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Automatic cloud detection for high resolution satellite stereo images and its application in terrain extraction

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The automatic extraction of terrain from high-resolution satellite optical images is very difficult under cloudy conditions. Therefore, accurate cloud detection is necessary to fully use the cloud-free parts of images for terrain extraction. This paper addresses automated cloud detection by introducing an image matching based method under a stereo vision framework, and the optimization usage of non-cloudy areas in stereo matching and the generation of digital surface models (DSMs). Given that clouds are often separated from the terrain surface, cloudy areas are extracted by integrating dense matching DSM, worldwide digital elevation model (DEM) (i.e., shuttle radar topography mission (SRTM)) and gray information from the images. This process consists of the following steps: an image based DSM is firstly generated through a multiple primitive multi-image matcher. Once it is aligned with the reference DEM based on common features, places with significant height differences between the DSM and the DEM will suggest the potential cloud covers. Detecting cloud at these places in the images then enables precise cloud delineation. In the final step, elevations of the reference DEM within the cloud covers are assigned to the corresponding region of the DSM to generate a cloud-free DEM. The proposed approach is evaluated with the panchromatic images of the Tianhui satellite and has been successfully used in its daily operation. The cloud detection accuracy for images without snow is as high as 95%. Experimental results demonstrate that the proposed method can significantly improve the usage of the cloudy panchromatic satellite images for terrain extraction.

1. Introduction

Dense image matching technology is the key to the automatic extraction of terrain surfaces from high-resolution satellite images. Common dense matching methods currently used with satellite images include the method presented by Toutin (2004), which computes parallax based on the normalized, multi-scale correlation coefficient. Then 3D coordinates of points are calculated using forward intersection. Zhang and Gruen (2004, 2006) established the multiple primitive multi-image (MPM) matching for stereo satellites such as IKONOS. This method addresses areas with poor or repetitive textures. Zhang and Fraser (2009) improved upon this method. In addition, Krauß et al. (2005a,b) proposed an effective dynamic time-warping algorithm. Hirschmuller (2005, 2008) also presented a semi-global matching algorithm, which was used by d'Angelo (2010) to effectively process images obtained from the stereo satellite WorldView-2. Consequently, d'Angelo and Kuschk (2012) developed a method to eliminate blunder stereo matches with two images. This technique displays sub-pixel accuracy and was generated using the matching method based on frequency domain, which was presented by Nagashima et al. (2006). Xu et al. (2013) also used the matching method based on frequency domain to effectively match digital surface models (DSMs) from satellite images with short base lines.

Satellite image information is lost because of clouds, and the automatic extraction of terrain information are inaccurate (Grün, 2000). Cloud coverage is an important indicator of image quality. As a result, cloud detection is necessary in satellite image processing and distribution systems. In a ground processing system, the cloud coverage percentage should be estimated and recorded into the metadata. This information is also helpful for data query and ordering, and can improve the efficiency of data distribution. When

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panchromatic images are used for this purpose, the main difficulties are caused by irregular distribution of clouds, e.g., thick and gauzy clouds, and the existence of snowy areas on the ground that may have similar brightness and spectral characteristics as clouds.

Considerable research has been conducted on these issues (Jedlovec, 2009) .The primary methods developed can be classified into three categories:

(1) Methods based on mono temporal images: The characteristic of multispectral bands is used for threshold segmentation (Kubo et al., 2001; Marais et al., 2011; Zhang et al., 2002) and classification (Gao et al., 2003; Wang et al., 2013) .Automatic cloud cover assessment is the most widely used method (Irish, 2000; Soille, 2008; Watmough et al., 2011). The penetrability of the infrared band also efficiently prevents cloud disturbance in satellite images through atmospheric correction to facilitate the effective extraction of cloudy areas. This method is extended to MODIS and SeaWiFS images (Liang et al., 2001; Liang et al., 2002). Furthermore, infrared bands are used to reduce the influence of clouds by recovering information in the visible spectrum bands (Wang et al., 2005). Clouds and shadows are combined using a Markov random field to detect clouds (Le Hégarat-Mascle and André, 2009).A detail map is constructed to help detect cloud using RGB color images (Zhang and Xiao, 2014).

