Road Extraction Assisted by Laser Data

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Abstract
How to make road extraction automatically remains a great challenge up to now. Published researches show that existing approaches are partly available for dealing with shadowed parts of roads especially to rural roads. In this paper, a new approach is proposed to apply laser range data to automatically extract urban roads from digital images. The extraction process is composed of three steps. The first step is working on laser images, where parameters like height and edges of high objects are obtained from the original laser images. At the same time, a new concept called "associated road line (ARL) graph" is developed to assist the road extraction from digital images. The second step deals with digital images, where road edges are obtained through Canny operator. The result proved that ARL graph is a homeomorphous mapping of real road line (RRL) graph. The gaps between segments of RRL are bridged through parts of its ARL through topological transformation. Finally, the shadowed parts of RRL are reconstructed with the help of spline approximate algorithm. The preliminary result proved that this approach is effective and has a potential advantage for efficient extraction of roads from complex patterns of urban road network.

1. INTRODUCTION

Road extraction from digital images has received attention because of the increasing importance of geographic information systems (GIS). Roads are nothing but a kind of networks on the ground for transportation of people and commodities. Nowadays, the original road function has been extended to a modern concept which is not only limited to a simple traffic concept, but also to include an economic and political concept (Baumgartner, et. al., 1997).

However, how to make road extraction by fully automatic means through computer technology remains a great challenge up to now. While, it is relatively easy to do road extraction in rural areas, the cases in urban areas are challenging a great complicatedness of roads induced from complicated road environment. Some sections of roads are occluded by shadows of high buildings, trees, road markings, and vehicles. In this way, there are obstacles to extract road. Removing out the influence of these complex road characteristics on road extraction and reducing it to a simple road nature for automatic road extraction are still an unresolved problem in the field of road extraction.

It is the purpose of this paper to study the above-mentioned open problem and try to develop a new road extraction approach, which is called the road extraction assisted by laser data, the REAL in short. For this, let us take first a look at what geometric properties roads have and suitability of existent road extraction approaches for urban areas. It is common knowledge that all roads are designed with uniform width everywhere. In other words, its edges on both sides are nearly parallel to each other, and its centerline has the least curvature variation at each point on it to ensure road traffic safety (Grun and Li, 1997). As far as our knowledge goes, all existing semi-automatic and automatic road extraction approaches basically take these two geometric properties as their constraint to search road edges. Published researches have shown that some of the existent road extraction approaches are partly dealing with shadowed parts of roads. Yet, they are basically designed, especially for road extraction of rural roads. A typical kind of these approaches is "Semi-Automatic Feature Extraction by Snakes" (Trinder and Li, 1995). This approach uses the geometric property of equal width as a constraint. Its purpose is to search for road edges and make a combination of edge information with variable curvature of road centerline as an integrative constraint. Hence, it helps to meet with a road gradient having smooth and minimal variation. In other words, this method may define the structure of line features. Another approach is the "zip-lock" snakes developed by Neuenschwander, et al., (1995). In fact, it is a modification of the snakes' approach. By the use of automatic detection of seed points, semi-automatic schemes can be extended to automatic ones. As mentioned above, although most roads are designed as the objects with their smooth surface and firm geometric properties, their appearances might be different in digital images. Especially, it is extremely difficult for road extraction to handle large objects, such as buildings and trees, due to their occlusions and shadows. Figure 1 shows these problems.

Not all available road extraction approaches have a good ability

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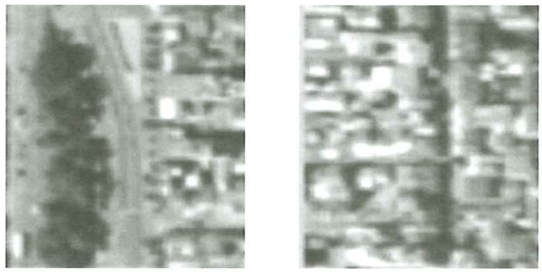
to solve these problems. For this reason, we developed a new road extraction approach in this paper. This approach intended to automatically extract roads from digital images assisted by laser data (LD). As it is known, laser scanning altimetry could enable to generate a 3D topography information of objects on the ground under all circumstances. The occlusions coming from weather and shadows of buildings and trees and so on don't influence the LD quality. Therefore, it is wise to integrate these two kinds of data for creating our new automatic road extraction approach. As explained below, firstly, the height information from LD could be utilized to remove out all high rising objects, like buildings, trees, etc. It is assumed that none of the roads should traverse these high regions. Secondly, the edges of buildings and trees obtained from LD could be used to define the "associated road line (ARL) graph". The ARL assists us to automatically simulate real road gaps caused by occlusions and shadows coming from high objects. Through the use of topological transformation, a homeomorphous mapping, and approximate spline algorithm, our new REAL approach can be accomplished. A discussion on this approach is outlined below.

