Integrated Spectral and Geometrical Information for Road Extraction from VHR Satellite Images

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Brief Introduction

The basic problem addressed in the PhD. thesis is road network extraction from Very High Resolution (VHR) satellite images. This thesis includes many references to recent studies, and can be used as a textbook or reference book by undergraduate and graduate students in the fields of remote sensing, photogrammetric engineering, urban science, information science, machine learning, and geographic information science.

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Preface

With the advent of modern satellite sensors, it is possible to produce massive satellite images that provide rich land cover information. Object extraction, one of the fundamental images processing technologies, plays an important role to process these satellite images. With auxiliary of object extraction technologies, it is possible to generate useful information and knowledge from satellite images. Among various geo-information, road network extraction has been received much attention, partly due to its fundamental role in modern society and partly due to its challenging. Although this topic has been researched for decades, the results extracted are commonly unsatisfactory due to the extremely complicated natural scene and thus this topic is still not well resolved. Overall, road extraction from satellite images is still in its infancy and there is still large room to deep the insight into this topic.

An obvious trend of road extraction in the field of remote sensing is shifting from low/middle resolution satellite images to Very High Resolution (VHR) satellite images. Compared to low/middle spatial resolution satellite images, VHR satellite images can provide much more structural details of road feature. Naturally, road extraction from VHR satellite images can exploit spatial information in addition to spectral information, which is only available information source for low resolution satellite images. Road extraction from VHR satellite images has been receiving increasing attention in recent years.

This thesis focuses on the road delineation from Very High Resolution (VHR) satellite images by exploiting multiple road information, such as geometrical and spectral information. Specially, several metrics are proposed to measure road geometrical characters in VHR satellite images. To make full use of available road information, a framework has been designed to combine the multiple information sources (i. e., geometrical and spectral features) to improve road extraction accuracy. A new method has been designed to shift traditional road extraction methods from pixel-based to object-based. By doing so, it is convenient to measure road features at object level that in turn improves road extraction accuracy as well as computational efficiency. Traditional road centerline extraction methods suffer from ′spur′ problem. To tackle this limitation, two methods have been proposed to extract accurate road centerlines from classified road images. The presented work relies on advanced computer vision methods, such as tensor voting and subspace constrained and mean shift (SCMS). The proposed method does not require rigorous road topology hypothesis in advance and thus has high generality. An information fusion method has been presented to combine multiple road extraction results produced by different methods or from different sensors. By contrast to state-of-the-art, the new work is designed from the viewpoint of computational geometry and sheds new insight on fusion of various road results from multiple methods or different sensors. Finally, a seed point based semi-automatic method has been presented to eliminate road gaps to improve the completeness of road network extracted. The presented method can be used to process big road gap, which is a challenging work for most cutting-edge technologies. The experimental results demonstrate the usefulness and feasibilities of the proposed method in this thesis.

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The authors

March 18, 2019 in Changsha

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Chapter 1 Introduction

Urbanization is happening in just a few years in East Asia, according to the World Bank (2015), as shown by the mass movement of people to cities and the emergence of urban settlements. The region will have more decades of urban growth as economies shift from agriculture to manufacturing and services. Within the advent of modern acquisition sensors (i. e., Ziyuan-3, Ikonos, and QuickBird), Very High Resolution (VHR) satellite images have become increasingly available and thus it is possible to monitor urbanization from space. Figure 1. 1 presents three satellite images over Xuzhou city, China, captured by different sensors.

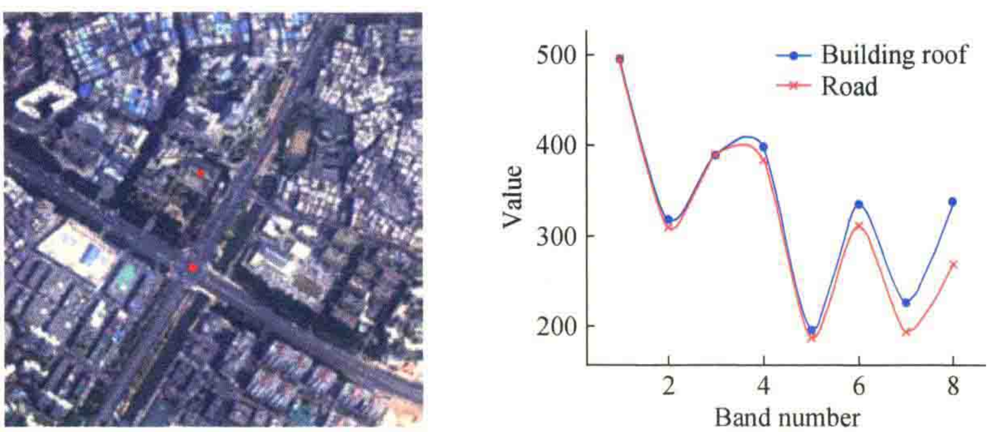
(a)Landsat (b)Ziyuan-3 (c)QuickBird

Figure 1. 1 Satellite images with different spatial resola tions over Xuzhou, China

