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ScienceDirect

Advances in Space Research 56 (2015) 92–105

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Automated quantitative measurements and associated error covariances for planetary image analysis

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Received 12 June 2014; received in revised form 23 March 2015; accepted 25 March 2015
Available online 9 April 2015

Abstract

This paper presents a flexible approach for extracting measurements from planetary images based upon the newly developed linear Poisson models technique. The approach has the ability to learn surface textures then estimate the quantity of terrains exhibiting similar textures in new images. This approach is suitable for the estimation of dune field coverage or other repeating structures. Whilst other approaches exist, this method is unique for its incorporation of a comprehensive error theory, which includes contributions to uncertainty arising from training and subsequent use. The error theory is capable of producing measurement error covariances, which are essential for the scientific interpretation of measurements, i.e. for the plotting of error bars. In order to apply linear Poisson models, we demonstrate how terrains can be described using histograms created using a 'Poisson blob' image representation for capturing texture information. The validity of the method is corroborated using Monte Carlo simulations. The potential of the method is then demonstrated using terrain images created from bootstrap re-sampling of martian HiRISE data.

Keywords: Terrain; Texture; Likelihood; Statistics; Errors

1. Introduction

The analysis of planetary surface images represents an important aspect of many exploration missions. From the early 2000s there have been many high-profile missions launched within the inner solar system which have imaging capabilities. These include: Mars Odyssey (NASA, launched 2001); Mars Express (Wilson, 2004) (ESA, launched 2003); Mars Reconnaissance Orbiter (McEwen et al., 2007) (NASA, launched 2005); Mercury orbiter mission MESSENGER (Hawkins et al., 2007) (NASA, launched 2004); dual asteroid mission DAWN (Russell et al., 2007) to Ceres and Vesta (NASA, launched 2007); and the Moon mission Lunar Reconnaissance Orbiter (Houghton et al., 2007) (NASA, launched 2009). These missions have provided planetary scientists with almost complete coverage of Mars, Vesta, Mercury and the Moon, including significant subsets with resolutions down to 0.25 m.

Scientific applications for planetary images are numerous and varied. Most involve the identification and quantification of features of interest. For example, impact craters can provide a wealth of information regarding geological evolution. The total density of craters, as summarised using size-frequency distributions (SFD), can be used to infer relative surface ages (Neukum et al., 2001). There also is much interest in drainage systems on Mars, with recent seasonal flows being observed within the walls of some craters (Lanza et al., 2010). The distribution and orientation of ancient drainage systems can also be used

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http://dx.doi.org/10.1016/j.asr.2015.03.043
0273-1177/

to infer Mars' climate history (Irwin et al., 2011) and the timing of some geodynamic events (Phillip et al., 2001). Other example features are associated with an active carbon dioxide cycle on Mars, which is especially evident around the polar regions (Piqueux et al., 2003). Seasonal eruptions of sublimating CO_2 causes dark patches to appear around dunes, radiating fissures to develop known as 'spiders' and geysers to eject fans of dark material. The study of these events can help researchers better understand this CO_2 cycle. Additionally, the density, morphology and orientation of dunes can be used to estimate the availability and size of grains (Edgett and Christensen, 1991), and also wind speed and direction (Bagnold, 1974). However, the growing quantity of image data is rapidly out-pacing the resources available to individual researchers wishing to inspect large numbers of images in detail.

