AUTOMATIC ROAD EXTRACTION FROM MULTISPECTRAL HIGH RESOLUTION SATELLITE IMAGES

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ABSTRACT

In this paper we propose an approach for automatic road extraction from high resolution multispectral imagery, such as IKONOS or Quickbird, in rural areas. While aerial imagery usually consists of 3 spectral bands, high resolution satellite data comprises 4 spectral bands with a better radiometric quality compared to film, but a worse geometric resolution. Therefore, strongly making use of the spectral properties of satellite imagery is a way to mitigate the geometric disadvantages and achieve results comparable to those from aerial imagery. To this end, we employ local as well as global properties of roads. The extraction starts with the extraction of Steger lines in all spectral channels. The lines are used as cues for roads to generate training areas for a subsequent automatic supervised classification. The result of the classification, the road class image with its well behaved characteristics, is used as an additional source for the extraction of road candidates. Our novel verification process for road hypotheses makes use of geometric conditions as well as the spectral properties of roads by computing the road energy from the road class image. From the verified road hypotheses a final road network is generated by first bridging small gaps based on a weighted graph and then searching for missing connections in the network by calculating local detour factors. The missing connections are closed by optimizing ziplock snakes between pairs of seed points and are then verified. An evaluation of the results is carried out by comparing our results with manually extracted reference data demonstrating the potential as well as the problems of the approach.

1 INTRODUCTION

The advent of high resolution optical satellite imagery such as IKONOS or Quickbird opens new possibilities for the extraction of linear features such as roads. The advantages of this data compared to aerial imagery are the almost worldwide availability and the radiometric resolution of 11 bit in usually 4 spectral bands. The geometric resolution with 1 m for IKONOS and 0.6 m for Quickbird is worse than for aerial imagery, but for the purpose of road extraction in a lot of cases still sufficient.

The worldwide availability of the data makes it possible to produce topographic databases for nearly any region of the earth, for example for military purposes and disaster prevention or relief. At present, information extraction from images is performed mostly manually, and thus time and cost intensive. To overcome this bottleneck, automatic means are needed. In the field of road extraction most of the existing work was either done for aerial imagery or for satellite imagery with a resolution worse than 2 m. Our goal is to develop an approach for automatic road extraction for high resolution multispectral satellite imagery based on techniques originally devised for aerial as well as medium resolution satellite imagery.

There is a large body of related work on road extraction from aerial and satellite imagery. For an overview we will focus on recent work or work which employs similar data or techniques, e.g., classification, construction of networks, bridging of gaps, or snakes, as our approach. In (Fischler et al., 1981) two types of operators are combined: the type I operator is very reliable but will very likely not find all features of interest, whereas the type II operator extracts almost all features of interest, but with a possibly large error rate. Starting with the reliable type I road parts, gaps are bridged based on the type II results employing F^* search. (Wiedemann et al., 1998) extract and evaluate road networks from MOMS-2P satellite imagery with a resolution of about 6 m employing global grouping. The basis of this approach is the Steger line operator (Steger, 1998). A framework for the extraction of multispectral lines and edges for the recognition of roads in SPOT or Landsat imagery is proposed in (Busch, 1996). The use of snakes for the detection of changes in road databases from SPOT and Landsat satellite imagery is demonstrated in (Klang, 1998). (Wallace et al., 2001) present an approach designed for a wide variety of imagery. It is based on an object-oriented database which allows the modeling and utilization of relations between roads as well as other objects. Recently, road extraction using statistical modeling in the form of point processes and Reversible Jump Markov Chain Monte Carlo was proposed by (Stoica et al., 2004).

There is an increasing number of papers on road extraction from high resolution satellite imagery, particularly IKONOS. (Dial et al., 2001) gives an overview over the properties of the IKONOS sensor and presents a road extraction approach making use of the multispectral capabilities of the imagery. A system for road extraction from multispectral imagery based on fuzzy logic is proposed by (Amini et al., 2002). (Mena and Malpica, 2003) segment color images using the Dempster-Shafer theory of evidence for the fusion of texture, to extract linear features. (Péteri and Ranchin, 2003) employ a multiresolution snake for the extraction of urban road networks given existing but imprecise GIS data. (Doucette et al., 2001) present a semi-automatic approach that uses a pre-classified imagery to detect roads using the so called ”self-organising road map” (SORM). In (Zhang and Couloigner, 2004) a multi-resolution analysis approach based on wavelets, road junction detection, and grouping is proposed. (Mohammadzadeh et al., 2004) introduce an approach based on fuzzy logic and mathematical morphology.

