

ROAD NETWORK EXTRACTION BY HIERARCHICAL GROUPING

*Yandong WANG and John TRINDER

School of Geomatic Engineering
The University of New South Wales
Sydney, NSW 2052, Australia
ywang@intermap.ca, j.trinder@unsw.edu.au

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ABSTRACT

This paper presents an automatic method for road network extraction from low-resolution images using hierarchical grouping technique. The method consists of three major steps: firstly it extracts line features from original images and generates smooth lines in a split-and-merge operation; a hierarchy of line images is created using different thresholds for line length, based on the generated line images; the linear features in the line images are then grouped hierarchically. Finally, knowledge of road networks is applied to remove non-road segments to form a complete road network. The paper includes results of tests on the implementation of these procedures.

1 INTRODUCTION

Automatic road extraction aims at recognizing roads in images and locating them accurately, and thus providing up-to-date information of roads for various applications such as updating of GIS data for mapping and urban planning. The former concerns the identification of roads in images, while the latter concentrates on determining their spatial positions in the image. Obviously, identifying roads in the image is more difficult than defining their locations, as recognition requires the use of domain knowledge of roads (Gunst 1996; Trinder and Wang, 1998).

A road is a man-made object in the real world, which serves as a tool for communication between two different communities. It has distinct geometric and radiometric surface properties, as well as topology. In low-resolution images, a road is a line feature with distinct contrast against its background, and it connects to other roads to form a road network. These properties are widely used for delineation of roads in the existing methods for road extraction, in which a road is usually delineated in three steps, i.e. road finding, road tracking and road linking. In road finding, a line operator is usually applied to find seed points of roads (Bajcsy and Tavakoli, 1976; Fischler et al, 1981; Ton et al, 1989; Trinder and Li, 1995). Some other methods such as wavelet transform (Grün and Li, 1995) and gradient direction profile analysis (Wang et al, 1992) are also used to detect seed points of roads. At this stage, existing maps and GIS can also be used to provide approximate positions of existing roads and their properties (Maillard and Cavayas, 1989; Bordes et al, 1997) or possible structures and shapes of roads (Cleyenbreugel et al, 1990). Once the seed points of a road are found, they are extended in a local area based on some geometric and photometric criteria. Road points can be tracked by graph searching (Fischler et al, 1981; Wang and Howarth, 1987; Wang et al, 1992), by dynamic programming (Grün and Li, 1995) or by an active testing method (Geman and Jedynak, 1996). Due to the effects of occlusions such as shadows cast by trees and overpasses, vehicles on the road, surface anomalies, etc., the tracked roads are usually divided into segments. Therefore, segments are finally linked together to form continuous roads based on geometric constraints such as collinearity and proximity (Vasudevan et al, 1988; Ton et al, 1989).

This paper presents a novel method for automatic road network extraction from low-resolution images. The method uses image processing for finding road candidates and knowledge of road networks for elimination of false roads. It operates in three major steps. Firstly, it extracts lines from the original image using a line operator such as a morphological operator. A split-and-merge operation is applied to the extracted lines to generate smooth line segments. A hierarchy of line images is generated by applying several thresholds of line length to the extracted line images. Progressing through the levels of the hierarchy will result in an increasingly dense distribution of line segments. Lines are grouped according to their similarities in geometry and radiometry. The grouping of line segments starts from the top of the hierarchy (with sparse distribution of line segments) to create the main structure of the road network. It then proceeds through the levels of the hierarchy to the lowest level (most densely distributed set of line segments) to add

more detailed road segments in the grouping. Finally, knowledge of road networks is applied to remove non-road segments to form a complete road network.

2 GENERATION OF LINE IMAGES

2.1 Line Extraction

In low-resolution images, a road is a smooth line feature which has distinct contrast against its background. Its width in the image depends on the image scale. A main road is usually one to three pixels wide when the ground resolution of the image is around 10 m. Thus, a road can be extracted by a line operator such as a morphological operator (Dougherty, 1992). The main advantage of the morphological operator is that it is unnecessary to define the width of the road to be extracted, and thus roads with different widths can be extracted at one time. However, due to the complexity of remotely sensed imagery, the extracted line features may not correspond to roads, but non-road features which have similar radiometric properties as roads. For road extraction, only roads should be retained while the detected non-road line features are noise, and therefore they should be removed. As an extracted line feature only possesses limited information about the road, such as pixel gray values of line and their gradients of gray values, it is usually difficult to distinguish roads and non-road objects by only using this type of information. It is recognized that a road is a smooth line feature while most non-road line features usually have irregular shapes. Based on this observation, a split-and-merge operation is used to generate smooth lines in this study. Lines with irregular shapes may be split into short segments in this operation, and thus can be removed by a thresholding operation.

