ISPRS Journal of Photogrammetry and Remote Sensing 136 (2018) 58–72

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Effects of illumination differences on photometric stereo shape-and-albedo-from-shading for precision lunar surface reconstruction

Wai Chung Liu [a], Bo Wu [a,*], Christian Wöhler [b]

[a] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hung Hom, Hong Kong
[b] Image Analysis Group, TU Dortmund, Dortmund 44227, Germany

ARTICLE INFO

Article history:
Received 10 November 2017
Received in revised form 18 December 2017
Accepted 19 December 2017

Keywords:
Surface reconstruction
Shape-and-albedo-from-shading
Photometric stereo
Illumination differences
LROC NAC

ABSTRACT

Photoclinometric surface reconstruction techniques such as Shape-from-Shading (SfS) and Shape-and-Albedo-from-Shading (SAfS) retrieve topographic information of a surface on the basis of the reflectance information embedded in the image intensity of each pixel. SfS or SAfS techniques have been utilized to generate pixel-resolution digital elevation models (DEMs) of the Moon and other planetary bodies. Photometric stereo SAfS analyzes images under multiple illumination conditions to improve the robustness of reconstruction. In this case, the directional difference in illumination between the images is likely to affect the quality of the reconstruction result. In this study, we quantitatively investigate the effects of illumination differences on photometric stereo SAfS. Firstly, an algorithm for photometric stereo SAfS is developed, and then, an error model is derived to analyze the relationships between the azimuthal and zenith angles of illumination of the images and the reconstruction qualities. The developed algorithm and error model were verified with high-resolution images collected by the Narrow Angle Camera (NAC) of the Lunar Reconnaissance Orbiter Camera (LROC). Experimental analyses reveal that (1) the resulting error in photometric stereo SAfS depends on both the azimuthal and the zenith angles of illumination as well as the general intensity of the images and (2) the predictions from the proposed error model are consistent with the actual slope errors obtained by photometric stereo SAfS using the LROC NAC images. The proposed error model enriches the theory of photometric stereo SAfS and is of significance for optimized lunar surface reconstruction based on SAfS techniques.

1. Introduction

Photoclinometric surface reconstruction methods such as Shape-from-Shading (SfS) and Shape-and-Albedo-from-Shading (SAfS) estimate the three-dimensional (3D) shape of a surface on the basis of its interactions between an illumination source and a sensor through the image intensity of each pixel. Each pixel contains the combined information of the slope and the other physical properties such as albedo and roughness. SfS or SAfS aims at solving for slope information and convert it into 3D shapes. These techniques have been used for lunar and planetary surface reconstruction (Lohse and Heipke, 2004; Grumpe et al., 2014; Wu et al., 2018) to improve the quality of mapping products such as digital elevation models (DEMs) and are well-known for creating pixel-wise DEMs even in textureless areas where image matching is ineffective (Lohse and Heipke, 2004). Lunar and planetary DEMs are critical to most extraterrestrial scientific and engineering applications, and hence, the incorporation of SfS or SAfS methods into conventional surface reconstruction routines such as stereo photogrammetry and laser altimetry has gained considerable attention (Kirk et al., 2003b; Grumpe et al., 2014; Wu et al., 2018).

More robust SfS or SAfS surface reconstruction results can be achieved by incorporating images of the same location under different illumination conditions (e.g., images with sunlight coming from different angles). This is referred to as photometric stereo (Woodham, 1980). Multiple illumination directions allow for a more reliable determination of surface slopes and hence, better reconstruction. In practice, the availability of multiple illumination directions is limited depending on the target body and the mission design. For example, images of lunar equatorial areas are usually illuminated either from the east or from the west (Wöhler, 2004). In this case, the quality of reconstruction is likely to depend on the azimuthal difference between the illumination sources of the images as it directly implies an abundance of excess information.

* Corresponding author at: Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
E-mail address: bo.wu@polyu.edu.hk (B. Wu).

https://doi.org/10.1016/j.isprsjprs.2017.12.010
0924-2716/

However, an explicit and systematic analysis of the relationship between the quality of the SfS or SAfS reconstruction and the illumination difference is not common, which bases quality estimation mainly on experience or the rules of thumb. In this paper, we present an algorithm for photometric stereo SAfS and an error model that describes the relationship between the illumination difference and the SAfS reconstruction quality. Doing so can allow for (1) the estimation of the SAfS slope error on the basis of known information (i.e., illumination conditions and image statistics) prior to any actual process and (2) the estimation of the relative quality between multiple pairs, which can help in choosing the best pair or adjusting the weights among pairs if multiple photometric stereo pairs are used. The rest of this paper is organized as follows: After a literature review of photoclinometric surface reconstruction in Section 2, the photometric stereo SAfS algorithm and the mathematical derivation of the error model are described in detail in Section 3. Then, the error model is verified by using real lunar images from the LROC NAC in Section 4. Finally, the findings are concluded and discussed in Section 5.

