which, under certain conditions, enables a distinct refinement of the original DEM generated by image matching. This is the basis for subsequent modifications of the image shades towards homogenization and optimization of relief shading in the image maps. After a brief description of SFS in the context of Calculations of Variations and Least Squares Adjustment by directly solving the minimization functional, several promising results are discussed in some detail.

INTRODUCTION

Since January 2004 HRSC on Mars Express has collected an enormous amount of color and stereo image data that have been transmitted to Earth and processed by ESA and DLR. Until now some 45 Gbyte of raw data up to a resolution of ten meters have been processed from over 1600 orbits at altitudes of some 300 km above the surface of Mars. It is highly probable that the nominal mission ending in December 2005 will be extended another two years. This will enable the mapping of practically the entire planet in stereo. Lead by G. Neukum as Principal Investigator, the Mars Express HRSC Co-Investigator Science Team consists of five working groups, one of which is solely dedicated to the derivation of spatial data and generation of digital image maps. The other groups are concerned with mainly geological, mineralogical, spectrophotometrical and atmospheric studies that already have resulted in some breathtakingly new findings.

The Photogrammetry and Cartography working group aims at the generation of digital and analog orthoimage maps at various scales both for systematic and insular mapping for different applications. The topographic heights are derived from the HRSC stereo imagery by photogrammetric image matching. Since the fidelity of image matching is good only for regions with sufficient texture and contrast, topographic areas with little or no contrast – and these are abound on Mars – have to be processed by a complementary method. Most promising results have been obtained so far by shape-from-shading (SFS), a method originating from Computer Vision (see, e.g., Horn, 1970; Zhang et al., 1999). The principle of SFS as applied to planetary cartography has been shown in more detail in, e.g., (Dorrer et al., 1998) and (Dorrer, et al., 2004).

SFS will be presented in the following chapter in the context of a higher level process denoted De-Re-Shading (DRS). DRS aims at improving the quality of the generated orthoimage maps in terms of homogenization and optimisation of relief shading. It is envisaged that the entire method will be integrated in the general HRSC cartographic data processing flow. The last chapter will be a demonstration of recent results obtained through extensive experiments with HRSC data. Main emphasis has been placed upon presenting the refinement capability of SFS, in particular the improvement of topographic detail and its compatibility to relief shading in the orthoimage.
CONCEPT OF DE-RE-SHADING

By De-Shading we understand the process of extracting illumination induced shading from an (ortho-)image by modelling scene radiance reflected on the surface with the help of a prior digital elevation model (DEM). The modelling is carried out by shape-from-shading, and as a side-product the DEM will be substantially refined. In contrast to this, Re-Shading is considered as illumination of the SFS-refined DEM with an optimal light source direction in order to avoid relief reversal (optimisation) and seamline discontinuity (homogenisation) between adjacent scenes. Fig. 1 shows a certain scene illuminated under four different directions (see arrows). Notice that the two lower samples suffer from unwanted relief reversal. Fig. 2 is a mosaic of two scenes, yet with different illumination directions each. Note the distinct discontinuity in the middle.

The DRS process has been demonstrated in detail in (Dorrer, et al., 2004) and need not repeated here. In principle, the first part, viz., de-shading, is of rather high complexity and is based methodically on SFS as kernel; see next section. For a certain scene the procedure accepts preprocessed data only, viz., an orthoimage together with a prior DEM determined by photogrammetric image matching. These and other auxiliary data, e.g., field of sun direction, quality and completeness of the DEM, are provided by the DLR data processing group. Since the employed orthoimage is based upon the prior DEM, we will in the near future transfer our improved DEM back to the DLR group for the purpose of using it as basis for the derivation of an improved orthoimage. This in turn will then a second time be used for the SFS routine in a somewhat recursive process for further refinement.

In the second part, viz., re-shading, the SFS-refined DEM’s will simply be illuminated from a single optimal direction common to all processed neighbouring scenes in order to avoid relief reversal (Fig. 1) and discontinuities on the seamlines of the mosaicked scenes (Fig. 2). The latter homogenisation process has not yet been realised.

Shape-from-Shading (SFS)

SFS has been and still is treated in an extensive mathematics and theory oriented literature covering detailed problems of limited nature with mostly synthetic imagery. Real applications on a larger scale are rare, still under investigation, and have evolved relatively late in the context of planetary mapping. Because of the complexity of SFS, practically all of the studies may be considered still on the research level, even though the results presented here in the next chapter are rather promising. Interesting and important research works have been contributed by (Heipke, et al., 2001), (Kirk, et al., 2004), (Fua, 1997), (Dorrer, et al., 2004). An excellent yet mathematics restricted survey is given by (Zhang, et al., 1999). While pure shape-from-shading is confined to single images only, modern research wants to expand to multi-image concepts (Heipke, et al., 2001) or incorporate other constraints such as prior DEM (Dorrer, et al., 2004) or stereo (Fua, 1997).
Applied to real-world imagery, SFS is a non-trivial and—when restricted to single images—generally ill-posed problem. Therefore from the very beginning (Horn, 1970) various constraints were incorporated to ensure convergence to a somewhat smoothed solution, enforce integrability, and allow for additional or boundary information. Besides this mathematical property there are limitations to SFS from the physics point of view. These are limited knowledge of the reflectance model, i.e., the bi-directional reflectance distribution function (BRDF), hence the balance between diffuse and specular reflection, surface albedo, i.e., the degree of reflectivity as a function of space-variant surface material, shadow regions and their special treatment, etc. In our current approach we use Lambert reflection, i.e. constant BRDF, and constant surface albedo.

