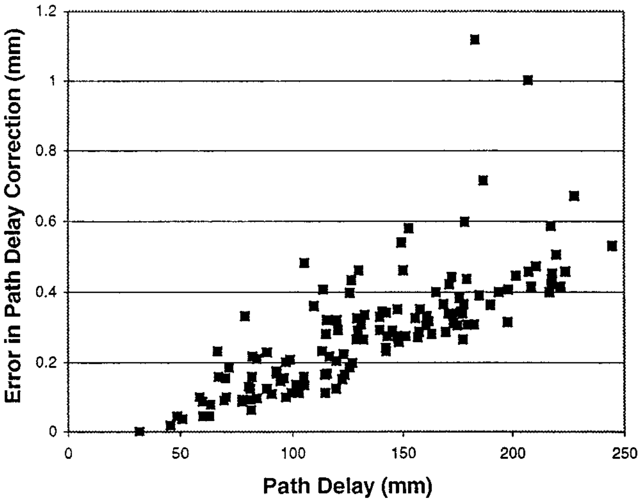

Fig. 2. Error in path delay (PD) retrieval if a simplified 1.2 mm/y correction is applied for all values of PD rather than correcting the TB at 18 GHz directly and then reprocessing the TBs through the PD retrieval algorithm. Data is selected from TMR overpasses near Lampedusa Island (LAT 35.39N, LON 13.10E) during 1992–1996.

to the PD retrieval algorithm. The difference between these two PD estimates is shown in Fig. 2 as a function of the latter (more accurate) PD.

In Fig. 2, a large majority of the differences cluster in a relationship that is roughly linear with PD. This cluster forms a distinct lower bound on the differences (ranging from no difference at very low PDs to a difference of approximately 0.5 mm at $\mathrm{PD} = 250$ mm). The samples in the cluster generally correspond to cloud free and low wind conditions. In these cases, there is nearly a linear relationship between the TBs at 18, 21, and 37 GHz and the PD [5]. Therefore, calibration biases in TB at 18 GHz will be linearly related to errors in PD. One simple improvement on a blanket 1.2 mm/y correction to the PDs might, then, be to incorporate this additional linear correction as a function of PD. However, such an improvement will not properly handle the numerous outlier points in Fig. 2 that lie above the lower bound cluster. These points arise from cloudy and/or higher wind conditions in which the relationship between TBs at each frequency cannot be explained by PD alone. Differences of 0.5–1.1 mm occur at PDs values well below the 250 mm maximum and in a manner not well correlated with PD. In these cases, it is best to reapply the full TMR PD retrieval algorithm to the drift corrected TBs.

A correction algorithm has been developed for the drift in calibration of the 18-GHz TMR channel. The resulting correction to TB varies linearly with TB and is greatest at lower TBs, dropping to zero when TB equals the physical temperature of the on board reference load. Given that the TB at 18 GHz that is typically measured by TMR on orbit over ocean only ranges over approximately 126–170 K, a constant drift correction of 0.27 K/y during the first four years of the mission is likely adequate for most purposes. A constant drift of this magnitude roughly corresponds to a constant drift in the retrieved PD of 1.2 m/y. However, use of a constant PD correction is found to result in small but systematic errors in the PD at the 1-mm level that are correlated with PD, with cloud cover, and with wind speed. Since all of these characteristics can have spatial scale sizes that are significantly greater than the individual TMR sample spacing of 45 km, the effects of these systematic errors can be important even though the magnitude of the errors is an order of magnitude smaller than the individual sample error. For this reason, it is recommended that, for highest quality PD retrievals, the drift correction be applied to 18-GHz TBs and then the corrected TBs be reprocessed through the PD retrieval algorithm.

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The Line Segment Match Method for Extracting Road Network From High-Resolution Satellite Images

Wenzhong Shi and Changqing Zhu

***Abstract*—This paper presents an approach, with emphasis on the newly proposed line segment matching method, for extracting urban road networks from high-resolution satellite images. The approach is based on the characteristics of the images, knowledge about road networks, and the related mathematical models. The approach is applied to several images of urban areas and is proved to be effective in both visual effect and positional accuracy.**

***Index Terms*—High-resolution satellite image, line segment matching method, mathematical morphology, road network extraction.**

I. Introduction

Data extraction from remotely sensed images is the focus of research issues in, for example, automatic mapping and GIS data capture. Features extracted from images can be either linear features, such as roads,

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W. Shi is with the Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong.