In this paper we propose a novel approach for automatic road extraction from pan-sharpened IKONOS images which makes use of the 1 m panchromatic resolution as well as the multispectral information. It is designed for the automatic extraction of roads in rural and suburban areas. The paper is structured as follows: Section 2 gives an overview while Section 3 sketches the technique used for classification. In Section 4 the individual steps of the extraction, namely line extraction, our novel road hypotheses verification, and road network generation are detailed. Section 5 presents experiments showing the potential of the approach. The paper ends with conclusions.

2 OVERVIEW

Our approach makes use of local as well as global characteristic of roads. **Locally**, roads are modeled as elongated regions with a locally constant spectral signature in the multispectral imagery (MSI) and a maximum width. **Globally**, roads are modeled in terms of their function for humans. They are designed for the optimal transport of goods and persons from one point to another and therefore they form a topological network.

The strategy derived from this is divided into four main steps (cf. Fig. 1). First, lines are extracted in all image channels and employed as initial road hypotheses as well as for the generation of training areas. Based on the latter the MSI is classified using a supervised classification. Employing the results of the classification together with the geometric properties of the lines, the road hypotheses are verified in the third step. Finally, the verified road hypotheses are fused and globally grouped into the road-network. Before detailing our work on road extraction, we give a short account of the classification approach we employ.

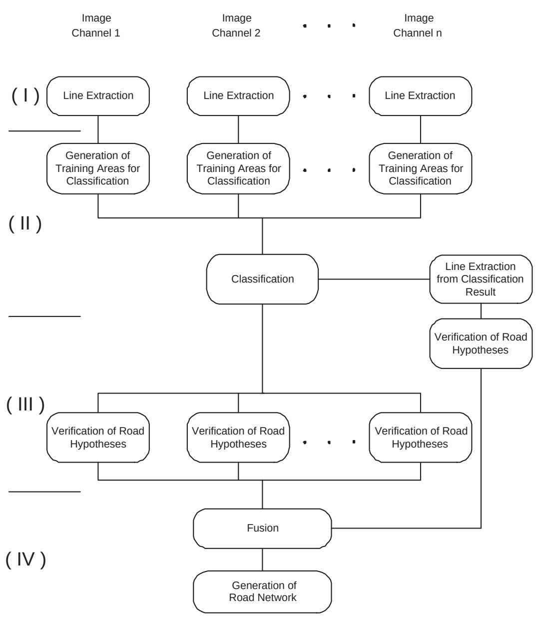

Figure 1: Road extraction from high resolution multispectral imagery

3 CLASSIFICATION

Roads in high resolution satellite imagery mostly correspond to elongated regions with a locally constant spectral signature. Here, we employ a fuzzy classification proposed in (Bacher and Mayer, 2003). The goal is to calculate a membership value for the road class for every pixel. The approach consists of two main parts: (1) automatic generation of reliable training areas and (2) fuzzy classification.

Training areas are generated from linear features that satisfy the following conditions:

- There exist parallel edges close to each other on both sides of the linear feature.
- The variation of the grey value within the region between the parallel edges is small.

Preliminary training areas are extracted separately in every channel of the MSI. They are then fused to generate the final set of training areas, which need to have a minimum number of road pixels (50 pixels were used for the presented examples) to describe the spectral properties of the road class in a representative way.

The **classification** is carried out fuzzy-based. A Gaussian membership function is set up, using the mean and standard deviation of the gray values in each channel, for every training area. Using these functions, combining the results of the single training areas, and finally performing a rank filtering, a final membership value for every pixel to the road class is calculated. By this means we can model roads made of different materials. An example for a so-called ”road class image” is shown in Figure 2.