Although we can obtain massive satellite images, the useful knowledge is still limited. This is in part due to it is unable to timely process these images. To meet this challenge, object extraction plays an important role in processing these satellite images to produce useful information. Among various object features, road extraction from satellite images has received much attention in the past decades. This is because that updated road layers in Geographic Information Systems (GIS) are critical for many urbanization issues, such as urban expansion estimation, urban planning, and traffic/

population movement monitoring. Despite this is not an easy task, especially in urban areas, computer-aided road network extraction from remotely sensed images provides a new opportunity to meet this challenge. Meanwhile, road extraction with the aid of computer can reduce manual work load and improve efficiency. However, after years of development, there is still no compelling evidence that the state-of-the-art can produce reliable and satisfactory results for any situation (i. e., rural, urban/rural, and urban environments) or any spatial resolution. Numerous road extraction methods have been proposed but it remains unclear as to when these methods will be operational, as there is still rare commercial software regarding this topic. Therefore, the road extraction problem remains a tremendous obstacle in the field of remote sensing. The is because that a number of factors complicate the road extraction task, as summarized in the following section.

Spectral similarity. The extraction of roads is particularly problematic in urban areas due to the spectral similarity of roads and other impervious surfaces such as buildings, as illustrated in Figure 1. 2. Indeed, the spectral separability of asphalt road surfaces and bituminous roofs is still not easy since they tend to share similar spectral properties.



(a)Road and building roof points are shown in red

(b)Spectral values of road and building roof points

Figure 1. 2 The spectral similarity between road and building roof

Material change. In real world scenarios, roads are made of various construction materials, such as cement and asphalt. Generally, different materials lead to different spectral characters. For instance, cement roads have high intensity values on multispectral images, while asphalt roads low intensity values [Figure 1.3(a)]. Hence, the variety of road material threats to the reliability and accuracy of state-of-the-art methods, as most of methods can only process one of these two cases (i.e., high intensity road or low intensity road).

(a)Material Change (b)Occupy

Figure 1.3 Two complicated scenarios for road extraction

Occupy. This problem is further exacerbated by issues related to the occlusion of road surfaces by trees, shadow and the presence of vehicles [Figure 1.3(b)]. The occlusion of trees and shadow commonly leads to discontinuities of the road segments extracted. Meanwhile, vehicles on the road result in redundant 'holes' of the road segments extracted. This issue is particularly common in dense urban environment, such as Hong Kong.

To overcome aforementioned challenges, the integrating of spectral and spatial information plays an important role. Given the extreme difficulty of distinguishing road feature from other man-made structures (such as car park and building roof), deriving complementary information (i.e. geometrical feature) from VHR satellite image is a rational option. In any case, understanding to what extent the combination of spectral and geometrical information improves the road extraction performance in VHR satellite image requires further research and dialogue.

1.1 State-of-the-art road extraction methods

To date, road extraction from VHR satellite images has received a lot of attention, and various methods have been proposed. These methods can be roughly classified into two groups: ① automatic and ② semi-automatic. In general, semi-automatic methods can produce satisfactory result and thus are much closer to the operational level than automatic methods. The reason is that automatic methods generally cannot achieve satisfactory results in complicated scenes (i. e., dense urban environment). In contrast, the human interaction is more robust to these cases. Despite this advantage, however, semi-automatic delineation of roads from satellite images suffers problems of cost, accuracy, and efficiency, resulting in labor-intensive processes. Automated tools to assist analysts in this process would be of tremendous benefit for the production of timely road data set. A comprehensive review is available in (Mena, 2003), where road extraction methods are further categorized loosely into: ① seed point based method, ② active contours, ③ machine learning, ④ object-based method, and ⑤ other road extraction methods. However, many include methods that cross domains (for example, by exploiting the combination of machine learning and object-based method). The methods are outlined as follows.