C. Zhu is with the Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong and also with The Institute of Surveying and Mapping, Information Engineering University, Zhengzhou 450052, China.

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or area features, such as buildings. This paper studies linear feature extraction, particularly for road networks in urban areas.

Methods for road feature extraction have been developed in recent years. The developed methods were mainly for aerial photos or low- and middle-resolution satellite images. In [1], Barzohar *et al.* presented an automatic approach to search the main roads on aerial images by using statistical techniques. In [2], Chanussot *et al.*studied the automatic detection of the linear features in synthetic aperature radar (SAR) satellite data. In [3], Katartzis *et al.* presented a model-based approach to the automatic extraction of linear features, where five parameters need to be set before extraction. In [4], Gruen and Li developed a road extraction approach by seed points and B-spline curve. In [5], Gruen and Li proposed a method based on dynamic programming, LSB-snakes, and supported by GIS data. Methods of road feature extraction were also studied in [6]–[9].

Extraction of road network from high-resolution satellite images is becoming a new research focus. Recently, several high-resolution satellite images have become available for civilian applications, due to the development of remote sensors and satellite technologies. These include images from IKONOS, KVR-1000, and Quick Bird. With the high-resolution satellite images, the application of remote sensing images can be moved from the traditional application areas such as natural resource and environmental protection to urban applications where more detailed information about ground features are required. Extracting a road network is one of the potential applications of the high-resolution satellite images for urban areas. This technology can be used for data capture and data updating for GIS. The latter applications are particularly valuable for the areas where urban road networks change rapidly, such as in many developing countries. Therefore, the focus of this study is on developing an approach for extracting urban road network from high-resolution satellite images. Besides the general description of the approach, this paper describes the newly proposed line segment match method in detail.

II. The Road Network Extraction Approach

In this study, we first proposed an approach for extracting road network in urban area from high-resolution satellite images. The approach is described with a framework including the components of an analysis of characteristics of the high-resolution satellite images, particularly on urban road networks; generating a binary image; a newly proposed solution for road network detection—*the line segment match method*; the processing of detected road network; and accuracy evaluation.

A. Characteristics of High-Resolution Satellite Images

For the road extraction, developed methods heavily rely on the characteristics of the images. Therefore, the first fundamental task for the high-resolution image-based road extraction is to analyze the characteristics of roads on the images.

In comparison to the low- or middle-resolution satellite images, the high-resolution satellite images contain more ground details and the smaller details on the earth's surface can be represented more clearly. There is a higher chance to extract more detailed road features from the high-resolution satellite images than from the low- or middle-resolution ones. On the other hand, there are also more difficulties in extracting road features from the high-resolution satellite images, since there are more nonroad ground features which appear on the images. Hence, it is necessary to develop a new approach to extract road features according to the characteristics of the high-resolution satellite images, which is the core of this study.

Fig. 1 is a 1-m resolution satellite image for an urban area in Valparaiso, Chile. This image will be used as an example to describe the proposed road network extraction approach in detail in this paper.

Fig. 1. One-meter resolution satellite image of Valparaiso, Chile.

Fig. 2. Generated binary image from the original image of Fig. 1.

From Fig. 1 and other high-resolution satellite images, in general, roads are in the shape of a long narrow rectangle or a band-shaped line, and the width of a road is in several pixels. Roads are generally straight or slightly curved; there is less chance that a road is highly curved. In many cases, urban roads are darker in tone, and this tone is different from the neighboring objects, such as buildings. The length of a road is longer than the buildings and longer than or equal to a street block. The pattern of the roads is normally in a network in an urban area. These characteristics of urban roads on high-resolution satellite images will be used as a basis for the urban road network extraction method developed in this study.