(2) Methods based on multi-temporal images: Time series analysis and threshold segmentation are used to detect cloud (Champion, 2012; Derrien and Le Gléau, 2010; Dinchang et al., 2008; Gabarda and Cristobal, 2007; Hagolle et al., 2010; Liew et al., 1998). Some supervised classification methods, such as neural network, K-nearest neighbor, self-organizing feature map, and support vector machines, are widely used (Hau et al., 2008; Hughes and Hayes, 2014; Jang et al., 2006; Laban et al., 2012) . Clouds and shadows are simultaneously detected using two date images (Jin et al., 2013).

The abovementioned detection results of threshold segmentation and classification methods based on single-temporal images are closely related to the threshold, the selection of which is difficult. The influence of snowy and hazy areas is also difficult to exclude. Plantations, irrigation, and bare land easily influence cloud detection in cloud-shadowed areas. When multispectral images are used to detect clouds, atmospheric correction becomes a pre-processing step. Furthermore, methods based on multi-temporal images may incorrectly classify these images because of the changing features over time, the discrepancies in hue among different temporal images, and the registration error.

(3) Methods based on stereo vision: Panem et al. (2005) presented a method to automatically extract cloudy areas based on stereoscopic vision using SPOT5 images. The parallax of images can be obtained by dense match after aligning panchromatic and multispectral images with shuttle radar topography mission (SRTM). Parallax changes are significant at the edges of cloudy areas; therefore, these areas can be automatically extracted. Given the short baseline between panchromatic and multispectral images, this method can extract only clouds higher than 600 m. Cloudy areas are positioned differently in two separate images and thus the cloudy areas extracted using this method are larger than those in a single image. Moreover, cloudy areas are extracted through horizontal parallax without considering vertical parallax. Considerable research has used stereo to retrieve the cloud top height (Manizade et al., 2006; Marchand et al., 2010; Marchand et al., 2007; Naud et al., 2006; Naud et al., 2002; Seiz, 2003; Zong et al., 2002) .Muller et al. and Denis et al. assumed that wind has no effect on the clouds along the track between two stereo images (Denis et al., 2007; Muller et al., 2007). Wind information is necessary under certain condition. They also emphasized the match methods in cloudy areas. Their methods are mostly based on low-resolution images. This situation cannot always be true on high-resolution images. The cloud moves and its shape changes. Therefore the dense matching results are unpredictable. Figs. 1 and 2 show that the cloudy areas cause considerable errors to dense match results. The matched points in cloudy areas are sometime lower or higher than the terrain. The images in Fig. 1 are from a stereo of IKONOS, and those in Fig. 2, are from a triple stereo of ZY-3.

Clouds cause errors in image matching, but this is helpful for cloud detection. The proposed method takes advantage of the prior knowledge that the clouds are separated from the non-cloud terrain. Compared with other stereo cloud detection methods, the proposed method does not emphasize the accuracy of the match results of cloudy areas, and utilizes stereo matches with a large difference to the reference digital elevation model (DEM) as seed points for the image based region growth to reliably detect cloudy areas. But some areas, such as those with inadequate texture, glacier and snowy areas cause errors in dense match. These areas have significant height differences with the reference DEM. These areas except glacier and snowy areas can be distinguished when the image information is used. The glacier and snowy areas are similar to the cloudy areas in intensity when only panchromatic images are used, so the characteristics of the dense match results are integrated to classify the cloud area.

The proposed method is on the basis of the distinct characteristics of clouds on images and DSMs. The main difference of the proposed method is that the movements and shape changes of clouds are considered in the stereo framework using high resolution images. Firstly, a matching DSM (M-DSM) is obtained through the dense matching of stereoscopic images. After the M-DSM is registered with the reference DEM, the elevations are compared to extract seed points of potential cloudy areas. Then, cloudy areas are classified by combining the image information and height information. Finally, the inaccurately matched areas in M-DSM that are attributed to cloud coverage are replaced by the reference DEM. The rest of the paper is structured as follows: Chapter 2 presents the main process of the proposed method. Chapter 3 displays the experimental results and analysis. Chapter 4 summarizes and concludes the study.

2. Methods

The main process of the proposed method is illustrated in Fig. 3. The process involves the use of existing DEM data as reference, with which the image based DSM is compared to create a difference DEM after registration. The regions in the difference DEM that have significant elevation differences are regarded as potential cloud coverage. Then the cloud detection combines the image information and DEM difference results. Finally, the inaccurately matched areas in M-DSM are filled on the basis of the obtained cloud coverage.

2.1. DSM generation and co-registration

The dense matching method utilized in this study is MPM matching, which can automatically generate DSMs under complex terrain conditions, such as large arid and semi-arid loess landforms, steep mountainous areas, and large deserts (Zhang and