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A new shape from shading technique with application to Mars Express HRSC images ☆

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ABSTRACT

We have developed a new optimisation based shape from shading algorithm which is able to make use of sophisticated camera and reflectance models and does not require a good initialising surface. Surface shape consistent with ground truth is obtained when the technique is applied to both synthetic rendered surfaces and real images captured by the Mars Express orbiter and HRSC instrument. The obtained surfaces provide improved fine surface detail over that found using stereo techniques and demonstrate the applicability of the technique to real images.

1. Introduction

1.1. Literature review

Shape from shading (SFS) is a technique for estimating surface shape from a camera image using variations in the observed brightness across that surface. Many different techniques for achieving this have been proposed, and can usually be considered as being either propagation or optimisation based.

Propagation methods for solving the SFS problem start with knowledge of the surface height at a number of known points and gradually extend that known area by calculating the height at neighbouring positions. Since Horn's method of characteristic strips (Horn, 1970), there have been a number of variations on this theme. The level sets (Kimmel and Bruckstein, 1994), and fast marching (Kimmel and Sethian, 2001; Tankus et al., 2005; Yuen et al., 2007) methods have been shown to work well for smooth surfaces with known surface height at local maxima. These have included the use of perspective camera models. A similar approach to propagating surface height is expressed by the minimum downhill principle (Bichsel and Pentland, 1992).

Although propagation SFS algorithms have achieved very good results on relatively simple surfaces, the problem of initialising local height maxima to the correct values is still unsolved for realistic surfaces (despite some interesting recent progress on enforcing smooth traversals (Zhu and Shi, 2006)).

Optimisation techniques for SFS minimise a cost function which describes how well the estimated surface approximates the input image. They usually also include additional penalty terms in the cost function to prevent incorrect minima of the cost function being found. Early work by Horn (Horn and Brooks, 1986; Horn, 1990) provides a good introduction to this approach. Kirk's algorithm (Kirk, 1987), and its application to Mars images (Kirk et al., 2003) demonstrates good results if the initial shape estimation stage is successful, but can perform badly otherwise. The use of conjugate gradient descent to refine an initial surface estimate (assumedly from a stereo technique) has been popular (Leclerc and Bobick, 1991; Thompson and Clay, 1993; Fassold et al., 2004), but can suffer from finding bad local minima if the initial shape is not close to that of the real surface. A deformable model formulation (Samaras and Metaxas, 2003) has been shown to effectively recover shape and refine reflectance parameters for relatively simple surfaces. This included the use of the diffuse reflectance model presented by Oren and Nayar (1994). A recent variation has been the use of appearance similarity matching as an additional term in the cost function (Huang et al., 2007). Zhang et al. (1999) provide a review paper which can be referred to for a review of a selection of older shape from shading algorithms.

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1.2. Problem description

A review of the literature indicates that there is a need for a SFS technique which satisfies a number of requirements for application to real images and has been tested on such data. We consider the most important requirements to be reliable achievement of good results without any initial surface shape knowledge, and use of flexible camera and reflectance models. Specifically, the camera model must be capable of representing orthographic, perspective, and push-broom cameras. The reflectance model should be able to represent any bi-directional reflectance distribution function so as to allow the modelling of surfaces which exhibit some degree of specularity, rather than just the commonly used Lambertian reflectance model.

1.3. HRSC DEM generation review

To demonstrate practical application of the proposed shape from shading algorithm, we apply it to imagery captured by the Mars Express High Resolution Stereo Camera (HRSC) (Neukum and Jaumann, 2004). There has been a considerable amount of work reported in the literature on the comparison of digital elevation models created from HRSC images (Albertz et al., 2005; Dorrer et al., 2004; Heipke et al., 2007), and of HRSC models with those from other missions (Kim and Muller, 2009). This has included the use of SFS to refine models created using stereo techniques. The work presented here is significantly different in that we use only SFS to generate elevation models, and do not initialise the SFS process using a stereo generated model.

2. A new SFS algorithm

2.1. Definitions

Given a single greyscale image I of a surface with relative height function $U(x,y)$ with x and y defined parallel to the camera focal plane, the task of SFS is to find U across visible (x,y) such that the surface derivatives $p(x,y) = \frac{\partial U}{\partial x}$ and $q(x,y) = \frac{\delta U}{\delta y}$ best satisfy constraints imposed by I.

