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High-precision co-registration of orbiter imagery and digital elevation model constrained by both geometric and photometric information

Xin Xin[a,b], Bin Liu[a,*], Kaichang Di[a,c], Mengna Jia[a,b], Jürgen Oberst[d,e]

[a] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, No. 20A, Datun Road, Chaoyang District, Beijing 100101, China

[b] University of Chinese Academy of Sciences, Beijing 100049, China

[c] Lunar and Planetary Science Laboratory, Macau University of Science and Technology—Partner Laboratory of Key Laboratory of Lunar and Deep Space Exploration, Chinese Academy of Sciences, Macau, China

[d] Technical University Berlin, Straße des 17, Juni 135, 10623 Berlin, Germany

[e] DLR Institute of Planetary Research, Rutherfordstr. 2, 12489 Berlin, Germany

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A B S T R A C T

The alignment of images to a reference digital elevation model (DEM) has many applications, especially in planetary exploration. In this paper, we propose a novel high-precision co-registration method for pixel-based matching between an image and a reference DEM to rectify the ever-increasing number of orbiter images to DEMs in a unified reference frame automatically. First, the DEM is converted to a simulated image using a hillshading technique based on a photometric model and the illumination conditions of the image. Then, an initial matching between the simulated and input images is performed based on affine scale-invariant feature transform (ASIFT). The rational function model (RFM) of the image is established and used as a geometric constraint. Then, with tie points (TPs) generated by the initial ASIFT matching, the RFM geometric model of the image is refined, and the gross errors in the TP set are iteratively eliminated. Finally, a high-precision co-registration by pixel-based Least-Squares (LS) image matching is performed using the refined geometric model. Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) and SLDEM2015 (a combined product of Lunar Reconnaissance Orbiter Laser Altimeter (LOLA) and a DEM generated by the Japanese Selenological and Engineering Explorer (SELENE) terrain camera) images are used in our experiment. Results using 17 NAC images at different latitudes demonstrate that the proposed co-registration method is effective and can attain an accuracy of 18.3 pixels in the image space and 25.17 m (0.5 pixel of the reference DEM) in the object space. The method offers an automatic and high-precision matching of LRO NAC images to SLDEM2015. It is also applicable to the co-registration of other orbital images to a reference DEM.

1. Introduction

With previous and ongoing planetary exploration missions, significant amounts of orbital data (e.g., images and laser altimetry data) have been acquired. Owing to the precision limitation of orbit and attitude measurements, there are widespread spatial inconsistencies among the multiple-source data such as multi-images and laser-altimetry-derived digital elevation models (DEMs). To fully exploit these data for scientific and engineering applications, it is necessary to co-register the data to a unified reference frame. Co-registration of images to a reference DEM can provide accurate control points for high-precision geometric processing of the images, including geometric model refinement, instrument calibration, and automatic rectification. Another application of the aligned images and DEMs is in the area of reflectance-based surface reconstruction. The high-precision co-registration of images and DEMs is required when constructing a higher-resolution DEM using a coarse DEM and a high-resolution image using shape-from-shading techniques (Grumpe and Wöhler, 2011, 2014; Wu et al., 2017).

As images and DEMs represent different types of surface information, a pixel-based (area-based) image matching method cannot be applied to an image and DEM registration directly. The co-registration between an image and a DEM is mainly feature-based, such as using craters and ridges (Michael, 2003; Wu et al., 2013). The performance of the feature-based matching method depends on the precision of the feature extraction, which is poor in featureless areas. The precision of feature-based matching methods is typically less than that of pixel-based methods. An approach for the registration of stereo images and a

* Corresponding author.
E-mail address: liubin@radi.ac.cn (B. Liu).

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DEM (or laser altimeter points) is based on a combined block adjustment where 3-dimensional (3D) laser altimeter points are back-projected to the stereo images and used as conjugate points (Soderblom and Kirk, 2003; Yoon and Shan, 2005; Wu et al., 2014). The altitude of the DEM or laser altimetry measurements is used as a constraint equation in block adjustment processing. Another approach for the registration of lunar stereo images and a DEM (or laser altimeter points) is based on surface matching using the iterative closest point algorithm (Di et al., 2012). However, these two approaches for the co-registration of stereo images and a DEM are not applicable to the co-registration of a single image and a reference DEM.

It should be noted that the matching methods mentioned above do not consider the radiometric information during the image in the matching process. In a previous research, pixel-based methods for matching imagery with DEMs considering radiometric information were proposed using earth observation data (Horn and Bachman, 1978). To perform the traditional pixel-based matching method, the simulated image with radiometric information was generated from a DEM by illuminating it with the illumination geometry information of the real image. This method was designed based on the assumption that the DEM itself, as well as its gradients, could be considered as an illumination-invariant representation of the image (Horn, 1977). This assumption does not hold in areas with a variety of surface features, especially in human settlements. Thus, this method was studied only in mountainous terrain without vegetative coverage.

Conversely, on the barren surfaces of the moon and Mars, this method would be more applicable. Similar studies of co-registration between altimeter tracks and images (Soderblom et al., 2002; Soderblom and Kirk, 2003; Nefian and Coltin, 2014) were also based on this assumption. These methods considered the radiometric information of the images; however, because of the large sampling interval of the laser altimeter, the quality of the simulated images was poor, limiting the precision of the co-registration. Thus, these methods are not widely used.