1.1.1 Seed point based method

The first category starts from user-defined road seed points, followed by road segments delineation, which exploits spectral/spatial characters of roads to recognize road network elements. In this category, a piecewise parabola model (Hu et al., 2004) was presented to delineate the road centerline network. This method firstly applies the piecewise parabola model around the seed point, followed by the least square matching to solve the parameters of the precise parabola to be extracted. Similar methods are presented in (Kimmel, 2004; Lin et al., 2011). To reduce the seed point number, kernel density estimation incorporating the geodesic method is presented in (Miao et al., 2014b). For a specified pixel, road footprint (Hu et al., 2007) and angular texture signature (Lin et al., 2008) are defined to measure the road probability from the shape prospective. In (Bicego et al. , 2003; Zhou et al. , 2005), particle filtering is utilized to trace a segment initiated by the seed point. The shortage of particle filtering is that it fails to process road branches. To overcome this limitation, particle filtering and extended Kalman filtering were integrated in (Movaghati et al. , 2010) to process complicated road cases. The single-image mode was discussed in the foregoing road extraction methods. As an extension, Dal Poz et al. (2012) presented a semi-automatic method for rural road extraction from stereoscopic aerial images. This method derives the road seed points to formulate the object-space road model, followed by optimization using dynamic programming. Figure 1.4 illustrates an example of seed point based method.

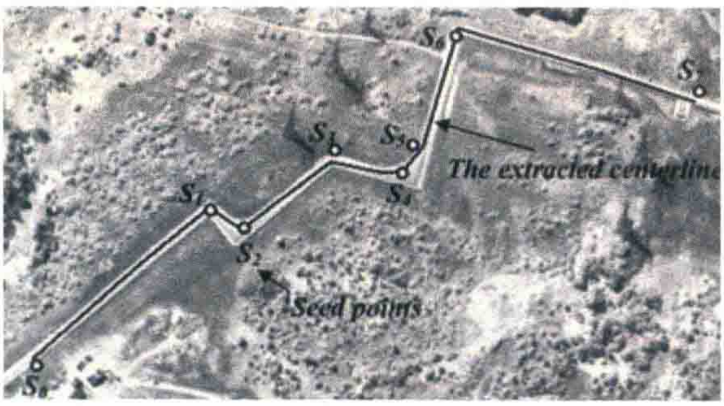


Figure 1.4 An example of seed point based method

The source image is from (Hu et al. , 2004)

1.1.2 Active contour

The second category method relies on the user defined initial contour to implement so-called active contour model to extract roads from satellite images. Two fundamental papers reporting the application of active contour in road extraction were given in (Gruen and Li, 1997; Laptev et al. , 2000). Previous studies show that, in a variety of road extraction tasks, a single snake suffers from many limitations, such as the failure in disconnected road networks and enclosed regions. To tackle this limitation, a family of quadratic snakes (Marikhu et al. , 2007) has been proposed for road extraction. This method combines advances in oriented filtering, thresholding, Canny edge detection, and Gradient Vector Flow (GVF) energy, which surpasses consistently outperforms a single snake. Similarly, a higher order active contour model (Rochery et al., 2005) is designed to solve the road discontinuity issue caused by shadows and trees. The parameter tuning and computational cost of active contour are addressed by Li et al. (2015). The substitution of the traditional regularization term by a Gaussian kernel benefits fewer parameters and larger time step, which in turn improve the result smoothness and computational efficiency. To improve road extraction accuracy, active contour model has also been studied to integrate with other methods, such as graph cut (Rajeswari et al., 2011), the multi-resolution analysis (Péteri et al., 2003), and Newton snakes (Butenuth and Heipke, 2012). A comparison of different active contour models for road extraction was given by Nakaguro et al. (2011). An example of road extraction using active contour is given in Figure 1.5.