II. LASER DATA AND IMAGE PROCESSING

Laser scanning data

Laser scanner is a device used to measure physical characteristics such as distance, density, velocity, shape, etc. It is based on sequential range measurement from an airborne sensor to points on the surface. Range is measured with highly collimated laser beam by detection of the turn-around time of flight. The precise position and orientation of the airborne platform could be known from differential GPS and INS measurements. This helps to calculate the geographic position of the surface points in three spatial dimensions to a decimeter accuracy (Sohne, et. al., 1993). The periodic deflection of the ranging beam across the direction of flight causes the sampled surface points to be distributed over a strip of 250-500m widths, which ultimately allows the generation of surface elevation



(a) (b)

Figure 1. Roads in aerial images

'images', i.e. of 2D arrays with elevation data in each cell (Hug, 1996). Figure 2 shows the laser data and its 3D reconstruction.

Laser scanner is also an active sensor which provides the illumination of the surface. The effective distance of laser scanner depends on the relationship between the received light intensity and the noise level. This makes the sensor of laser scanner insensitive to shadow's effects and occlusion problems different to passive sensors. These characteristics of laser scanner provide us a possibility to identify the roads under the shadows and occlusions of buildings and trees.

Image processing

Adaptive filtering

In general, automatic extraction of roads is divided into four main steps: (1) road features enhancement (adaptive filtering and wavelet transform), (2) selecting the road seeds and tracking the possible road points, (3) generating the road segments, and (4) linking the road segments and automatic extraction of roads. Road extraction by itself is one kind of feature detection. In order to detect the road features accurately, image processing should be conducted to enhance the road features, at the same time removing out the effects of noise in the whole path. Here, the adaptive filtering algorithm (Kenneth and Castleman, 1996) is adopted for gradient-based road enhancement. This filter smoothes each signal point. The

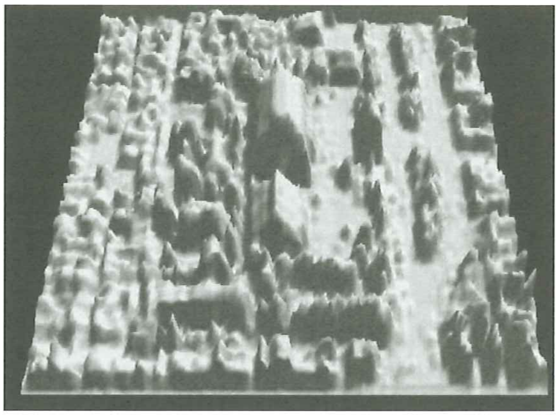


Figure 2. Laser data and 3D reconstruction

procedures of iterative convolution based on template can be represented as follows:

$$S^{(t+1)}(x) = \frac{1}{N}\sum_{i=-1}^{1} S^{(t)}(x+i)\omega^{(t)}(x) \quad (1)$$

Where $S^{(t+1)}$ is the signal after (t+1) times iterative and smooth results, and $\omega^{(t)}(x)$ is the template. In the processing, the filter smoothes each signal point, except those sudden change points while we set template $\omega^{(t)}(x)=0$, so the edges have been enhanced. The merits of this algorithm are: (1) edges would be sharpened after the smoothening iterative filtering, and (2) the image would be adaptively smoothed, and, on the contrary, the edges on the image would be sharpened. Figure 3 (c) shows the results of adaptive filtering algorithm.

The original input image is aerial photograph. Because of the noise effect of the image on Figure 3 (b), gray values of the edge sides haven't showed distinct change. However on Figure 3 (c), after the adaptive filtering, edges of the images have been enhanced, and the other regions have been smoothed. From the Figure 3, we are able to find that, adaptive filtering algorithm is suitable to detect lines as well as noise restraint.

Edge detection

In the real world, all physical objects have their boundaries. When we observe these boundaries of objects on the digital image, the sudden change of gray value between the two sides of edges presents us very important information. In terms of the sudden change of gray value, edge detection becomes possible. The purpose of edge detection is for image understanding and computer vision.

It is well known that the typical edge detection operators such as Sobel algorithm, Laplacian of Gaussian (LOG) operator, Canny operator, etc. have different advantages and applicable ranges (Haralick, 1984). In this paper, Canny operator is applied to fulfill the edge detection of both aerial image and laser image.