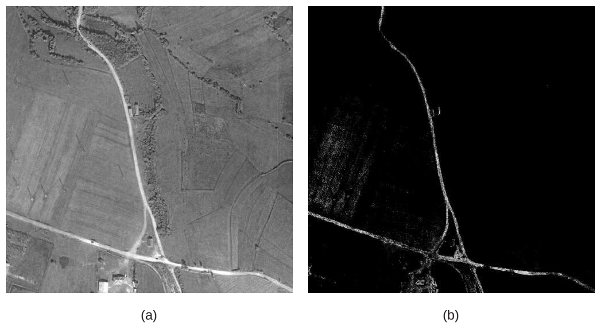

Figure 2: Original image (a) and result of automatic classification (b), where the brightness corresponds to the degree of membership to the road class

4 ROAD EXTRACTION

The approach for road extraction proposed in this paper extends (Steger et al., 1997, Wiedemann et al., 1998). We have adapted it for high resolution MSI by integrating a new module for the verification of road hypotheses, that does not only make use of geometric constraints, but also of the spectral properties of roads. The extraction strategy consists of the steps (I), (III), and (IV) shown in Figure 1. (I) and (III) make use of the local properties of the roads while performing **line extraction** and generating road hypotheses followed by their **verification**. Finally, (IV) employs the global properties of roads by generating a **road network**.

4.1 Extraction of Lines

Line extraction is carried out using the differential geometric approach (Steger, 1998). Bright or dark lines can be extracted with sub-pixel accuracy based on only a few parameters, e.g., the maximum width. Lines are extracted in the image channels as well as after the classification in the road class image to generate as many road candidates as possible. The road class image is useful as an additional channel for line extraction, because of the well known behavior of roads in it and the resulting simple and robust adjustment of the extraction parameters: Roads in the road class image always appear as salient bright lines with dark surroundings.

To allow reasonable speeds for driving, roads usually have a limited curvature. Thus, lines often change their meaning from roads to non-roads at points where the curvature is high. To deal with this, the extracted lines are split at points with high curvature and only then act as preliminary hypotheses for road parts for the next step.

4.2 Road Hypotheses Verification

Apart from the homogeneity of the grey value along the road, the assessment of the road hypotheses is done in (Wiedemann et al., 1998) only based on geometric conditions. Spectral properties are not used. To use as much knowledge as possible for the verification of road hypotheses, we developed a new method for assessing road hypotheses. Particularly, we calculate fuzzy values (Zadeh, 1989) for the following parameters:

- length μ_L
- average width μ_W
- road energy, i.e., average membership value μ_E of the road hypotheses to the road class

Figure 3 shows the criteria for the assessment of road hypotheses and the linear membership functions used for the calculation of the corresponding fuzzy values. The individual fuzzy values are combined into one final weight μ_R for each line with the fuzzy AND operator using equation (1).

$$\mu_R = \mu_L \wedge \mu_W \wedge \mu_E = \mathbf{MIN}(\mu_L, \mu_W, \mu_E) \qquad (1)$$

The road hypotheses are considered to be verified and are used for the following generation of a road network, if the final weight μ_R is above a given threshold.

4.3 Road Network Generation

For the verification the individual spectral channels are regarded separately leading to a strong redundancy. To generate a consistent set of roads, the results from the different channels are fused eliminating redundant roads in the same way as in (Wiedemann, 2002). Starting from the fused roads a network is generated in two steps:

First, remaining small gaps are eliminated based on a weighted graph. In this graph missing connections are detected by finding

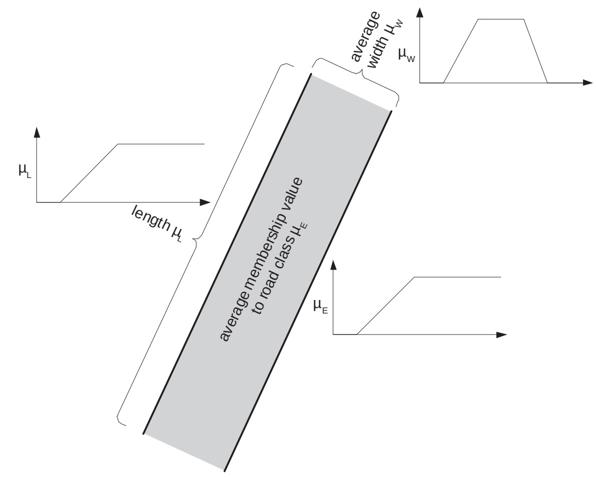

Figure 3: Criteria for the assessment of road hypotheses together with the membership functions for the evaluation of the corresponding fuzzy-values

the best path between pairs of seed points using the Dijkstra algorithm and calculating weights for the possible connection. A gap is closed if the connection is part of an optimum path, without making use of image information (Wiedemann et al., 1998).