2.2 Generation of Smooth Lines

A smooth line is defined as a linear feature in space which is continuous in its first and second derivatives. Thus, a smooth line can be generated by calculating its first and second derivatives and checking their continuity. In this study, smooth lines are created by using a split-and-merge operation which combines splitting and merging operations together. There are some existing algorithms for line splitting using different criteria (Ramer, 1972; Grimson, 1990). The method described in Grimson (1990) is very similar to the algorithm presented in Ramer (1972). It splits a line into straight segments in four steps:

- 1) determine the straight line connection between two end points of a line and measure the maximum deviation of the line from that connection (Figure 1);
- 2) if the maximum deviation exceeds a given threshold, the line is split into two segments at the point with the maximum deviation and the original connection line is replaced by two straight lines which connect the end points and the new splitting point;
- 3) repeat the above steps until the deviation is below the threshold; and
- 4) check consecutive segments to see if they can be merged into a single straight segment without exceeding the threshold.

To generate smooth line segments, the above algorithm was modified in this study. The modified algorithm works in the same way in the splitting, but the merging process includes a polynomial approximation of the split segments and merging of consecutive segments into smooth lines. Once a line is split into two segments, they will be approximated by a polynomial, and their spatial directions at the splitting point will be calculated. Two split line segments will be merged together if they have similar spatial orientations at the splitting point. In this way, smooth lines are maintained, while lines with irregular shapes are split into short line segments in the split-and-merge operation. The threshold for the maximum deviation used in this study is set as three pixels. The reason for choosing a constant for the threshold, instead of a function dependent on the length of the connection between two end points, is that the point with the maximum deviation does not always appear around the middle of the line.

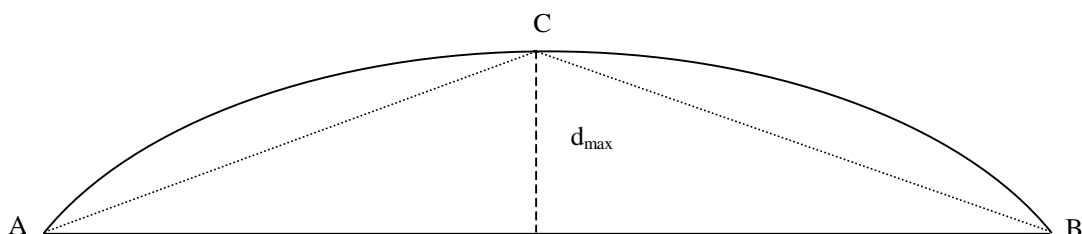


Figure 1. Split-and-merge operation of line segments

3 HIERARCHICAL GROUPING OF LINE IMAGES

3.1 Generation of Hierarchy of Line Images

After the split-and-merge operation, most non-road lines are split into short line segments while those corresponding to roads are usually maintained. Thus, non-road line features can be removed by a thresholding operation. However, the selection of an appropriate threshold is a problem. High threshold can guarantee the elimination of most non-road line features, but some short line segments corresponding to roads are also removed. Low threshold can keep most road segments, but does not result in the deletion of non-road line segments efficiently. At the same time, the existence of many non-road line segments makes the subsequent processing more complicated and may even cause unreliable results. To solve this problem, several thresholds are used instead of a single threshold to generate a hierarchy of line images. The line image at the top of hierarchy is generated using the largest threshold while the line image at the bottom of the hierarchy corresponds to the smallest threshold. In the line image at the top of the hierarchy, main road segments are retained, while most non-road line segments are removed. Most short line segments are retained in the image at the bottom of the hierarchy, but some non-road segments are also retained. Hence, line images in the hierarchy complement each other, and thus they can be combined to yield a more reliable road network from images.

3.2 Hierarchical Grouping of Line Images

Having generated a hierarchy of line images, line segments which are disconnected due to the effects of occlusions and other factors need to be grouped to form a road network. It can be seen that line images in the hierarchy have different characteristics. The line image at the top of the hierarchy possesses major line segments, most of which correspond to roads, while the line image at the bottom of the hierarchy contains most detailed information of roads and some non-road features as well. It might be easier to start grouping from the top of the hierarchy considering the simple structure of the line image at this level. However, some road parts cannot be extracted correctly as short line segments are removed in the line image at this level. Therefore, hierarchical grouping is proposed in this study, which commences from the top of the hierarchy and proceeds to the bottom. In grouping at top level, a main structure of road network can be formed reliably because non-road line features are removed in the line image at this level. In order to extract missing road segments, grouping proceeds to the next lower level and the results of the grouping achieved so far are used as a guide for grouping at this level. In this way, grouping is performed at each level until the lowest level of the hierarchy is reached. When grouping is performed through the hierarchy, more details of the road network can be detected. As grouping of line images is done hierarchically and the results of grouping at higher level is used at lower level, the effects of non-road features can be greatly eliminated, and thus a more reliable road network can be extracted.