III. THE REAL APPROACH

ARL Assumption from laser image

Topological property of RRL graph

It is well known that roads are built to meet the various requirements of people. Hence, road design follows some basic principles like: (1) roads are organized as a network, i.e. all roads should be connected with each other; (2) road components are classified into different categories; (3) according to the different categories, any road is designed to make its minimum variation of curvature at every point on its centerline in the range of maximum allowed slope, i.e., the change of road direction should be gradual and smooth in order to get a great assurance of road traffic safety; (4) the materials of road surface should be with strong spectral sensitivity; (5) almost all road segments should include road markings, sidewalks, and cycle-tracks alongside of them; and (6) every kind of roads should be associated with the buildings, parkings, and the other high objects, whose edges should be as parallel as possible with its centerlines. Thus, we assumed that these road design rules define the general attributes of road. Rule 1 in the principles of road design has motivated us to be particularly interested in, i.e., all road edges (equivalent the road centerlines) form a plane network of topology named a road network. The so-called road graph built by road edges is, as a matter of fact, nothing more than a single path in the topological network (Bredon and Glen, 1993). The so-called path in topology means a graph composed of a sequence of arcs with a finite number. All arcs are different from each other and can be passed through and each arc be passed one time only. That is to say, in this sequence of arcs, one of a couple of ends each arc must be regarded as the starting of this arc, while the another one being its terminal. The common end of two connected arcs must be the terminal of the first arc and the starting of the second arc. Similarly, the terminal of the second arc must be the starting of the third arc, and so on. The end of the arc is termed as summit (or top) of network. This

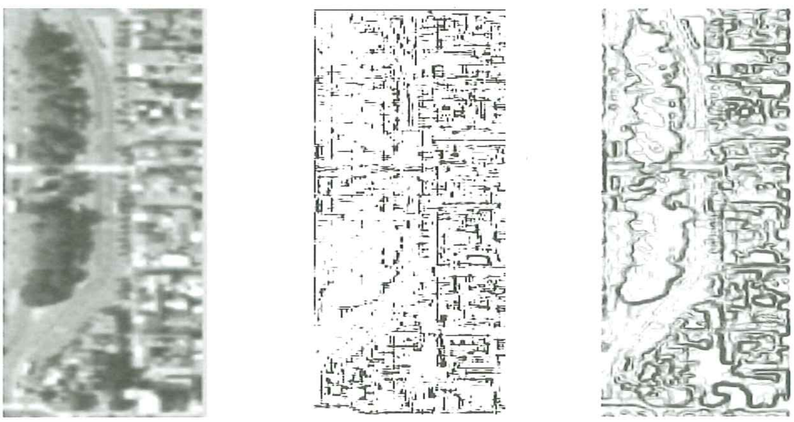

(a) (b) (c)

Figure 3. (a) original image, (b) detection result without adaptive filtering, (c) detection with adaptive filtering

paper doesn't go into the whole road network but, instead, a single path in it. A single path is also regarded as a sub network of the road network. Methods to investigate the topological property of any single path in the road network are explained below. For doing this, the concept of order of summit (Bredon and Glen, 1993) is introduced at first. In topology, the order of summit is understood by the number of ends of arcs situated at the summit under discretion. According to the definition of single path, on each of single paths the order of any summit between the starting and terminal of single path can but be equal to even number. Similarly, the order of either of summits at the starting and terminal of this single path could be equal to odd number. The reason is that there are two ends of arcs located at any middle summits. Only one arc is located at the starting and terminal of this path. Figure 4 demonstrates the idea graphically.

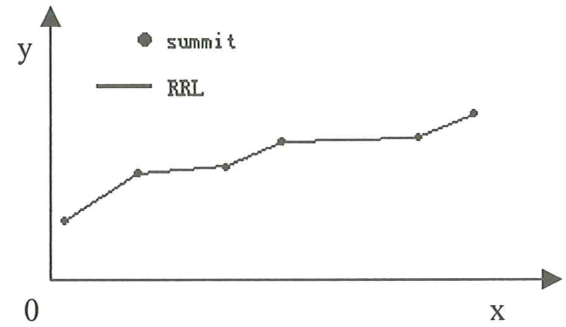


Figure 4. Sketch of the distribution summits of RRL graph

On this account, the following conclusions would be made on topological invariant of single road graph:

Theorem 1 Any of single road graphs has exactly two odd-order summits.

We know from topology (Bredon and Glen, 1993) that the graph having exactly two odd-order summits is nothing but a topological property. This property remains unchanged with all possible homeomorphous mappings to this graph. So it is also called a topological invariant. Homeomorphous mapping is also called topological transformation i.e., a kind of continuous and bijection operators. This invariant behavior describes the identical property of images of these graphs with respect to all possible homeomorphous mappings. In other words, all graphs are topologically equivalent (homeomorphous) to each other if and only if any of them has exactly two odd-order summits. A very interesting aspect is that a straight-line segment *[a, b]* has two odd-order summits, located at two ends *a* and *b* of this segment. According to what has been stated, any single path *L* in road network should be homeomorphous to any straight-line segment *[a, b]*. In this way, a single path *L* may be written as a set structure form which is shown as follows:

$$L := \{ (X, Y) ; X=X(t), Y=Y(t), \quad t \in [a,b] \} \qquad (2)$$

where (X, Y) is Descartes coordinates point on curve *L*, and *t* is a parameter. As a matter of fact, Equation (2) gives a definition of homeomorphous mapping *F* from straight-line *[a, b]* to graph *L* as follows:

$$F : [a,b] \to \quad L: \quad t \mapsto (X,Y) \qquad (3)$$

As can be seen, road graph *L* is nothing else than a simple curve in geometry, which is composed of simple arcs whose number is finite.