B. Binary Image Production

It may be difficult to extract road features directly from the original high-resolution satellite image, due to the existence of many details of nonroad ground features on the image. Here, we simplify the original image by transforming it to a binary image. The major issue for generating the binary image from the original image is to set a threshold for the binary processing. In this study, the threshold may be different from one image to another. However, the threshold can be obtained based on a series of experiments on the original image to be binary processed. The basic principle of determining the threshold is that generated road network outline on the binary image, based on the threshold, should be as close to the road network on the original image as possible. In our case, the recommended range of the threshold L is a value between 65 and 75 within the total 256 gray values for the 1-m resolution satellite images. Fig. 2 shows the binary image of Fig. 1 where the threshold is assigned to be 65. By binary processing, the outline of the road network becomes more visible on the binary image.

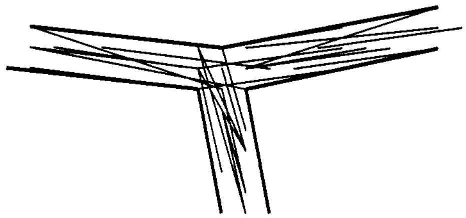

Fig. 3. Road with a certain width can be considered a set of straight-line segments.

C. The Newly Proposed Line Segment Match Method

Although we can obtain the road network outline based on the binary image, there still exists a lot of nonroad "noise." Therefore, the road network cannot be obtained from the binary image directly. A new method to detect road network from the binary image is developed and described below.

From the analysis in Section II-A, the road on a high-resolution satellite image is in a width of several pixels, and is in the shape of a long-narrow rectangle or a band-shaped line. Furthermore, the road network of the urban area, in general, can be considered as the composition of many rough straight road segments and slightly curved road segments, as shown in Fig. 2. The narrow rectangles and band-shaped lines indicate the direction and the position of the corresponding road.

In fact, the road segments that are in narrow rectangles or band-shaped line can be considered a set of straight-line segments with a certain length and direction that will be studied in detail; that is to say, these roads can be represented by the straight-line segments with a certain length and direction. Fig. 3 shows a simple example of two roads, where each road can be considered a composition of a set of straight-line segments. Therefore, to detect a road is actually to detect the corresponding straight-line segments with a certain range of length and direction. This forms the foundation of the road network detection method developed in this paper called *the line segment match method*. This is a feature-based method for road network extraction.

In this line segment match method, there are three major steps to extract road network.

1) First, we detect the straight-line segments at a starting point with a given direction of detection in the binary image. If there is a straight-line segment with the same gray value "1" and with a certain length, e.g., not less than 30 pixels, in the binary image, then this line segment is considered a part of a road. These detected straight-line segments form a part of the possible road network. Here, two straight-line segments are also considered one line segment if the gap between them is less than a threshold (three pixels in this example).

   The parameters of the minimum length of straight-line segment and of the maximum gap between two line segments are determined based on the knowledge about the roads for the study area. The values of the parameters are relatively stable to a certain type of road network, such as urban road networks. These depend on the characteristics of the type of road network and the resolution of the image. In general, the minimum length of straight-line segments is close to an average length of the street block of the area of interest. For 1-m resolution satellite images, it is suitable if the parameter of the minimum length of straight-line segment is 30, and the parameter of the maximum gap between two line segments is 3. These dimensions are also used in the other examples in this paper.

2) For a given direction, we recursively operate the above process (1) for all possible paralleled lines in this direction from one end of the image to the other. Each time, we move the position with one pixel unit along an edge of the image. As a result, all the possible components that form roads in this direction are detected.

3) Recursively operate the processes (1) and (2) for each possible direction. Here, we operate the processes, from -90° to 90° with one-third of a degree for each interval. As a result, a total of $3^{*}180$ directions are detected. We can thus detect out all the possible components of roads in all these directions, and thus obtain a coarse road network of the original image of Fig. 1. Fig. 4 illustrates the obtained coarse road network in all directions for this example.

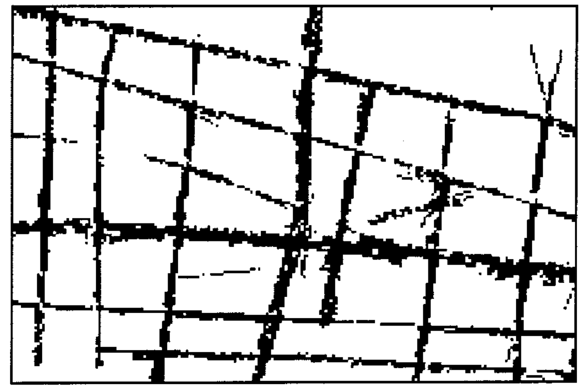

Fig. 4. Detected coarse road network of Fig. 1 in all directions.