In the grouping of line segments, collinearity and proximity are two commonly used criteria (Vasudevan, et al, 1988). When satellite and aerial images have simple structures, good grouping results can be achieved by using these two criteria. However, these criteria alone cannot yield satisfactory results when images have complex structures. In order to yield reliable grouping results, geometric and radiometric properties of features should be used (Henricsson, 1996; Wang, 1999) and a fuzzy function can be used to evaluate the quality of different connections (Steger, et al, 1997). It is assumed that two lines should be collinear in space and close to each other if they are two neighbouring segments belonging to the same road. At the same time, they should have similar geometric and radiometric properties. Thus, a grouping method similar to that used in Henricsson (1996), based on the similarity of geometric and radiometric properties of lines, is used in this study. To evaluate the similarity of two lines, a function which is the product of four similarity functions is defined, which has the following form:

$$S = S_d \times S_o \times S_p \times S_g \quad (1)$$

Where S_d , S_o , S_p and S_g are four functions describing similarities of lines in distance, spatial orientation, gray value and gradient orientation respectively.

All of these four functions are defined by a Gaussian function. For example, S_o is defined as:

$$S_o = \begin{cases} e^{-\left(\frac{\Delta\alpha_1^2}{T_\alpha^2} + \frac{\Delta\alpha_2^2}{T_\alpha^2}\right)} & \text{if } \Delta\alpha_1 < T_\alpha \text{ and } \Delta\alpha_2 < T_\alpha \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Where $\Delta\alpha_1$ and $\Delta\alpha_2$ are the differences of spatial orientations between two lines and their connections, and T_α is the corresponding threshold.

3.3 Removal of Non-Road Lines

After grouping of lines, line segments are connected to form continuous roads. At the same time, some non-road line features still exist together with roads. These non-road features need to be removed based on some properties of road networks before a complete road network is formed. It is well known that a road rarely exists individually, but connects to other roads to form a network. Some topological properties of road networks in an image can be represented by the following rules:

Rule one: if a line passes through two different edges of the image, then it is a road.

Rule two: if one end of a line connects to a road and the other passes through an edge of the image, then it is a road.

Rule three: if one end of a line connects to a road and its length exceeds a given threshold, then it is a road.

Other rules may also be developed according to the local characteristics of road networks. Using the above three rules, isolated and short line segments can be removed from the linked line images and true roads are retained.