ARL Graph based on laser image

It was explained in Section 3.1.1 that the homeomorphism of two graphs to each other implies that they have the same topological invariant. In this case, these two graphs make no differences to each other in the point of view of topology. Similarly, the background or the sources of data where they come from don't have impact. Furthermore, there exists a topological transformation to make these two graphs superpose upon altogether. Unfortunately, this theorem is nothing but a pure existential theorem of topological transformation. We can hardly find out this kind of topological transformation in practice. Even so, it could provide us a very useful elicitation. When we do a road extraction based on remotely sensed data such as aerial photos in the case where some parts of road are occluded by shadows of trees, buildings, etc., we can theoretically use any kind of information coming from the other sources to assist with recovering parts of real road where there is no aerial photo information due to contamination from shadows if and only if the edge curve drawn by this kind of assistant information is homeomorphous to RRL graph. However, in this paper we just try to use LD as supplementary information to undertake the REAL approach. In doing so, the following ideas were made: to put forward a concept of ARL graph and show the way on how to draw it out is based on LD; to verify homeomorphousness of the ARL graph to the RRL graph. Before doing this, some discussion is provided about LD.

In Section 2.1, it was discussed about the attributes of LD. LD could provide two kinds of useful information. One is the height information, which helps to decrease the computing workload and to remove out the false roadways on high objects. So that, the efficiency of detecting edge of images would signally be heightened. The second one is supporting information that we can discover in the circumstances of roadways under shadows of trees and occlusions of high objects. With respect to this kind of information, LD play a very crucial role in assisting the REAL approach. It can be seen that the major obstacle of road extraction lies in its impossibility of getting any information of circumstances about real road under shadows and occlusion on aerial photos and satellite images. In the extraction of roads through computer technology, the RRL is normally tracked along its gray scale attribute. If the tracing in some parts of road is interrupted by shadows or occlusion or absence of other information to determine the context of these parts, it is indeed impossible to carry out this road extraction and get over the interrupted parts of the road.

In this research, through the REAL approach, the first thing is detecting road edges by utilizing LD. Obviously, it is easy to detect edges of high objects as buildings and trees. Nevertheless, we should see that laser scanner is one of altimeters for measuring distance, density, velocity, and shape. It is hardly possible to make detection of road edge line because a road has almost the same height. So that, the gray scale values on both sides of roadside also would be nearly equal to each other. Although road information cannot directly be arrived from LD, an important fact may be found out that, information about the edges of buildings, trees, and another high objects on roadsides is particularly useful to realize the road extraction approach. On Figure 1 (a), it could be observed that, one side of the road is occluded by the shadows of trees. On the other side, there are buildings parallel with the road edge. At the same time, through the LD we found out that the ground under the shadows is very even with no high objects on it. On this account, according to Rule (6) in the principle of road design, we could make a guess that under the shadows, there must be one side of the road. In this way, we may regard the trees' edges coming from the laser image and associated with the road line together and along this road direction as another kind of road line, i.e. the ARL graph. In order to facilitate the computer processing, a buffer of the trees' edges were set, and only those lines parallel to the road direction and close to the road were taken up. See Figure 5 shows the detailed illustration of this procedure.

Needless to say, the ARL graph and the RRL graph come from quite different image sources, while the ARL graph is from LD, the RRL graph from aerial photo information. Both graphs, as rule are different from each other in geometric conformation. For instance, in the ARL graph, a curve formed by edges of trees, is irregular, behaving as changing of its curvature in a rapid and sharp way. On the other hand, the RRL graph should be a smooth curve, as changing of its curvature in a slow and exiguous way (see Figure 5). The role of ARL graph to assist extracting of road approach depends on topological homeomorphousness of the ARL graph to the RRL graph. As can be observed, no matter how rapidly and sharply the curvatures of the ARL graph change, the ARL graph is nothing less than a curve composed of a sequence of arcs whose number is finite.

Suppose the ARL graph has n arcs. That means, it has $n+1$ summits. It can be seen from Figure 6 that in this case, any of the summits in between two terminals of the ARL graph is an even-order summit because the number of ends of two arcs situated at this summit is equal to two. For both terminals of the ARL graph, each of summits on them is clearly an odd-order summit because there is only one end of one arc at it. In this way, we could arrive at the conclusions:

Theorem 2 The ARL graph based on LD exactly covers two odd-order summits.

Theorem 3 The ARL graph and the RRL graph are homeomorphous to each other.