In the second step, larger gaps are closed using the approach of Wiedemann (Wiedemann and Ebner, 2000) extended with a new module proposed by (Bacher and Mayer, 2003, Bacher and Mayer, 2004) for the verification of potential connections. Potential gaps are detected using the property of road networks, that most points can be reached from all other points with minimum detour. To make use of this property, link hypotheses are generated. The distance of adjacent points is calculated once along the network and once along the hypothetical optimal path, i.e., if nothing else is known the Euclidean distance. From these distances a detour factor is computed using equation (2).

$$detour\ factor = \frac{network\ distance}{optimal\ distance} \qquad (2)$$

The link hypotheses are checked with the new module, detailed below, starting with the hypotheses with the largest detour factor. If a link hypotheses is accepted, the new connection is inserted into the road network. Due to changes in the network, the generation of link hypotheses has to be repeated. This is iterated until no more new link hypotheses can be generated. The result of this global grouping step is the final road network.

The module for the verification of link hypotheses starts with the two end points of the potential connection. The goal is to find the optimum path between these points with respect to the geometric and radiometric characteristics of roads and use it to verify or reject the link hypotheses. For the determination of the path a ziplock snake (Neuenschwander et al., 1995) is optimized between the two end points employing the image information of the road class image (cf. Fig. 4). To verify or reject a link hypotheses, i.e., to decide if the hypotheses actually corresponds to a road, a grey value profile perpendicular to the snake direction is calculated for every snake point in the road class image. When evaluating the quality of a single point, the profile is first smoothed with a Gaussian kernel. Then, the maximum value along the profile and the position of the maximum are calculated. For a valid point the maximum should be close to the center of the profile and the second derivative along the profile at the maximum point should be significantly smaller than zero. A link hypotheses is accepted if the average evaluation value of all snake points is above a given threshold.

(a) (b) (c)

Figure 4: Optimization of a missing connection (a) using a ziplock snake and the road class image (b) as image information; (c) result

5 EXPERIMENTS

The proposed approach was tested on a large number of scenes. here we present results for two IKONOS pan-sharpened images. The area of the first image is located in northern Africa close to the city of Tunis (cf. Fig. 5). The second image is a part of the test image ”ikonos3” from the EuroSDR test on automatic road extraction (cf. http://www.bauv.unibw-muenchen.de/institute/inst10/eurosdr/) and is located in the Kosovo (cf. Fig. 6). For both images reference data was produced by manually digitizing the road network. For the Tunis test area two reference sets were aquired, one minimum reference (Hinz, 2003) consisting only of the main roads, and a second maximum reference containing also the small roads and the access ways. To evaluate the results, the parameters – Completeness, Correctness and Root Mean Square Error (RMS) – from (Heipke et al., 1998) were utilized.

The results for the Tunis test area (cf. Fig. 5 and Table 1) show, that the number of false positives is small when benchmarked with the maximum reference where all roads, including the small access ways are included. On the other hand, one can see from benchmarking with the minimum reference that more than 90 % of the main roads are extracted with a geometric accuracy of about 1 m.

For the Kosovo test image, the results (cf. Table 1) are presented in Figure 6. For this test area we have produced only one reference set, comparable to the maximum reference of the Tunis example. The results show, that most of the main roads in the image were correctly extracted. The approach can deal with sharp bends (upper left corner) or roads consisting of different materials (road from the center to the top). The results in the small village (south-west of the center) are not satisfying giving a clear indication why the approach is intended for open areas. The number of false positives outside the village is small and most of the missing roads are small access ways leading to fields.

Table 1: Evaluation of automatic road extraction results

Test area	Completeness	Correctness	RMS[m]
Tunis Min	0.91	0.66	1.01
Tunis Max	0.64	0.90	1.13
Kosovo	0.74	0.71	1.29

6 CONCLUSIONS

An automatic approach for the extraction of roads from high resolution multispectral satellite imagery has been proposed. The images are first classified resulting into the so-called ”road class image” comprising membership values for every pixel. Using the results of the classification and a number of geometric constraints, Steger lines are assessed as road hypotheses. Our novel verification process making use of spectral information for the verification of road hypotheses, considerably reduces the number of false positives, e.g., caused by small fields or hedges. Additionally, roads with high curvature or changing width, e.g., caused by shadows cast on them, can be extracted without adapting the parameters. Using the verified hypotheses, the road network is generated. For the validation of the approach, results of the evaluation for two test areas based on manually extracted reference data are shown, indicating the potential, but also the problems of the approach.