Based on the above literature review of matching methods for orbiter images and reference elevation data, we propose a novel method of pixel-based co-registration of lunar images and DEMs using both geometric and photometric constraints. First, the simulated image is generated based on the illumination condition of the orbital images. The rigorous sensor model (RSM) and rational function model (RFM) of the orbital image are established based on the SPICE (the abbreviation for Spacecraft, Planet, Instrument, Camera-Matrix, and Events) kernels (NAIF, 2014). Then, Harris feature points (Harris and Stephens, 1988) are extracted from the simulated image and back-projected to the orbital image as the initial matching tie points (TPs). Subsequently, a high-precision co-registration based on Least-Squares (LS) image matching is performed using a refined geometric model. From the co-registration, the RFM of the image is refined, and high-precision TPs between the image and the reference DEM are extracted simultaneously. Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images (Robinson et al., 2010) and SLDEM2015 (a combined product of Lunar Reconnaissance Orbiter Laser Altimeter (LOLA) and a DEM generated by Japanese Selenological and Engineering Explorer (SELENE) terrain camera images, Barker et al., 2016) images at different latitudes are used for experimental tests and validation of the proposed co-registration method.

2. Methodology

In the proposed method, the image is co-registered to a reference DEM through a pixel-based matching method using both geometric and photometric constraints. The framework of the proposed method is outlined in Fig. 1. Because the DEM has significantly lower resolution (60 m/pixel at equator) than the images (approximately 1.5 m/pixel) used in our experiments, we first upsample the DEM to the image resolution based on spline interpolation (Franke, 1982; Mitas and Mitasova, 1988). Then, the simulated images are generated using a hillshading technique based on the illumination conditions of the images. To obtain initial matching TPs and starting solution for the LS image matching, affine scale-invariant feature transform (ASIFT, Morel and Yu, 2009) is performed between the simulated and actual orbital images.

The RSM of the orbital image is established (Liu et al., 2017) based on the SPICE kernels. The RFM of the image is established based on the RSM and is used as a geometric constraint in the co-registration process. With TPs generated by the initial ASIFT matching, the RFM of the image is refined, and the gross errors of the TPs are iteratively eliminated. Then, evenly distributed feature points are generated on the simulated image and are projected onto the orbital image as predicted matching positions using the refined RFM. Finally, a high-precision co-registration based on LS image matching is performed and the geometric model is further refined.

2.1. Image simulation using DEM

In our research, image simulation is based on the hillshading technique. The key to this method is to present the reflectance of a small, flat surface as a function of the gradient of the terrain. An idealized reflectance model (the surface is assumed to be an ideal diffuser or Lambertian surface) is used in this case to establish the function (Eq. (1)) (Horn and Bachman, 1978; Horn, 1981) on the moon.

$$\Phi(p, q) = \rho\cos(i)/\cos(e) = \frac{\rho(1 + p_s p + q_s q)}{\sqrt{1 + p_s^2 + q_s^2}}$$
$$p_s = \sin(\theta)\cot(\phi),\ q_s = \cos(\theta)\cot(\phi) \tag{1}$$

where $\Phi(p, q)$ is the calculated simulated pixel intensity, i is the incidence angle, e is the emission angle, ρ is an albedo factor, θ is the solar azimuth of each image, ϕ is the solar altitude of each image (Fig. 2), p and q are the gradients of the surface in the line and sample direction, respectively, which can be estimated using the first-order differences of a small, flat surface of the DEM (Horn, 1981).

In this research, p and q for each pixel in the DEM are estimated based on eight-neighbor grid elevations. The solar azimuth and solar altitude used in Eq. (1) can be retrieved from the header file of the image. Then, the pixel intensity in the simulation image is calculated with the reflectance model. In the result, the simulated image has an illumination condition similar to that of the real image. The simulated image becomes a "bridge" to connect the DEM and the orbital image in pixel-based matching.

2.2. RFM and its refinement model

The RFM, which establishes the relationship between the image-space coordinates and object-space coordinates with the ratios of polynomials, is displayed in Eq. (2) (Di et al., 2003).

$$r = \frac{P_1(X, Y, Z)}{P_2(X, Y, Z)}$$
$$c = \frac{P_3(X, Y, Z)}{P_4(X, Y, Z)} \tag{2}$$

The three-order polynomials P_i (i = 1, 2, 3, and 4) have the following general form:

$$\begin{aligned} P_i(X, Y, Z) = {} & a_1 + a_2X + a_3Y + a_4Z + a_5XY + a_6XZ + a_7YZ + a_8X^2 \\ & + a_9Y^2 + a_{10}Z^2 + a_{11}XYZ + a_{12}X^3 + a_{13}XY^2 + a_{14}XZ^2 \\ & + a_{15}X^2Y + a_{16}Y^3 + a_{17}YZ^2 + a_{18}X^2Z + a_{19}Y^2Z + a_{20}Z^3 \end{aligned} \tag{3}$$

where a_1, a_2 …a_{20} are the coefficients of the polynomial function P_i, called the rational polynomial coefficients (RPCs). Construction of an RFM is a process of fitting the vast number of virtual points generated based on the RSM through an LS solution (Liu and Di, 2011; Liu et al., 2016). The RFM is considerably simpler and more independent of