Thus it can be seen that the ARL graph l also is a simple curve in geometry, which can be also represented by a set structure form as shown on equations 4:

$$l: =\{ (x, y) ; x = x(t), y = y(t), \quad t \in [a, b] \} \quad (4)$$

where (x, y) means Descartes coordinates of point on curve l.

IV. THE REAL—ITS FORMULATION AND NUMERICAL REALIZATION

The Homeomorphous mapping from ARL to RRL

As mentioned above, if two graphs have the same topological invariant, then these two graphs are homeomorphous to each other. It is to say, both of these graphs are topologically equivalent to each other. In this case, theoretically there exists a unique homeomorphous mapping making both graphs congruent with each other. However, this mapping is impractical. Hence, it is also possible and easily to get the numerical representation of this mapping in the circumstances like graphs of ARL and RRL.

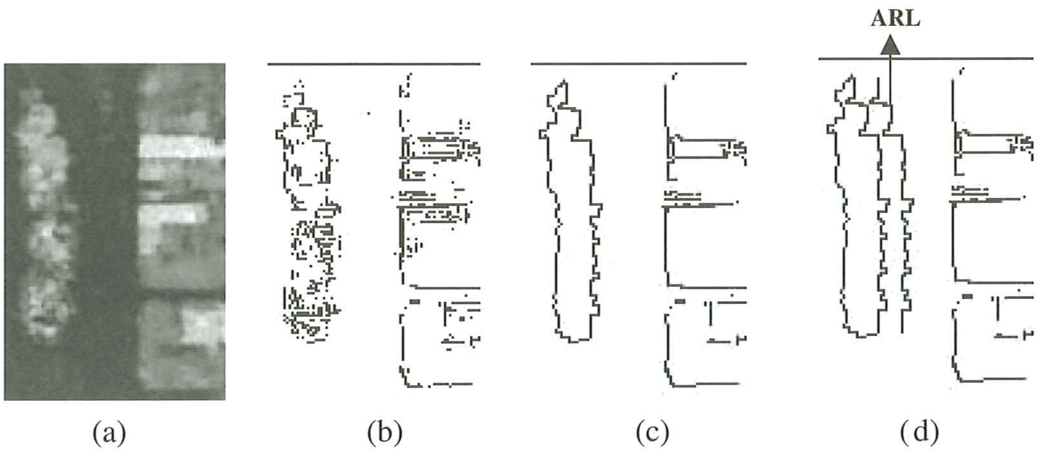


Figure 5. (a) laser image, (b) and (c) edge detection based on Canny, (d) ARL setting

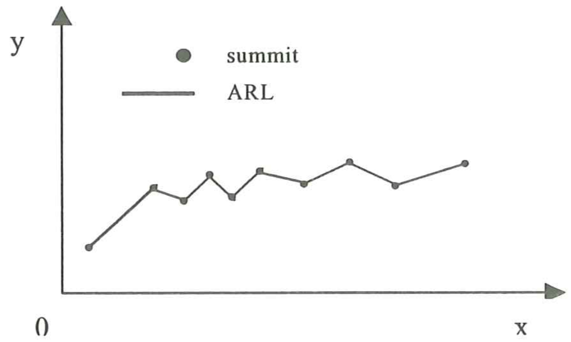


Figure 6. Sketch of the distribution of summits of ARL graph

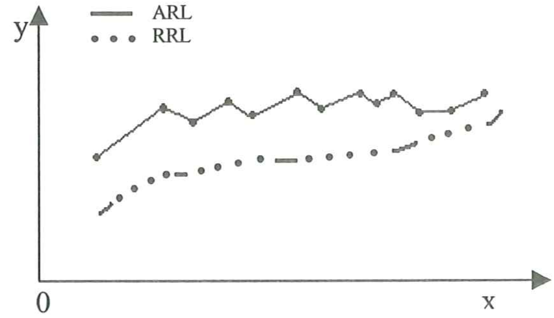


Figure 7. Homeomorphousness of ARL graph l to RRL graph L

The numerical representation problem of homeomorphous mapping from RRL graph L to ARL graph l is explained below. Suppose these two graphs are already given. Because L and l are simple curves, we have their set structure forms as equations (2) and (4). Following these two equations, we can immediately establish a mapping as:

$$H:\ l \rightarrow L:\ (x,y) \rightarrow (X,Y):\quad \begin{cases} X = x \\ Y = y - h \end{cases} \tag{5}$$

where h means Euclidian distance from point (x,y) to (X,Y):

$$h = |(x,y)-(X,Y)| = [(x-X)^2+(y-Y)^2]^{1/2} = y-Y \tag{6}$$

So h is a function of point (x,y) or (X,Y). On the other hand, the inverse H^{-1} of mapping H can be made as:

$$H^{-1}:\ L \rightarrow l:\ (X,Y) \rightarrow (x,y):\quad \begin{cases} x = X \\ y = Y + h \end{cases} \tag{7}$$

It is clear from (5), (6) and (7) that H is a continuous and bijection mapping. That is to say, we have:

$$\begin{cases} H(l) = L \\ H^{-1}(L) = l \end{cases} \tag{8}$$

It follows that H is a homeomorphous mapping (topological transformation). In the case where both l and L are just given in image way, it is impossible to make H analytically. Rather, it can be realized numerically in this case. Remark this theorem just shows a method how to numerically realize the homeomorphous mapping from l to L only on the assumption of knowing both curves l and L. At the same time, this homeomorphous mapping may be understood by a non-uniform stretching motion of l to L in the direction of y-axis to make l congruent with L (Figure 7).