(a)The original test image with initial contour which is shown in red triangle

(b)The active contour extraction result

Figure 1.5 An example of road extraction using active contour

1.1.3 Machine learning

The third category is based on the theory of machine learning. With the spurious of machine learning, this powerful tool in the field of computer science has naturally extended its application area into the road extraction. A general framework of machine learning is given in Figure1.6. Support Vector Machine (SVM), a powerful tool in machine learning, has come into wide use in road extraction (Fauvel et al., 2008;

Shi et al., 2014a; Song and Civco, 2004; Tarabalka et al., 2009). Meanwhile, artificial neural networks are applied to extract roads, which concentrated on evaluating different structures of neural networks along with different measuring units and descriptors (Mokhtarzade and Zoej, 2007). A multistage strategy for automatically extracting roads from high-resolution multispectral satellite images based on salient features was introduced by Das et al. (2011). This method incorporates the salient features of roads using P-SVM and Dominant Singular Measure (DSM). The path classifier was studied to automatic delineation linear features from images based on the global optimization with geometric priors (Türetken et al., 2011, 2012, 2013). The junction-point processes (Chai et al., 2013) and a higher-order conditional random field model (Wegner et al., 2013) were also exploited to extract road network from the image. Particularly, Mnih and Hinton (2010, 2012) addressed the application issue of machine learning in road extraction from aerial images.

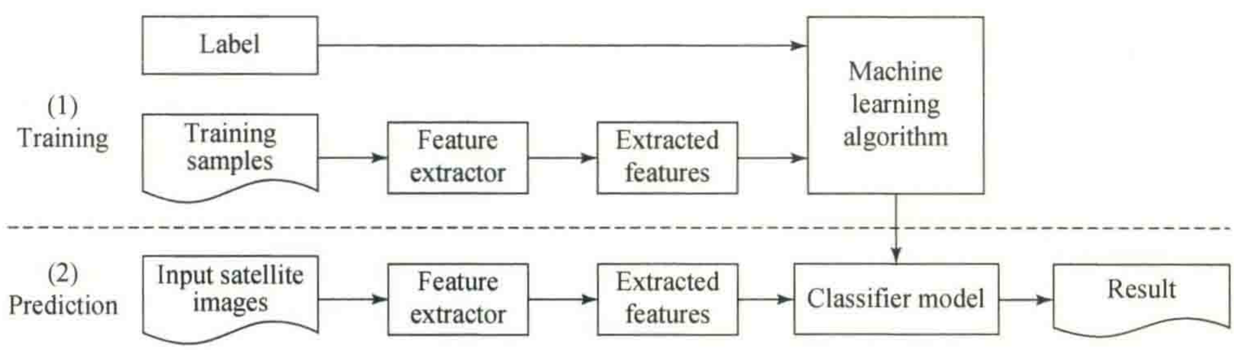


Figure 1.6 A general framework of machine learning

1.1.4 Object-based method

The fourth category is relying on the object level information (Figure 1.7) to extract road pixels. These algorithms are primarily pixel-based and sometimes accompanied by textural information extracted from rectangular regions, in which structural and conceptual information is not properly exploited. To overcome the shortcomings of the pixel-based methods and to reduce the semantic gap, object-based algorithms have been developed (Baatz and Schäpe, 2000; Benz et al., 2004; Herold et al., 2002). Object-based methods are known to achieve better results than pixel-based methods in processing VHR satellite images (Blaschke, 2010; Blaschke and Strobl, 2001; Cleve et al., 2008). A considerable number of studies have compared object-based approaches with traditional pixel-based classification methods (Baltsavias, 2004; Ehlers et al., 2006; Frohn et al., 2005; Im et al., 2008; Laliberte et al., 2004). Many of these studies have found that object-based methods typically produce higher classification accuracies than pixel-based methods do. A new work proposed by Huang and Zhang (2009, 2013) is based on SVM and multi feature model at both pixel and object levels. Peng et al. (2008) updated outdated road maps by incorporating generic and specific prior knowledge into a multi-scale phase field model. Zarinpanjeh et al. (2013) used object-based analysis for road map updates. Additionally, Grote et al. (2012) developed a method for road network extraction using object-based analysis. In this category, to improve road extraction accuracy, various road spatial features derived from objects have been presented and then integrated with spectral features. These spatial characters include shape features (Das et al., 2011; Han et al., 2012; Shi et al., 2014a; Song and Civco, 2004), directional mathematical morphological (Shi et al., 2014b; Valero et al., 2010), directional filter (Gamba et al., 2006; Negri et al., 2006), et al. It is worth to note that the methods in third and fourth categories frequently produce segments. The delineation of accurate road centerline from the classified image was addressed in Miao et al. (2013). Although integrating shape features in road extraction results in a

