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Photovoltaic panel extraction from very high-resolution aerial imagery using region–line primitive association analysis and template matching

Min Wang [a,b,*], Qi Cui [a,b], Yujie Sun [a,b], Qiao Wang [c]

[a] Key Laboratory of Virtual Geographic Environment (Nanjing Normal University), Ministry of Education, Nanjing, Jiangsu 210023, PR China
[b] Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, Jiangsu 210023, PR China
[c] Satellite Environment Application Center, Ministry of Environmental Protection, Beijing 100029, PR China

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ABSTRACT

In object-based image analysis (OBIA), object classification performance is jointly determined by image segmentation, sample or rule setting, and classifiers. Typically, as a crucial step to obtain object primitives, image segmentation quality significantly influences subsequent feature extraction and analyses. By contrast, template matching extracts specific objects from images and prevents shape defects caused by image segmentation. However, creating or editing templates is tedious and sometimes results in incomplete or inaccurate templates. In this study, we combine OBIA and template matching techniques to address these problems and aim for accurate photovoltaic panel (PVP) extraction from very high-resolution (VHR) aerial imagery. The proposed method is based on the previously proposed region–line primitive association framework, in which complementary information between region (segment) and line (straight line) primitives is utilized to achieve a more powerful performance than routine OBIA. Several novel concepts, including the mutual fitting ratio and best-fitting template based on region–line primitive association analyses, are proposed. Automatic template generation and matching method for PVP extraction from VHR imagery are designed for concept and model validation. Results show that the proposed method can successfully extract PVPs without any user-specified matching template or training sample. High user independency and accuracy are the main characteristics of the proposed method in comparison with routine OBIA and template matching techniques.
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1. Introduction

Object-based image analysis (OBIA) generally follows the technical route of "segment and then classify," in which segments become the object primitives for subsequent feature extraction and analysis. By utilizing its rich features, OBIA can be a better choice than pixel-based image analysis (PBIA) for extracting information from high-spatial-resolution images (Benz et al., 2001, 2004; Blaschke, 2010; Myint et al., 2011; Blaschke et al., 2014; Robson et al., 2015). After decades of development, OBIA has been recognized as the "paradigm" technique for extracting information from a median-/high-resolution imagery (Blaschke et al., 2014).

OBIA generally extracts information by rule- or sample-based classification (Blaschke et al., 2014; Cheng and Han, 2016; Ma et al., 2017). For rule-based OBIA, rule flexibility and transferability (Hofmann et al., 2011) are critical issues. Moreover, supervised classification highly relies on training samples, either in OBIA or PBIA. In recent years, along with the advent of deep learning techniques, studies have combined image segmentation with deep neural network for classifying remote sensing images (Liu et al., 2015; Gonzalo-Martin, 2016; Audebert et al., 2016; Cheng, et al., 2016). However, currently, a large volume of training data are generally required for deep-learning-based classification (Krizhevsky et al., 2012; Lecun et al., 2015; Zhang et al., 2016a, 2016b; Han et al., 2018).

Although differences in stages such as feature extraction and classification exist, mainstream OBIAs commonly feature a segmentation-driven, region-based technical route. Accurate region primitives (segments) are important factors for OBIA. However, as an ill-posed problem (Belgiu and Drăguţ, 2014; Drăguţ

* Corresponding author at: Key Laboratory of Virtual Geographic Environment (Nanjing Normal University), Ministry of Education, Nanjing, Jiangsu 210023, PR China.

E-mail addresses: sysj0918@126.com (M. Wang), 547646661@qq.com (Q. Cui), wangqiao@sepa.gov.cn (Q. Wang).

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et al., 2014; Troya-Galvis, 2015), over- and under-segmentation errors and imprecise segment boundaries are common in segmenting remote sensing images. Typically, shape defects are often found in manmade objects extracted by OBIA without post-editing. In addition, a region-only-based technical framework hinders the utilization of many useful PBIA techniques in OBIA, e.g., straight line detection and frequency-domain analysis, and limits its technical flexibility and performance.

As an important element for image understanding (Burns et al., 1986), straight lines can play a more important role than in current OBIA techniques. In previous studies (Wang and Wang, 2016; Wang et al., 2017c), we proposed a new OBIA model, i.e., the region–line primitive association framework (RLPAF), which promoted straight-edge lines as line primitives for feature extraction and analysis along with regions. RLPAF combines the advantages of image segmentation and straight-line detection and achieves information complementarity between region and line primitives. The region–line association features extend the OBIA feature set, hence enhancing OBIA performance. RLPAF is capable of handling over-segmentation errors in image segmentation (Wang et al., 2015, 2017b) and extracting manmade objects from high-resolution images (Wang et al., 2017a). In our previous study (Wang et al., 2017c), we further developed an RLPAF-based OBIA system, RSFinder, for engineering applications.

On the one hand, region–line collaborative analysis alleviates the influence of segmentation errors in OBIA. However, geometrical inaccuracy originating from image segmentation sometimes hinders accurate object extraction and mapping. On the other hand, template matching is a traditional technique in processing digital images; it finds small parts of an image and matches them with the template image (Brunelli, 2009). A fixed template normally prevents the occurrence of inaccurate shapes during segmentation. In remote sensing images, many manmade objects have straight boundaries and basically fixed shapes, such as photovoltaic panels (PVPs) investigated in this study, as well as road traffic signs, aquaculture waters, vegetable greenhouses, vehicles, and building roofs. These objects can theoretically be extracted by template matching with high accuracy. In addition, objects with complex configurations can be detected by decomposing them into simple parts (Sirmacek and Unsalan, 2009; Chen et al., 2014; Wu et al., 2014). Based on these advantages, template matching has been widely used in extracting objects from remote sensing images (Stankov and He, 2014; Leninisha and Vani, 2015; Leckie et al., 2016; He et al., 2017; Qiu et al., 2017).

However, critical technical problems exist for template matching. Creating and editing templates may be tedious and image dependent. Therefore, new templates that can adapt to image color, resolution, and imaging angle changes are possibly needed. Even within a single image, template matching can still fail due to object deformation. In this regard, template scaling and rotation (Lin et al., 2015; Fan et al., 2015) and parametrically or free-form deformation (Hung et al., 2012; Leninisha, 2015; Yu et al., 2107) are proposed to address this object deformation, which increases method complexity.

One goal of this study is to extract a typical kind of small manmade objects, i.e., PVPs, from very high-resolution (VHR) images. PVPs are the pivotal equipment in photovoltaic power generation, which utilize semiconductor materials acting under light conditions and convert solar energy directly into electrical energy. After their deployment, regular inspections of PVPs are required to determine the number, distribution, and damages of the panels, which are important for power plant site planning and equipment maintenance. As PVPs are often widely deployed, manual inspection is tedious (Malof et al., 2017). To this end, unmanned aerial vehicle (UAV) inspection is a suitable solution for PVP distribution survey.

Both OBIA and template matching have their own respective drawbacks in accurately extracting PVPs even though PVPs have a simple appearance. In this study, we combine OBIA, i.e., object recognition after segmentation, and template matching to improve their performance. The novelty of this study lies in several new RLPAF-based concepts including the mutual fitting ratio and best-fitting template (BTP), an automatic template generation scheme, and an accurate template matching method for PVP extraction. User-specified templates or training samples for object detection/classification are not required, which is the advantage of the proposed PVP extraction method. In addition, the proposed method can precisely detect each PVP in shapes in comparison with previous photovoltaic array detection methods (Malof et al., 2016, 2017) that detect PVPs as a whole. Although the proposed techniques are specifically applied to PVP extraction, they have important reference values for extracting similar types of manmade objects from VHR images.

This study is organized as follows: Section 2 introduces several newly proposed concepts including mutual fitting ratio and BTPs, which originated and are extended from RLPAF, and the implementation of the proposed method. Section 3 presents the experiment in which UAV images were used for PVP extraction. The novelty of the method and advantages are also comprehensively discussed in this section. Section 4 summarizes this study and introduces future work.

2. Methodology

PVPs commonly appear as blue blocks mounted with white strips along the sides. However, imaging angle and PVP inclination often cause significant deformation of PVPs in VHR images. Within a narrow view field, parallelograms properly generalize the PVP shape in VHR images. However, PVP angle, orientation, size, and tone may vary within the image, which challenge manual template editing, as illustrated in the experimental data used in this study. We proposed several novel RLPAF-based concepts for automatic template generation to address these problems. Fig. 1 shows the entire route of PVP extraction. Image segmentation and straight-line detection first obtain the region and line primitives. Segments with suitable shapes and colors are

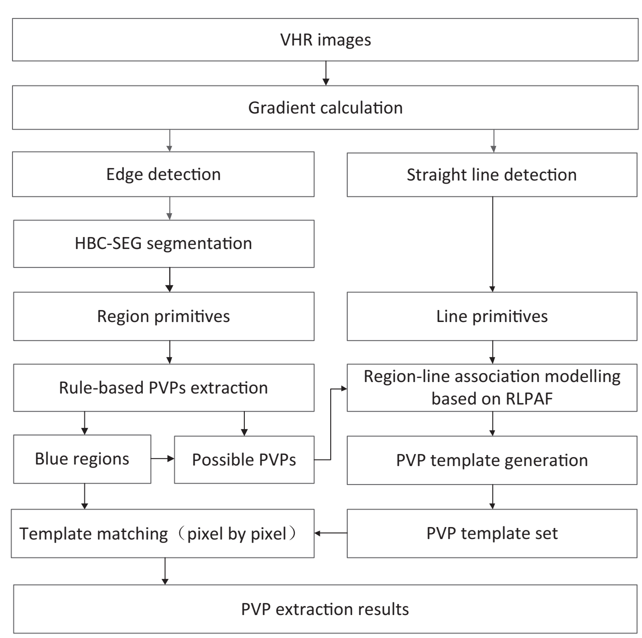

Fig. 1. Technical route of PVP extraction.

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