Formulation of the REAL problem and homemorphism-matching of RRL graph

In our REAL, the whole ARL graph is given; instead, there are only several_segments of road desired to extract with information from aerial photo. In this case, we cannot at first hand make use of the above-named method to reach our goal. In this section, we will explain the methods to extract the gaps between two segments with aerial photo information.

Let's take Descartes coordinate system O-xy, where x-axis is as parallel as possible to the RRL graph L desired to extract. Indicate a point on L as (X, Y), and on its ARL graph l as (x, y). For simplicity and without losing of universality, suppose L has two road segments Δ_1 and Δ_2 with aerial photo information. It could be written:

$$\Delta = \Delta_1 + \Delta_2 \tag{9}$$

In this case, we have three gaps in L with no aerial photo information, denoted as G_0, G_1 and G_2, respectively; that means:

$$L = G_0 + \Delta_1 + G_1 + \Delta_2 + G_2 \tag{10}$$

See Figure 8 for further details. Now, let sign Gap denote the subset of L as:

$$Gap = L - \Delta = G_0 + G_1 + G_2 \tag{11}$$

Suppose we have drawn the ARL graph l from original laser image. At the same time, let δ_j and λ_k denote the projections of $\Delta_j (j=1,2)$ and G_k $(k=0,1,2)$ on graph l in the direction of y-axis, respectively. We put:

$$\begin{aligned} \delta &= \delta_1 + \delta_2 \\ \delta^c &= l - \delta = \lambda_0 + \lambda_1 + \lambda_2 \end{aligned} \tag{12}$$

In this way, the formulation of the REAL problem should be reduced to reconstructing information of subset Gap of L. For doing this, we firstly need to create a homeomorphous mapping H^* from δ to Δ. The discussion in Section 4.1 could be written as follows:

$$H^*:\ \delta \rightarrow \Delta:\ (x,y) \rightarrow (X,Y):\quad \begin{cases} X = x \\ Y = y - h \end{cases} \tag{13}$$

where h is defined on each point $(x,y) \in \delta$ or $(X,Y) \in \Delta$. The second step was to find an extension of mapping H^* to δ^c. This is to find out such a mapping $\hat{H}$ that is defined in the domain l and its restriction on δ is equal to H^*, i. e. $\hat{H}$ is equal to H^* if all points $(x,y) \in \delta$:

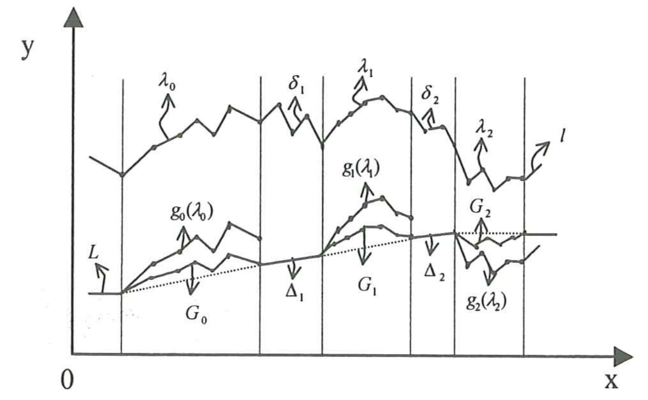


Figure 8. Homeomorphous mapping of ARL to HOMAR

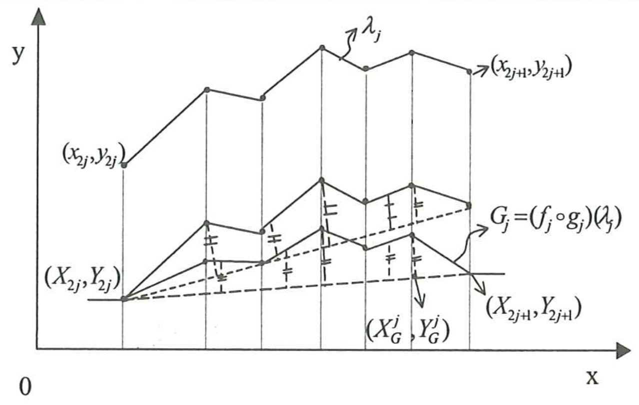


Figure 9. Sketch of operator $(f_j \circ g_j)$: $\lambda_j \rightarrow G_j$

$\hat{H} = H^*$: $\delta \rightarrow \Delta$: $(x,y) \rightarrow (X,Y)$:

$$\begin{cases} X = x \\ Y = y - h \end{cases} \qquad (14)$$

We know from functional analysis (Hu, 2001) that originally there is not any a unique extension $\hat{H}$ of mapping H^* to δ^c because of inverse space of mapping $\hat{H}$ being much 'larger' than its image space.