Our future plans comprise, e.g., to use the spectral properties of roads together with the road width, to automatically classify roads into different road classes. From visual inspection it is possible to distinguish paved roads from dirt roads.

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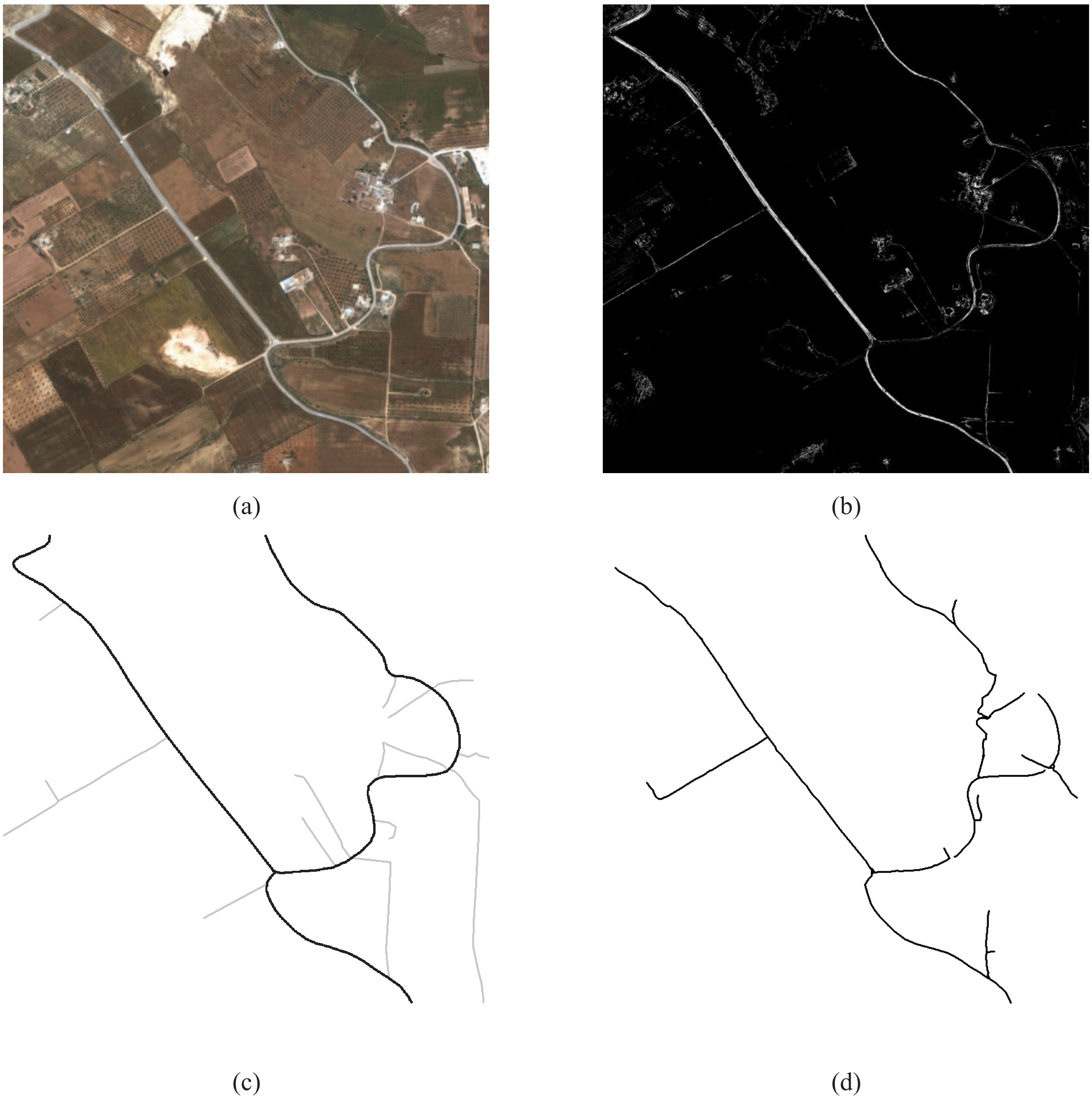