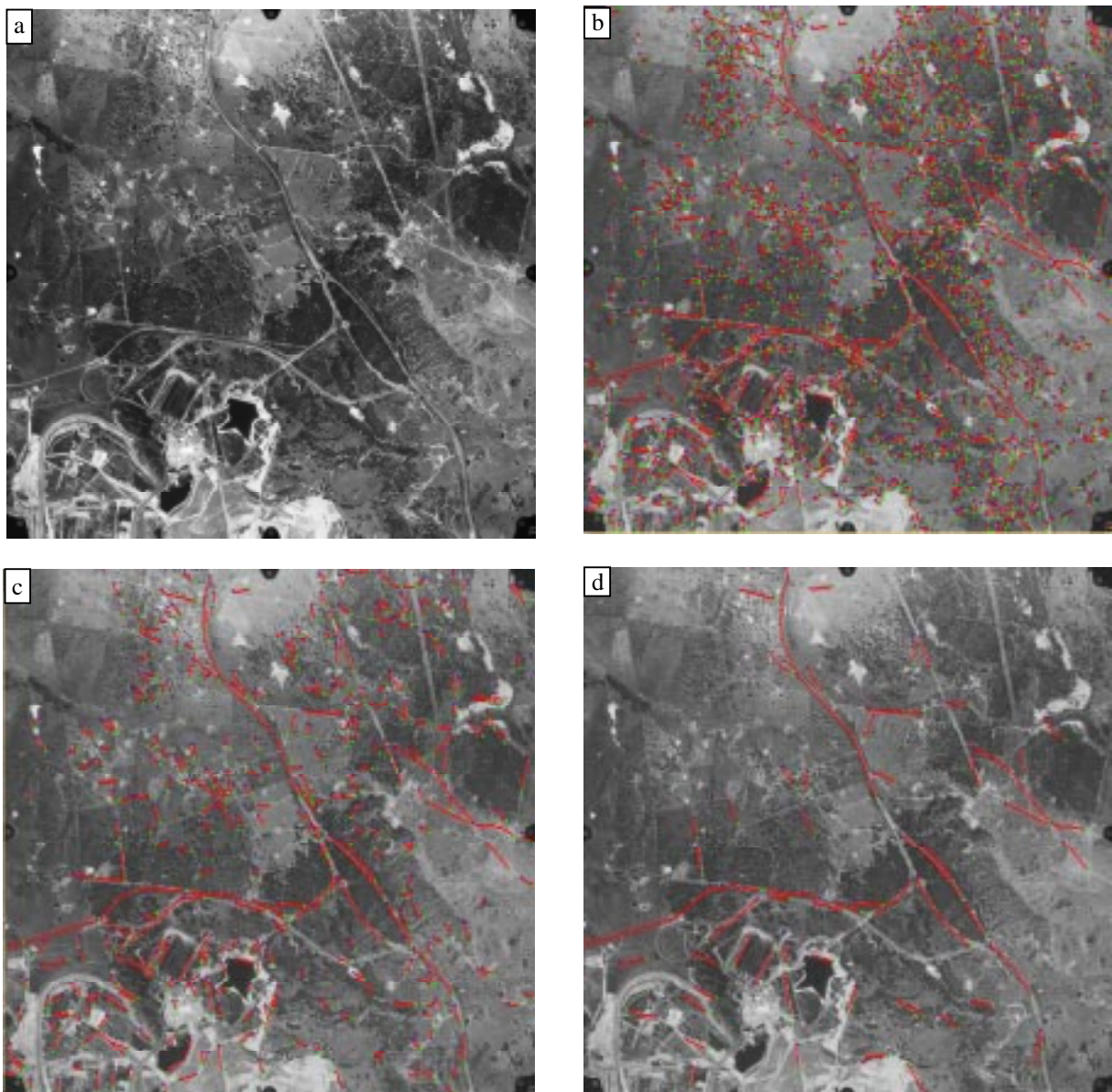


Figure 2. Hierarchical grouping of line images a. an aerial image b, c, d. line images generated using thresholds of 5, 10 and 20 pixels.

4 TESTS AND RESULTS

An aerial image in Hunter valley, New South Wales was used in this study. The original image has a scale of 1:25,000 and has been scanned with a pixel size of 30 μm . To generate a low-resolution image, the original image was resampled at a reduction factor of 15, resulting in an image of 500 \times 500 pixels with a ground resolution of 11.25 m, giving an image with similar resolution to SPOT panchromatic images. The image covers a rural area with two main roads, as shown in Figure 2a. A morphological operator was used in this study to extract line features. After line extraction, line points are tracked and small gaps (< three pixels) are bridged to form elongated line segments based on the criterion of collinearity. Smooth line segments were generated using a split-and-merge operation. Three different thresholds of 5, 10 and 20 pixels were used to generate the hierarchy of line images as shown in Figure 2b, c and d. As can be seen, the line image using the threshold of 5 pixels contains most road parts and many non-road line features which are very short (Figure 2b). Due to blurred road surface around the middle and lower right of the image, roads in these areas were not extracted correctly by the line operator. With the increase of the threshold, more non-road line features were removed, but some road segments were eliminated due to high curvature of the road around the middle of the image (Figure 2d). It can be seen that the line images at different levels of the image hierarchy give different degrees of details of roads. Grouping of lines started from the top of the hierarchy, i.e., the image shown in Figure 2d, and the grouping results are