Hence, we would determine the needed extension $\hat{H}$. For this, we have applied the following method. Analysis on Figure 8 could primarily help us with the subset λ_0 of ARL graph l. We take a shifting operator g_0 like as follows:

g_0: $\lambda_0 \rightarrow g_0(\lambda_0)$: $(x,y) \rightarrow (X^0, Y^0)$:

$$\begin{cases} X^0 = x \\ Y^0 = y - h_0 \end{cases} \qquad (15)$$

where h_0 means the distance from the starting (X_0, Y_0) of the RRL to the starting (x_0, y_0) of the ARL graph. Curve $g_0(\lambda_0) := \{(X^0, Y^0)\}$ is the image of curve λ_0 with respect to operator g_0, see Figure 9.

Next, we take such an operator

f_0: $g_0(\lambda_0) \rightarrow G_0 : (X^0, Y^0) \rightarrow (X, Y)$:

$$\begin{cases} X = X^0 \\ Y = Y_G^0 + D^0 \end{cases} \qquad (16)$$

where $Y_G{}^0$ is equal to vertical coordinate of intersection $(X^0, Y_G{}^0)$ of straight line $x = X^0$ with straight line connecting the starting (X_0, Y_0) and terminal (X_1, Y_1) of G_0, and D^0 is a directional and perpendicular distance from a point $(X^0, Y^0) \in g_0(\lambda_0)$ to the chord connecting point $(X_0, Y_0) \in G_0$ with point $(X^0{}_1, Y^0{}_1) \in g_0(\lambda_0)$. If curve $g_0(\lambda_0)$ is up the straight line from (X_0, Y_0) to (X_1, Y_1), D^0 is taken as positive; otherwise it would be taken as negative. In this way, equations (15) and (16) were defined with a composite operator λ_0:

$(f_0 \circ g_0)$: $\lambda_0 \rightarrow G_0$: $(x,y) \rightarrow (X,Y)$:

$$\begin{cases} X = X^0 \\ Y = Y_G^0 + D^0 \end{cases} \qquad (17)$$

Similarly, for gaps G_1 and G_2, we can finally write for all graphs G_j $(j=0,1,2)$ as follows:

$(f_j \circ g_j)$: $\lambda_j \rightarrow G_j$: $(x,y) \rightarrow (X,Y)$:

$$\begin{cases} X = X^j \\ Y = Y_G^j + D^j \end{cases} \qquad (18)$$

where the definitions of $Y_G{}^j$ and D^j $(j=1,2)$ are similar to $Y_G{}^0$ and D^0. From above-shown, we can write down the extension $\hat{H}(l)$ of mappin H^* to δ^c as follows:

$$\hat{H} = \begin{cases} H^* & on \quad \delta \\ (f_j \circ g_j) & on \quad \delta^c \end{cases} \qquad (19)$$

where operators H^* and $(f_j \circ g_j)$ are defined as equations (14) and (18). It is easy to prove that mapping H is a continuous and bijection mapping, i.e. its image $\hat{H}(l)$ is nothing but a curve homeomorphous to both ARL graph l and RRL graph L. For an easy understanding, take a look at the sketch map Figure 9. From this figure we can see that $\hat{H}(l)$ is a curve with a simple structure, which is composed of a sequence of limited number of arcs and just has two odd-order summits at the starting and terminal of the RRL graph. At the same time, we can see that on δ_j curve, $\hat{H}(l)$ is absolutely congruent with segment $\Delta_j (j=1,2)$ of the RRL graph with aerial photo information, and on δ^c, represents gaps G_j $(j=0,1,2)$. On this account, we call curve $\hat{H}(l)$ the homeomorphism-matching of RRL graph coming from ARL graph, and the HOMAR for short.

The Numerical realization of the REAL—approximation by cardinal Spline

Yet, the new curve, the HOMAR $\hat{H}(l)$, does not meet the goal set in this paper. As a matter of fact, the curvature of this curve is changed in a rapid and sharp way, but it is not the case for RRL graph. According to the principle of road design, the curvature of RRL should be smooth. Therefore, it stands to reason that we need to further smooth it in order to make a numerical realization of the reconstruction of gaps in RRL without aerial photo information. Here we adopt the so-called approximate spline algorithm to arrive at our purpose. Normally, traditional approaches in road extraction get the spline through manual selection of seeds. For this reason, these approaches are called semi-automatic extraction of roads. In addition, in these approaches, discrete points are selected by the preferences, depending on the operators' experience. In this research, because we have got $\hat{H}(l)$ from ARL graph and $\hat{H}(\delta) = H^*(\delta) = \Delta$ from (10), discrete points might be obtained automatically from the ARL graph. The kind of spline, which is adopted in this study, is explained below.