Figure 5: Tunis; (a) IKONOS image, of size 1131 x 1090 pixels; (b) road class image; (c) reference data – black minimum reference, black + grey maximum reference; (d) result of automatic road extraction

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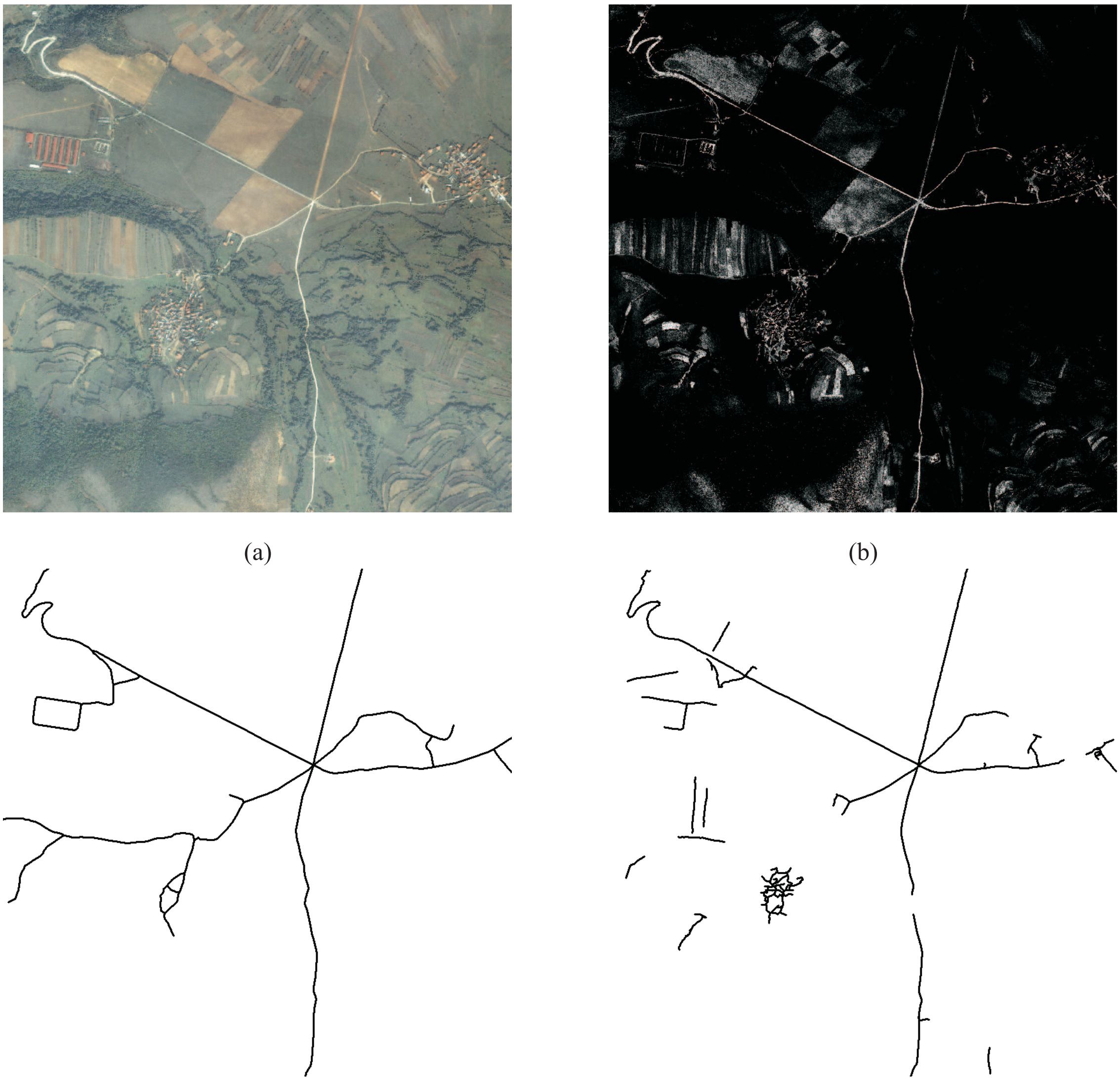

(a) (b) (c) (d)

Figure 6: Kosovo; (a) IKONOS image, of size 2251 x 2251 pixels; (b) road class image; (c) reference data; (d) result of automatic road extraction

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