2. Related work

Single-image Shape-from-Shading (SI-SfS) (Horn, 1990) is the most fundamental form of photoclinometric surface reconstruction. Profiles parallel to the illumination direction are referred to as characteristic strips and contain the richest shape information as they depend most strongly on the light source direction (Horn, 1977). In photoclinometry, the 3D shape of a surface is related to the reflected energy (i.e., image intensity) by reflectance models such as Lambert, lunar-Lambert (McEwen, 1991), and Hapke (Hapke, 1981, 1984, 1986, 2002); however, this relationship describes the slope of the surface, which implies an underlying shape, instead of the actual 3D shape of the surface (i.e., 3D points or heights). Kirk (1987) and Horn (1990) proposed algorithms for implementing SI-SfS in image-based slope estimation to generate 3D shapes (e.g., DEMs) from the estimated slopes. These algorithms have laid the foundation for the use of SfS in planetary mapping and scientific applications. For example, SfS derived DEMs were used for safety assessment of the Mars Exploration Rovers (MER) landing sites (Kirk et al., 2003b) and the candidate Mars Science Laboratory (MSL) landing sites (Beyer and Kirk, 2012). SfS algorithms have also been implemented in the USGS Integrated Software for Imaging Spectrometers (ISIS) (Kirk et al., 2003a). They were also used in scientific studies such as spectral analysis of lunar surface (Wöhler et al., 2014) and lunar crater analysis (Salamunićcar et al., 2014). Photoclinometric surface reconstruction performs well in local scale reconstruction but has poor large scale accuracy. Thus, methods have been developed (Grumpe et al., 2014; Wu et al., 2018) by incorporating low-resolution 3D information (e.g., low-resolution DEMs) into SI-SfS algorithms. These algorithms have successfully improved large scale accuracy while maintaining high-resolution local scale detail of the resulting DEM. DEMs or slope maps from SI-SfS have a resolution comparable to that of the input images, which is apparently higher than that of mapping products generated using other methods such as photogrammetry and laser altimetry, and can therefore provide better information for scientific and engineering purposes (Beyer and Kirk, 2012).

Simultaneously utilizing images acquired under different illumination conditions is referred to as photometric stereo. The idea of photometric stereo was first proposed by Woodham (1980), who defined it as images acquired under the same viewing condition but different illumination conditions. This condition generally holds for most remotely sensed images as they are usually taken in the nadir or near-nadir viewing geometry at different solar azimuth angles. Woodham (1980) demonstrated with synthetic examples that photometric stereo can be used for determining robust surface slopes and laid the foundation of photometric stereo photoclinometric reconstruction. Heipke (1992) introduced the use of photometric stereo in topographic mapping, which is referred to as multiple-image Shape-from-Shading (MI-SfS). This concept was further developed and investigated for planetary mapping and modeling (Lohse and Heipke, 2004; Wöhler, 2004; Lohse et al., 2006). MI-SfS gives plausible results in textureless areas and has demonstrated value in high-resolution surface modeling.

The result of photoclinometric surface reconstruction is affected by uncertainties from various sources. These error sources were critically reviewed by Jankowski and Squyres (1991); they include errors from imaging devices (e.g., noise) and the relevant planetary body (e.g., albedo and photometric function). Slope error models were developed on the basis of single-image photoclinometry to relate slope errors from photoclinometry to the addressed error sources. Uncertainties in photometric functions or reflectance models have been studied rigorously, and critical improvements have been made to minimize or model these uncertainties. For example, Hapke (1984) addressed the effects of macroscopic roughness of a surface to its reflectance and proposed a modified version of the Hapke (1981) model with considerations of roughness. Labarre et al. (2017) investigated the roughness addressed by Hapke (1984) and proposed a simplified version of the model. Oren and Nayar (1994) proposed similar corrections related to roughness but on the basis of Lambert reflectance and a statistical estimation of surface roughness. These modified reflectance models have been used in photoclinometric reconstruction in later planetary mapping works such as O'Hara and Barnes (2012). The relationship between various error sources and the quality of photoclinometry has been studied in research conducted after Jankowski and Squyres (1991). For example, Greenberg et al. (2011) investigated the relationship between macroscopic roughness and the quality of photoclinometry, and highlighted the importance of error suppression strategies and considerations of uncertainties in photoclinometry. Liu and Wu (2017) addressed the relationship between photometric stereo SAfS and the azimuthal illumination difference, and suggested that the best combination of a photometric stereo pair would be at 90° (e.g., one image with sunlight coming from the north and the other with sunlight coming from the east) to yield results with minimal error. However, Liu and Wu (2017) did not consider the zenithal illumination differences.

3. Effects of illumination differences on photometric stereo SAfS

3.1. Photometric stereo SAfS algorithm

As shown in Fig. 1, the photometric stereo SAfS routine begins with a photometric stereo pair under given imaging and illumination conditions. At any point (x,y), its surface slope $(p,q)|_{x,y}$ should satisfy the following reflectance constraints:

$$G_i(p,q)|_{x,y} = \overline{G_i}\big|_{x,y} = \frac{I_i|_{x,y}}{A_{x,y}} \tag{1}$$

where for two images $i = (1, 2)$, $G_i(p,q)|_{x,y}$ is the reflectance model estimated using the surface slope (p,q) at point (x,y), $\overline{G_i}\big|_{x,y}$ is the expected reflectance computed by dividing the image intensity I_i by the intrinsic albedo $A_{x,y}$. It is insufficient to solve for p, q and $A_{x,y}$ simultaneously on the basis of these two reflectance constraints. However, Eq. (1) for $i = (1, 2)$ can be combined as follows:

$$\frac{G_1(p,q)|_{x,y}}{G_2(p,q)|_{x,y}} = \frac{\overline{G_1}\big|_{x,y}}{\overline{G_2}\big|_{x,y}} = \frac{I_1|_{x,y}}{A_{x,y}}\frac{A_{x,y}}{I_2|_{x,y}} = \frac{I_1}{I_2}\bigg|_{x,y} \tag{2}$$