D. Road Network Processing

In order to achieve the road network, we will now process the coarse road network illustrated in Fig. 4. First, we need to fill in the holes on the image using the closing operation of mathematical morphology [10]. Then, the road network is thinned by a morphological thinning algorithm. Finally, we connect the small gaps and delete short splinter after thinned.

Fig. 5 shows the result of extracted road network (in white) of Fig. 4 by the above processing overlapped on the original image of Fig. 1. We can thus assess accuracy of the extraction by comparing the extracted road network with the original roads network on the image.

Fig. 6 is another example of IKONOS images that are processed by the proposed approach where the extracted road networks (in white) overlapped with the original images.

E. Accuracy Assessment

Figs. 5 and 6 indicate most of the major roads of the urban area on the original images and can be extracted very well in terms of position and direction. It can be seen that the positional difference between the extracted road network and the road network on the original image is very small.

Furthermore, we evaluate the accuracy evaluation based on the following values:

$$\text{Identification accuracy} = \frac{\text{length of road correctly identified}}{\text{total length of road}}.$$

The identification accuracies for Figs. 5 and 6 are 91.54% and 92.12%, respectively. The statistical results show that the extracted road networks by the proposed approach have high accuracy, which is also verified by other examples of road network extraction in this study. Therefore, the proposed approach is efficient for urban road network extraction from high-resolution satellite images.

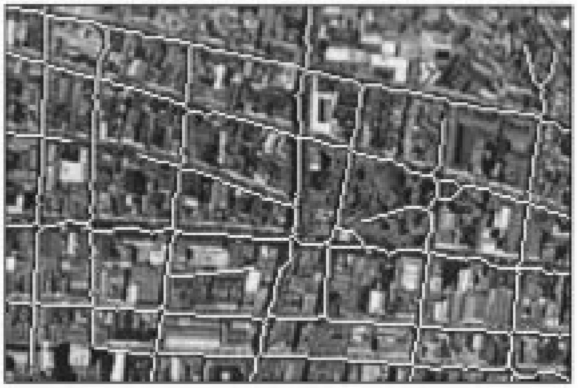

Fig. 5. Overlay of the extracted road network on the top of the original image of Valparaiso shown in Fig. 1.

Fig. 6. Extracted road network overlapped with the original image of Athens.

III. Conclusion Remarks

In this paper, we proposed an approach for extracting road network for the urban areas from high-resolution satellite images. The approach is based on the characteristics of high-resolution satellite images, the knowledge about the roads, and mathematical techniques, such as mathematical morphology. The proposed approach is a quasi-automatic one—there is no need to preselect seed points as most of the semi-automatic methods did—although a few parameters needed to be set.

According to the characteristics of the high-resolution satellite images, in this paper, first we developed a method for detecting coarse road network—*the line segment match method*. Next, we processed the detected coarse road network based on knowledge about the roads and morphological methods, and obtained the final extracted road network. We also evaluated the accuracy of the extracted road network.

The *line segment matching method* is developed especially for urban road networks on the high-resolution satellite images, where the road is in the shape of a long narrow rectangle or a band-shaped line the width of several pixels. Compared with the methods for extracting roads on a lower resolution image where roads are normally expressed as a line with one or two pixel widths, the line segment match is actually able to extract more complex expression of roads. Furthermore, the developed method in this study is for extracting urban road networks, while previous studies were mainly for extracting roads only.

The threshold for generating a binary image from the original image may vary from one image to another. The recommended range of the threshold is between 65 and 75 in general, according to our experimental studies for the 1-m resolution images. The principle of determining the threshold value is that generated road network outline on the binary image based on the selected threshold value should as close as possible to the road network on the original image. There are two parameters in the *line segment match method:* the minimum length of straight-line segments and the maximum gap between two line segments. Based on our experiments, for 1-m high-resolution images, it is adequate that the parameter of the minimum length of the straight-line segment is taken as 30 pixels and the parameter of the maximum gap between two line segments is taken as three pixels. These two parameters are relatively independent to various types of urban road networks from the examples presented in this paper.

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