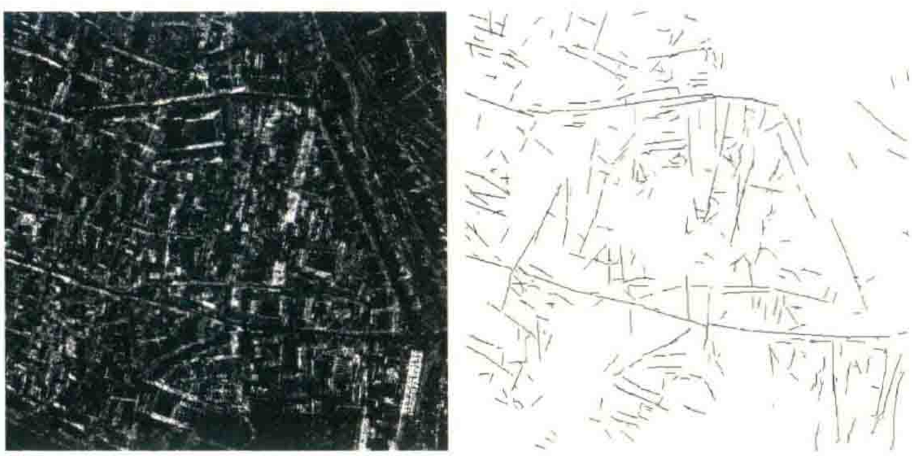
(a)A test optical satellite image

(b)The derived objects where the boundary between objects is shown in red

Figure 1.7 An example of producing objects from satellite image good performance, it is challenging to obtain a universal linear feature extraction method for all situations (Gamba et al., 2006), and this book will further study this issue.

1.1.5 Other road extraction methods

There are also some other interesting road extraction methods. A wavelet based approach for road extraction from VHR satellite images was presented by Zhang and Couloigner (2004). Some new researches based on SAR imagery and LIDAR systems also have recently been presented (Gamba et al., 2006; Negri et al., 2006; Poullis and You, 2010). An example of road extraction using SAR image is reported in Figure 1.8. Doucette et al. (2001) proposed an automated road centerline extraction method that exploits spectral content from high-resolution multi-spectral images. The method is based on anti-parallel edge centerline extraction and self-organized road mapping. A fast linear feature detector for road extraction was introduced by Shao et al. (2011). This method only considers ridge line (or bright ribbon) extractions that are mostly roads in aerial and satellite images. An interesting method that combines road color feature with road GPS data to detect road centerline was given in (Cao and Sun, 2014).



(a)A SAR image over Pavia, Italy (b)Corresponding road extraction result

Figure 1.8 An example of road extraction from SAR image

1.2 Book outline

Based on the aforementioned issues, four objectives of this book have been identified as: ① to design several measures to evaluate the road shape features; ② to propose a practical and effective method to extract road segments from the VHR satellite images; ③ to design a framework to characterize accurate road centerlines from classified road images; and ④ to propose a method to connect large road gaps to eliminate road discontinuities. The structure of this book is organized as follows:

Chapter 2 presents a new approach for urban main road centerline extraction from optical satellite images integrating spectral-spatial classification, Local Geary's C, road shape features, locally weighted regression and tensor voting. This method has three main contributions: ① initial road network extraction by fusion of spectral-spatial classification based on GANMM and homogeneous property measured by Local Geary's C; ② false roads removal based on roads shape feature to extract reliable roads; ③ road centerline extraction based on locally weighted regression and road network generation using tensor voting.

Chapter 3 explores a novel object-based road extraction method for VHR satellite images. Specially, the main contributions of this chapter are: ① a novel proposal for two object-based filters to enhance road features in VHR satellite images; ② the design of a hybrid feature set to extract road features; and ③ the integration of tensor voting (TV), active contour methods and the geometry information to simultaneously fill road discontinuities and improve the road smoothness.

Chapter 4 addresses the issue of automatic dense urban road extraction. The main contributions are four information fusion strategies designed from the viewpoint of computational geometry.

Chapter 5 explores ways of delineating accurate centerlines from classified road maps. We investigate two ways of performing accurate road centerline extraction, called Feature Point based Subspace Constrained Mean Shift (F-SCMS) method and Gaussian Mixture Model based Subspace Constrained Mean Shift (GMM-SCMS) method.

Chapter 6 presents a novel algorithm to eliminate large road gaps to improve the road extraction performance. The main contribution of this chapter is that the road gap elimination problem is converted to a seed point based road extraction issue.

Chapter 7 concludes remarks, followed by a brief look at future research for improving road network extraction algorithms presented in this book.