Citizen science and automated methods have both been proposed to alleviate the problem. High-resolution images are being mapped with the aid of large numbers of volunteers using web-based interfaces. These include the mapping of small lunar craters as part of the MoonZoo (Joy et al., 2011) and Moon Mappers projects (Robbins et al., 2012), and the mapping of seasonal carbon dioxide 'fans' on Mars via Planet Four (Hansen et al., 2013). Automated approaches to crater counting (Salamuniccar and Loncaric, 2010; Ding et al., 2010; Bandeira et al., 2010; Burl et al., 2001; Kim et al., 2005; Simpson et al., 2008; Bauer et al., 2011; Sawabe et al., 2005; Ding et al., 2008; Kamarudin et al., 2012; Wetzler et al., 2005), and valley and channel network mapping (Wei and Stepinski, 2009; Wei and Stepinski, 2006; Molloy and Stepinski, 2007) have also been tested with some success. Automated approaches tend to follow the same general design pattern: raw image data is encoded using a higher-level descriptive format (edge strings, Haar transform, texture descriptors, templates, etc.), before being fed into a classifier (decision trees Ho, 1995, support vector machines Steinwart and Christmann, 2008, boosting Freund, 1990, etc.) or searched for signal response peaks (Hough transforms, template matches, etc.) Performance is then evaluated empirically in terms of numbers of correct versus incorrect classifications. The reported efficiencies of these algorithms usually range between 60% and 80% for correct detections, with many false positives reported. These approaches tend to focus on specific types of features, limiting their applicability in general terrain analysis tasks. They also involve a minimal amount of error analysis, which is unfortunate given that quantitative scientific tasks must take careful consideration of noise and uncertainty if data is not to be over-interpreted. Ideally, all measurements should be presented with accompanying error information, including honest assessments of statistical errors and any systematic biases.

Whilst under-represented in the literature, theoretical (predictive) methods of error analysis do exist, but require a good understanding of the inner-workings of an algorithm, i.e. they represent white-box methods, as opposed to black-box methods where the inner-workings of an algorithm are hidden from their users. Advocates of a theoretical approach have analysed numerous low-level algorithms using statistical perturbation models (Ramesh and Haralick, 1992; Ramesh et al., 1997). The use of error propagation in computer vision (Haralick, 2000; Foerstner, 1994) has been demonstrated on tasks such as the extraction of 2D points and determining the accuracy of parameters of fitted shapes (Yi et al., 1994). It has also been applied to assess the performance of multi-stage shape extraction from 2D projections (Sun et al., 2001), and in the use of linear shape models (Ragheb et al., 2013). A comprehensive example of theoretical error analysis can also be found in Liu (2000), where propagated location uncertainty assists in target recognition in image data. Error propagation has also been used to investigate the effects of noise in Hough transforms (Ji and Haralick, 2001) and also in iterative algorithms (Qi, 2003), such as expectation maximisation (EM).

We present a generic terrain analysis system, incorporating a detailed error theory for the prediction of statistical and systematic sources of uncertainty, allowing measured values to be used with confidence. An overview of the technique is given in Section 2 before a detailed methodology in Section 3. An outline of this method can be seen in the block diagram of Fig. 1. We test this system using a range of terrain images, including craters, dunes and CO_2 cycle features in Section 4, followed by a discussion of the method's successes and limitations in Section 5 before concluding.

2. Problem specification and definition of terms

We have selected the problem of making surface area measurements of user-defined martian terrains and to achieve levels of accuracy predicted by a theoretical error analysis. This problem is to be solved in an automated manner, making use of high resolution digital imagery. To ease understandability of the proposed solution we present an overview of the problem and notations used before a detailed methodology is provided.

Visually, a terrain can be approximated as a mixture of repeating pixel patterns, with different combinations of patterns giving rise to different textures. Additionally, within any class of terrain (e.g. dunes) there will typically be multiple 'sub-textures' (e.g. ripples at differing orientations). Any local arrangements of pixels can be encoded as a binary vector $\mathbf{X} = \{X_1, X_2, \ldots, X_l\}$, with elements $X_i \in \{0, 1\}$, providing a maximum of $m = 2^l$ discrete observable patterns. A range of potential image encodings is available in the computer vision literature such as BRIEF, which can record local bright-dark patterns using pixel pair comparisons (Calonder et al., 2010). The specific BRIEF-based encoding selected for this work is described in detail in Section 3.1; for now it is sufficient to interpret this vector as an observation of a small image patch.