Previously, U has been defined on a discrete height grid, and p and q are defined as their discrete approximations. However, in this case we use a depth grid $D_{(i,j)}$ defining depths along unit viewing vectors $V_{(i,j)}$ at each point (i,j) from offset positions $O_{(i,j)}$. The assumed projection model for the image $I(i,j)$ is therefore defined by the vector grid V and offset grid O as shown in Fig. 1.

A reflectance function $R(p,q,v)$, where v is a unit viewing direction vector defines the surface reflectance properties so that given a current estimate U' (defined on D) of the true surface U, the resulting modelled image brightness can be found for each point in D. The calculation of this image brightness from surface orientation allows the construction of a brightness constraint or image irradiance equation.

$$I_{(i,j)} = R(p(i,j), q(i,j), V_{(i,j)}) \tag{1}$$

This is a requirement that the modelled brightness must be the same as the observed brightness in the original image and can be re-arranged to provide a cost function which can be minimised numerically.

$$f_b = \sum_{i,j} (I_{(i,j)} - R(p(i,j), q(i,j), V_{(i,j)}))^2 \tag{2}$$

It is assumed here that the image has been calibrated so that image intensity I is proportional to image irradiance and that a scaling factor has been included in the reflectance function so that $R(p,q,v)$ models calibrated image intensity, not irradiance.

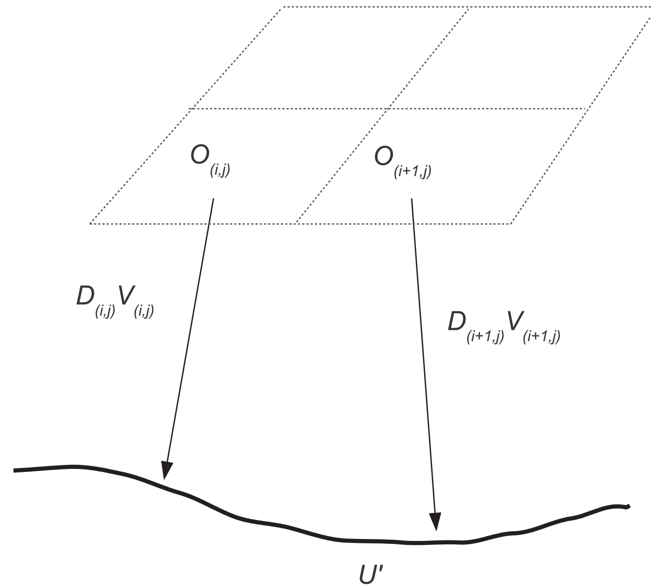

Fig. 1. Diagram showing the definition of the current surface estimate U' using an offset position grid O, depth grid D and viewing direction grid V.

2.2. Reflectance models

Two reflectance models are considered. Firstly, the Lambertian model given by

$$R(p,q,v) = \alpha \frac{p.\ell_x + q.\ell_y - \ell_z}{\sqrt{p^2 + q^2 + 1}} \tag{3}$$

is used. Here, ℓ is the unit light direction vector and α is a scaling factor related to the surface albedo and camera response.

Secondly, the simplified Oren–Nayar diffuse reflectance model (Oren, 1994) is considered. This is given by

$$R(\theta_r, \theta_i, \phi_r, \phi_i, \sigma) = E cos\theta_i (A + B\, Max[0, cos(\phi_r - \phi_i)] sin\alpha\ tan\beta) \tag{4}$$

$$A = 1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}$$

$$B = 0.45 \frac{\sigma^2}{\sigma^2 + 0.09}$$

where E is a combination of constants in the original specification, $\alpha = Max[\theta_r,\theta_i]$, $\beta = Min[\theta_r,\theta_i]$ and σ is a roughness factor. The angle of incidence is given by θ_i, the angle of reflection by θ_r and ϕ_i, ϕ_r are the azimuth angles for the light and viewing vectors, respectively.

In both cases p and q are calculated using central differences on the depth grid. The forward difference is not used as it can result in a surface with excessively sharp changes in gradient perfectly modelling a surface with a smooth image intensity gradient.

Although the SFS algorithm we describe here may use a different reflectance model at each grid point, we use a spatially constant model for all experiments shown here because we do not currently have a technique for estimating varying reflectance parameters for a real surface.

2.3. Camera model

By defining the camera projection model in terms of V and O, it is possible to represent a number of common camera types.

Orthographic camera model: