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Integrating fuzzy object based image analysis and ant colony optimization for road extraction from remotely sensed images

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Updated road network as a crucial part of the transportation database plays an important role in various applications. Thus, increasing the automation of the road extraction approaches from remote sensing images has been the subject of extensive research. In this paper, we propose an object based road extraction approach from very high resolution satellite images. Based on the object based image analysis, our approach incorporates various spatial, spectral, and textural objects' descriptors, the capabilities of the fuzzy logic system for handling the uncertainties in road modelling, and the effectiveness and suitability of ant colony algorithm for optimization of network related problems. Four VHR optical satellite images which are acquired by Worldview-2 and IKONOS satellites are used in order to evaluate the proposed approach. Evaluation of the extracted road networks shows that the average completeness, correctness, and quality of the results can reach 89%, 93% and 83% respectively, indicating that the proposed approach is applicable for urban road extraction. We also analyzed the sensitivity of our algorithm to different ant colony optimization parameter values. Comparison of the achieved results with the results of four state-of-the-art algorithms and quantifying the robustness of the fuzzy rule set demonstrate that the proposed approach is both efficient and transferable to other comparable images.

1. Introduction

Manual extraction of different objects from remotely sensed data is one of the most time consuming and expensive processing part of updating geo-databases (Zhang et al., 2011). Therefore, many research works have been concentrated on the automatic/semi-automatic extraction of objects from remotely sensed images. The rapid pace of emerging technologies resulted in fast creation of new imaging sensors during the last decade and further growth even with a higher rate is anticipated. Consequently, an increasing flood of information (imagery, 3D point cloud, video, *etc.*) acquired by VHR (very high resolution) satellites, Unmanned Airborne Systems (UASs), and even crowdsourcing can deliver much more sensor data that can be completely analyzed with the existing algorithms and software (Toth and Jóźków, 2015). This leads to the need for more advance and autonomous solutions for information extraction from remotely sensed data. Otherwise, it seems that costly and time consuming objects extraction process can be the Achilles' heel of map updating systems, which holds down the revision rate of geospatial databases.

Among all man-made objects, road networks are essential information due to their wide usage in various applications (Miao et al., 2014). Some applications of roads are immediately obvious. For example in EU, in spite of rapid growth of different types of transportation such as railways and planes, more than 71% of all inland goods transports and 82% of all passenger transports in 2012 used roads (European Road Federation 2012). Moreover, high quality and updated road network maps also provide important information for other applications such as smart city planning, sustainable development of urban areas, fleet management, emergency services, urban design, driving assistance systems, public health (Frizzelle et al., 2009), UAV Vision Based Navigation, disaster management, agricultural development (Tunde and Adeniyi, 2012), automated path planning for unmanned aerial vehicles, and traffic management (Wang et al., 2016b).

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Several factors can be considered to classify different road extraction approaches from remotely sensed image. One can consider, the type of sensor, the extraction technique or the degree of automation as a key factor. The utilized data can directly affect the appearance of roads and consequently the underlying road model. Since the 1970s, a plethora of methodological research has been pursued for road extraction from different types of remote sensing data including different passive and active data. The most important data sources used in literatures for road extraction consist of aerial images (Grote et al., 2012), satellite MS imagery (Ameri et al., 2016; Maboudi et al., 2017), LiDAR data (Quackenbush et al., 2013), SAR images (Saati et al., 2015; Hedman et al., 2010), hyper-spectral images and integration of multi-source data (Jin, 2011; Khesali et al., 2015; Tiwari et al., 2010; Cheng and Weng, 2016). In low and medium-resolution satellite images, roads appear as thin elongated structures. In high and very high resolution satellite images with finer GSD (ground sampling distance), roads are usually recorded as elongated homogeneous areas with bounded width so that different methods have to be applied (Mohammadzadeh et al., 2006; Li et al., 2016).

Road extraction based on the fuzzy logic: There are many road extraction approaches which used fuzzy logic to decrease the uncertainties in modelling the roads in VHR images (Grote et al., 2012; Saati et al., 2015; Li et al., 2016). Amini et al. (2002) used fuzzy inference system (FIS) for the identification of suburban roads in IKONOS images. Zhang and Couloigner (2006) designed a fuzzy logic based classifier for road identification. They also separated parking lots and buildings from road map using a fuzzy classification based on the angular texture signature (ATS) shape descriptors. Mohammadzadeh et al. (2006) proposed a pixel-based road extraction method which uses fuzzy-based mean calculation and mathematical morphology. The Authors improved their system by using a particle swarm optimization (PSO) to optimize the fuzzy cost function (Mohammadzadeh et al., 2009). Nikfar et al. (2015) utilized a Type-2 fuzzy logic system, which uses fuzzy membership functions to capture uncertainties in their road model. The main challenging parts of Type-2 fuzzy logic systems are high computation cost and parameter tuning. The authors employed a hybrid Genetic Algorithm (GA) to tune the parameters and achieved impressive results with different IKONOS images.