Methodically SFS is a problem of the Calculus of Variations with constraints and has mostly been treated as such, the reason being that both the elevation, $Z$, and its partial derivatives, $(p,q)$, occur as unknowns. In our approach we expressed the derivatives as convolutions of $Z$ with appropriate difference filters, thus leading to a Least Squares problem. In the continuous domain the basic SFS-equation is defined by the minimization integral

$$J(Z) = \int W \left( E - r R(p,q)^2 + I Q (Z - Z^{(0)})^2 \right) dX dY \ b \ \min$$

(1)

taken over a scene $W$ in the $(X,Y)$-plane. In this equation $Z$ represents the surface of the desired DEM, $Z^{(0)}$ is the prior DEM. $E$ is the irradiance (brightness) of the given orthoimage, $R$ is the modelled reflected scene radiance, $Q$ as quality height model is assumed to be proportional to the variance of $Z$, and $M$ is a shadow mask determined automatically via a proper threshold value. $I$ is a “penalty” factor weighing the significance of the elevation term against the irradiance term and $r$ is a constant factor representing albedo. It can be determined from

$$r = \frac{\int E dX dY}{\int R^2 dX dY}.$$  

(2)

Equ. (1) in discretized form is used iteratively by variation of $Z$, viz., by using the method of Conjugate Gradients, until the functional $J$ becomes minimal. For more detail see (Dorrer, et al., 2004). The method has been programmed in C. On a standard PC even scenes as large as 2000 by 2000 may be processed within 15 minutes of time.

**DISCUSSION OF RESULTS**

In the development process of a stable SFS-software package we have carried out a series of experimental tests by using genuine HRSC data. Preprocessing of the original data was carried out by DLR’s data processing Co-I Team group. The following examples result from our current program version that still has to be further refined and extended. In principle, and despite a few minor program deficiencies, the results confirm the refinement potential of SFS. They will be briefly discussed. The different scenes are from the two neighbouring orbits 905 and 927 that were taken over the Nanedi region at about 50° western longitude and between the equator and 14° northern latitude of Xanthe Terra. The topography is characterized by a heavily cratered, otherwise flat, surface generally inclined towards North and interspaced with several outflow channels and valleys. The surface lies below zero level with elevations ranging from 0 to –4000 m. All orthoimages have a pixel resolution of 50 m on the ground.

The pictures that represent only a small portion of many more examples, are composites of orthoimages and contour lines both from the prior photogrammetric DTM at the left and the DTM refined by SFS at the right. In this way the different “contour orthoimage maps” can be directly compared and assessed. In all examples, particularly obvious differences are marked by circles. The human viewer can easily note that the SFS-refined contour lines adapt extremely well to the surface topography perceived by relief shading. Both relief shading and contour lines build an entity, i.e., contour lines and shading seem to represent the same topography. This is not or much less the case with the contour lines derived from the prior DTM.

Fig. 3 shows a sort of alluvial fan as outflow relics from the channel valley above. The image covers an area of 11.5 km by 16 kmAs can be seen in the left image the prior 20-m-contours fail to represent minute topographic detail such as the lower fan terrace or some of the mountain ridges. The refined contours in the right image adapt to relief shading to a much higher degree. They appear to be much more regular, i.e. there is higher correlation between neighbouring contour lines, a sure sign of better quality. Fig. 4 shows a 5km by 5km area right on the NE-edge of a larger crater. A number of ridges as well as the transition from steep to flat slopes are much better represented in the right image. Note particularly the cirque-like feature on the upper right which is practically neglected by the prior contours in the left image, however shows perfectly in the refined contours image.
Figure 3. Comparison of contour lines (interval 20 m) between prior DTM (left) and SFS-refined DTM (right). Size 11,500m by 16,000m, maximal height difference 1375m

Figure 4. Comparison of contour lines (interval 20 m) between prior DTM (left) and SFS-refined DTM (right). Size 5,000m by 5,000m, maximal height difference 818m
OUTLOOK

Our current software prototype version has demonstrated that under certain conditions shape-from-shading is capable of a substantial refinement of given DTM’s. This is true even though there still exists a number of limitations and deficiencies. E.g., we are restricted to surfaces with a single albedo region only. SFS cannot, in principle, determine both elevation and albedo. However, it seems at least conceivable that a few different, clearly defined albedo regions may be processed by SFS. The Lambertian reflection law used, i.e., perfect diffuse reflection, is merely a rough approximation to a real BRDF. There do exist several other and perhaps more realistic reflection laws, yet applying these to SFS requires substantial research work. In spite of this, our results so far not only encourage us to continue with research but also seem to have a quality needed for applications such as in geology and cartography.

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