Spline curves are the curves with continuous attribute in each segment. They are calculated by polynomial transform algorithm. These splines are always represented by three orders polynomial with one or two orders continuous derivation. Cardinal spline is used as an interpolation algorithm in our REAL. A Cardinal spline is a curve that passes smoothly through a given set of points. Cardinal spline is 3rd order curve of each segment. A Cardinal spline is totally given by four consecutively controlled points, two middle points are the extreme points of the curve, and another two points are for calculating the slope of the end point (Figure 10).

Boundary slope is positive scale with arcs $P_{i-1} P_{i+1}$ and $P_i P_{i+2}$, t is tension.

V. PRELIMINARY EXPERIMENT AND CONCLUSIONS

The approach of REAL proposed in this paper has been preliminarily implemented on computer. We have tested the algorithm on the two kinds of images covered the same area, one is aerial photo, and another one is laser image. Firstly, we do the image processing to these two images for the purpose of image filtering based adaptive filtering, so that most of the noises on the images are removed (Figure 3). Secondly, after images are filtered, edge detection is necessary to make up our research; Canny operator is available in the experiment (Figure 5). Thirdly, we determine the ARL graph from the LD for the assistance of real roads simulation (Figure 5). Fourthly, Cardinal spline is got according to the result of homeomorphism-matching $\hat{H}(l)$ of ARL to RRL in this paper; all discrete points are selected automatically, different to the semi-automatic methods. The preliminary results are given in Figure 11.

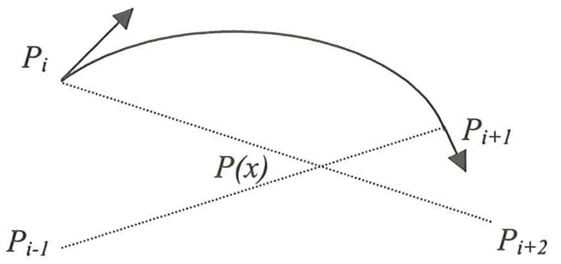


Figure 10. Illustration of cardinal spline

In this paper, the procedures of the experiment can be concluded as follows:

- We first applied LD to road extraction.
- Then put forward the concept of ARL graph acquired from LD.
- Graphs of ARL and RRL have been proven homeomorphous to each other in Section 3.
- Through the selected HOMAR $\hat{H}(l)$, the gaps can be bridged between real road segments with ARL.
- The controlled points of Cardinal spline are selected automatically, so the semi-automatic road extraction algorithms are improved.

Although we have got some progress in the field of road extraction assisted by LD, some obstacles yet remain to be further improved.

- In Section 3.1, methods to decide the ARL have been described clearly, as for the matching of the ARL and RRL. When we do the experiment, some noise on the images always affect the matching result. In the experiment, some false road segments were removed by the operators, not through image processing algorithm.
- The images cover the urban area, where the roads exhibit more complicated appearances than they are in rural areas. In this case, there are some cars and lanes on the extracted road. How to group these features would be the issue of further our research.

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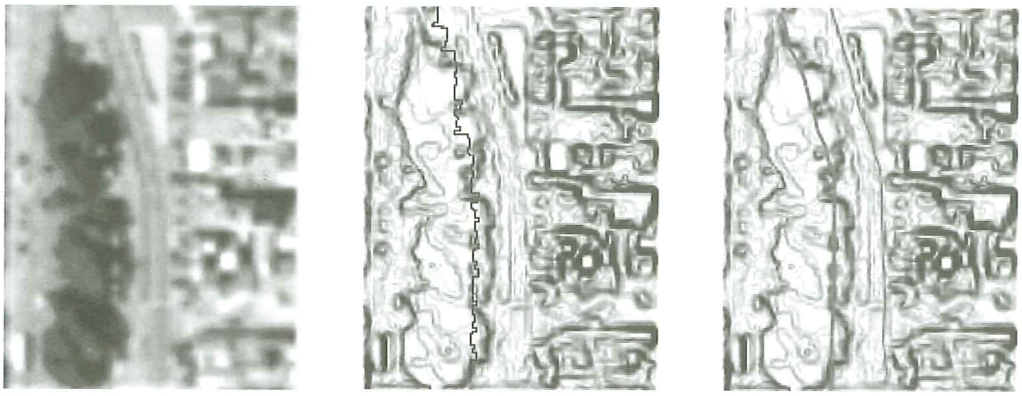

(a) (b) (c)

Figure 11. (a) aerial photo after adaptive filtering, (b) edge detection and the ARL selected, (c) extracted roads based on Cardinal spline approximate algorithm

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