Object (region) based road extraction: Object based image analysis (OBIA), as one of the emerging trends in the classification and object detection algorithms, is triggered by the availability of very high resolution images acquired by the advanced commercial satellite imaging sensors- such as Quickbird, GeoEye, SPOT, Pléiades and Worldview series. In light of complexity of scene in urban areas and by considering the fact that in high resolution images, linear characteristics of roads in urban areas are not very outstanding, object based approaches are more preferable for road extraction from high resolution images in urban areas (Weng, 2012; Maboudi and Amini, 2015; Miao et al., 2015). In almost all region-based approaches, first roads are segmented to provide processing entities *i.e.* objects (Grinias et al., 2016). Then different approaches utilize some strategies to detect road objects from others. In Miao et al. (2013) edge-filtering segmentation followed by a rule-based classification is used to achieve a binary road map. The methodology described by Grote et al. (2012) groups the over-segmented regions achieved by a normalized cut segmentation using some spectral and perceptual criteria. Next a fuzzy rule-based classification is exploited to classify the regions into road and on-road regions. In Huang and Zhang (2009) exploiting a multi-scale segmentation based on the fractal net evolution approach (FNEA), image is partitioned to regions. Next, at different scales, these regions are classified as road and non-road using a binary support vector machine (SVM) classifier. The multi-resolution segmentation implemented in eCognition Software is employed by Li et al. (2016) to generate initial regions. After removing vegetation, shadow and buildings, a region merging method based on binary partition tree (BPT) followed by two fuzzy rules is adopted to detect road regions.

Road extraction based on the ant colony optimization: To the best of our knowledge, there are a few distinguished research works which utilized ant colony optimization (ACO) for road extraction from VHR images. In Zarrinpanjeh et al. (2013), ACO is utilized for urban road map updating from GeoEye-1 pan-sharpened image and 1:2000 corresponding vector map. Their framework suggests a multistage process for verifying the existing road map, extracting new roads and finally grouping them. In Yin et al. (2015) an extension of ACO algorithm is proposed which integrates some geometrical features of polygons and edges of VHR remotely sensed images. This approach utilizes the direction of the roads as well as other objects in road context as heuristic information of ACO to extract the highways and main roads in urban areas. Maboudi et al. (2017) developed an object based road extraction approach which embedded objects shape and spectral properties in ACO for road extraction from IKONOS images.

Based on the object based image analysis, our algorithm leverages the integration of several spatial, spectral, and textural objects' descriptors, the capabilities of the fuzzy logic system for handling the uncertainties in the road modelling, and the effectiveness and suitability of ant colony algorithm for optimization of network related problems.

After this introduction and literature review, the remainder of the paper is structured as follows: Section 2 presents the overall structure of the proposed approach. Moreover, ACO algorithm, the utilized FIS, and the road descriptors are described in this section. Experimental evaluations as well as detailed comparisons between our approach and four state-of-the-art algorithms are provided in Section 3. The sensitivity test of our method to different ACO parameter values and assessment of the robustness of the employed fuzzy rule set are also presented in this section. Finally, the concluding remarks are drawn in Section 4.

2. Materials and methods

The overall structure of the proposed approach for road extraction from VHR imageries is illustrated in Fig. 1. Our approach which is based on the OBIA relies on a road model which analyses the image objects utilizing a fuzzy inference system. Fuzzy membership values of the objects are considered as the heuristic information of the ACO to detect road objects.

First, the multispectral VHR image is smoothed in order to reduce the road surface heterogeneity. Next, we segment the smoothed image using a multi-resolution segmentation algorithm to achieve processing entities *i.e.* image objects. Considering linguistic road properties defined by our road model, we define road descriptors through a FIS to assign a road membership value to each object. Then ACO exploits this information in order to discriminate the road objects.

2.1. Pre-processing

Region based approaches assume the radiometric homogeneity of the road surface. Thus, the radiometric noises caused by cars, ground markings, and shadows, *etc.* which increase intra-class spectral variance (Weng, 2012) may violate this postulation. There are some well-known approaches for smoothing the image for road extraction such as Gaussian filter (Zhang et al., 2011; Zhou et al., 2006; Bae et al., 2015; Hu and Tao, 2005), mean(Li et al., 2016) and Median filter (Mena and Malpica, 2005; Jin and Davis, 2005; Ünsalan and Sirmacek, 2012; Zhang et al., 2016). However, the