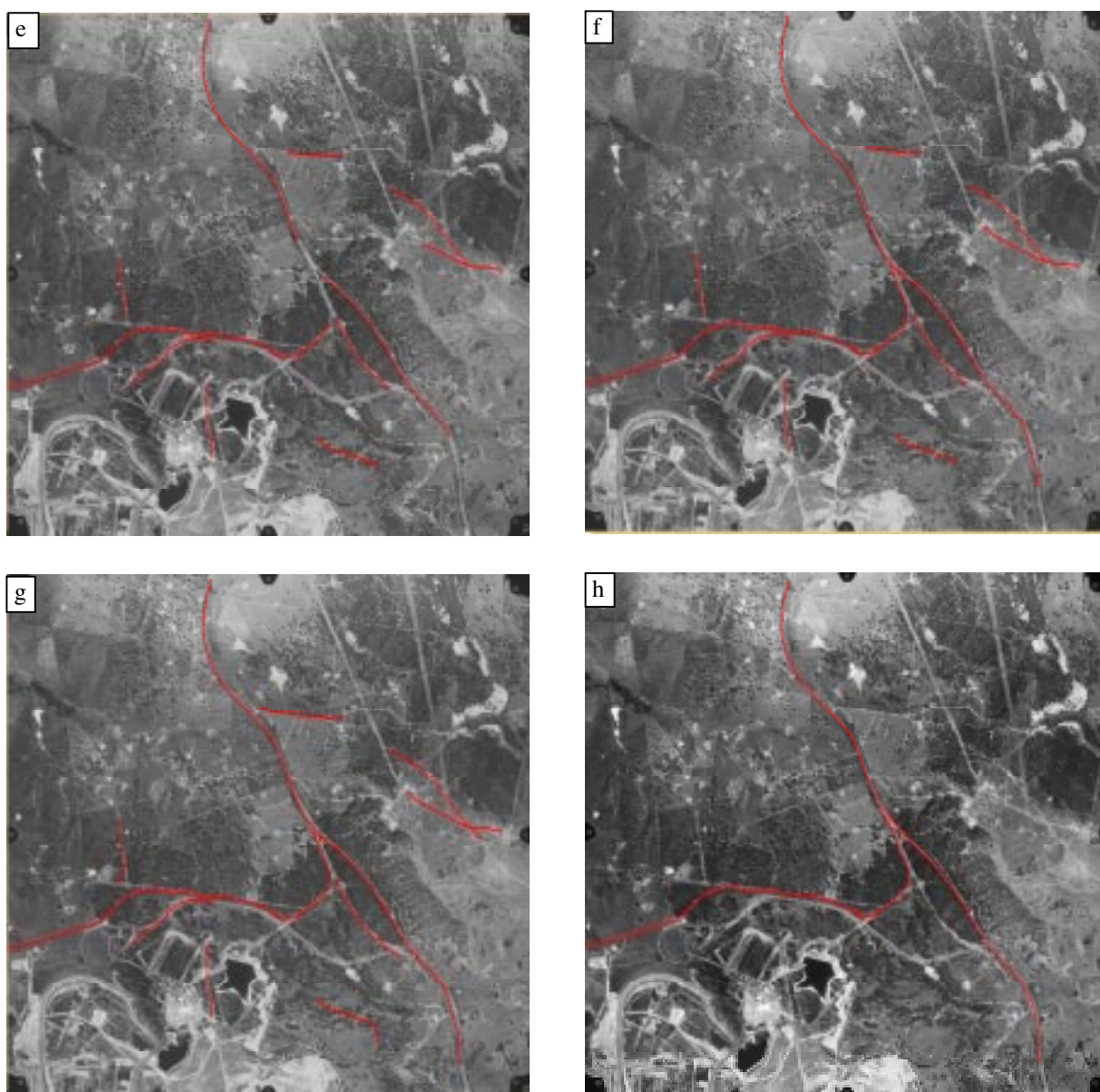


Figure 2 (continued) Hierarchical grouping of line images e, f, g, grouping results at three different levels h, final road network after removal of non-road features.

shown in Figure 2e. At this level, the main structure of the road network was well detected and some minor roads were extracted as well. However, some road parts were not extracted at this stage. With the extracted road network as a guide, grouping proceeded to the next level and short line segments around the detected roads were connected based on their similarities of geometric and radiometric properties. In this way, missing road segments were detected while the effects of non-road line features were eliminated effectively. The results of grouping at level 2 and 3 are shown in Figure 2f and 2g. As can be seen, the missing road segments were extracted successfully. However, some isolated line segments were retained. Some of them are minor roads while others correspond to non-road linear structures. Having applied the rules described in Section 3 to them, the isolated line segments were removed and the road network was retained, as shown in Figure 2h. There is a short segment missing at the bottom of the road running vertically. This is caused by that part of the image being blurred and hence the road was not extracted by the morphological operator.

5 CONCLUSIONS

This paper presents a novel approach for automatic road network extraction from low-resolution images. The method first extracts line features and generates a hierarchy of line images by image processing. The lines are then grouped hierarchically to form a complete road network. One advantage of the method is that it can avoid the problem of threshold selection. At the same time, hierarchical grouping of lines, i.e., from sparse to dense distribution of line segments, can eliminate most non-road features effectively during the grouping process, and thus can generate a reliable road network. Non road features can be removed using the knowledge of road networks. However, some minor roads will still be missing as the case in this study. It would be necessary to overcome these problems by a user friendly interface allowing an operator to easily determine lines which should be removed or added.

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