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Pattern Recognition Letters 24 (2003) 3037–3058

Pattern Recognition
Letters

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State of the art on automatic road extraction for GIS update: a novel classification

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Received 13 March 2003; received in revised form 14 May 2003

Abstract

This paper surveys the state of the art on automatic road extraction for GIS update from aerial and satellite imagery. It presents a bibliography of nearly 250 references related to this topic. The work includes main approaches on general methods of road network extraction and reconstruction, road tracking methods, morphological analysis, dynamic programming and snakes, methods multi-scale and multi-resolution, stereoscopic and multi-temporal analysis, hyper-spectral experiments, and other techniques for road extraction. Likewise, other approaches related in any way with the road extraction topic are also considered. Between them different papers on segmentation, vectorization, optimization, evaluation, semantic nets and neural networks, fusion techniques, fuzzy logic, and other methods are discussed. A novel classification of road extraction methods according to our criteria is included in order to provide a significant contribution to research in this topic.

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Keywords: Automatic road extraction; GIS update

1. Introduction

From Marr (1982), where a group of techniques and methods on computer vision are analyzed, the proliferation of the research in artificial vision and pattern recognition has been spectacular. In fact, Rosenfeld (2000) presents a bibliography of 1700 references related to computer vision and image

analysis, arranged by multiples subject matter. Previously, in the photogrammetry field, Förstner (1996) discusses objections against performance characterization of vision algorithms and explains their motivation. More recently, in (Petersen et al., 2002) a review of more than 200 applications on neural networks in image processing is presented. This paper discusses the present and possible future role of neural networks, especially feed-forward neural networks, Kohonen feature maps and Hopfield neural networks. The basis of these techniques can be studied in (Freeman and Skapura, 1991; Ripley, 1996).

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In the knowledge representation and manipulation topic McKeown et al. (1999b) proposes to reduce the time needed to create virtual worlds by improving the line simplification operation in the production process. In this case, direct application of an algorithm for simplification resulted in the generation of topological and terrain related anomalies that required manual identification and correction. Likewise, Grove et al. (1999) presents a research in order to add knowledge to the automatic systems, using the Geographic Information System (GIS) databases and multi-temporal objects representation. This paper proposes the application of semantic nets in order to achieve their objectives. An introduction about the basis of semantic nets can be found in (Winston, 1992).

Recently, Koenderink and Van Doorn (2002) approaches to the time of image processing, of which a large part involves the computation of features. This paper exposes that features can be defined as loci where absolute differential invariants of the image assume fiducial values, taking spatial scale and intensity scale into account. It also says that classical euclidian invariants do not apply to images because image space is non-euclidian, but rather it is a Cayley Klein geometry with one isotropic dimension. About this topic Goldstein (1980) can be consulted.

On the other hand Duygulu et al. (2002) describes a model of object recognition as machine translation. In this model, recognition is a process of annotating image regions with words. Likewise Agarwal and Roth (2002) presents an approach for learning to detect objects in still gray images, that is based on a sparse, part based representation of objects. And finally, in (Pedersen and Lee, 2002) the statistics of local geometric structures in natural images is analyzed. In this paper an extension of analysis to a filter based multi-scale image representation is presented.

Evidently, the scarce mentioned references constitute a small part of them dedicated to computer vision and pattern recognition. However, they all maintain any connection point with the automatic object extraction methods. In (Baltasvias et al., 2001) many references on cartographic features extraction can be found.

2. GIS update: cartographic object extraction

Actualization of cartographic and topographic data using imagery is an important application in the Earth sciences. Automatic extraction of objects from digital imagery is not only scientifically challenging but also of major practical importance for data acquisition and update of GIS databases or site models. Nevertheless, the scientific community knows that this problem is very big, and for solving it knowledge application in the automatic methods is indispensable.

2.1. Surveys mainly focusing on GIS update

In order to assist to the mentioned problem, Brennan and Sowmya (1998), Heipke et al. (1999) and Doucette et al. (1999) propose to include reasoning in the computer through an image interpretation guided by the GIS data-base. The last reference presents an approach to semi-automated linear feature extraction from aerial imagery, in which Kohonen's self-organizing map algorithm is integrated with existing GIS data. In (Heipke et al., 2000) different aspects of image analysis are discussed and a framework is provided for scene interpretation, which is based on the integration of image analysis and a GIS data model. Likewise, Eidenbenz et al. (2000) presents the project ATOMI whose aim is to update vector data of road centerlines and building roof outlines from 1:25000 maps.

GIS data models and nested classification are also used in (Straub and Weidemann, 2000; Straub et al., 2000a). These papers propose to simplify the object extraction task through an automatic image interpretation subdivided into more specialized problems like the extraction of buildings or roads and natural objects like vegetation or water. A complement of these works is Straub et al. (2000b). Also supported in the existing GIS information Agouris et al. (1998) presents an approach to the issue of extraction and tracking of objects in digital aerial images. In this case, the algorithms proposed are based on fuzzy systems theory according to Zadeh (1965), and are designed to function within an integrated geospatial environment, which comprises digital images and preex-

isting information on the objects depicted on them. Additionally, in (Agouris et al., 2001b,d) the integration of object extraction and image is based on geospatial change detection using an extension of deformable contour models, or snakes. The basis of the snake concept can be found in (Kass et al., 1987).

Many cartographic military systems of OTAN countries are using the framework presented in (Ohlhof et al., 2000). This paper reports on the results of two projects conducted for the AmilGeo of the German Federal Armed Forces. The first project consist of to establish an operational workflow to update existing Vmap Level 1 data using commercially available satellite imagery. The second project is a survey focused on the generation and update of Vmap Level 2 data using satellite and airborne imagery. Outside of the military environment (Bonnefon et al., 2002) presents a complete process to update and upgrade geographic linear features in GIS with methods as automatic as possible and with a quality evaluation. Also Busch and Willrich (2002) presents an approach in this topic.

2.2. *Surveys mainly focusing on cartographic object extraction*

Surveys on extraction and supervised classification appear in (Ford and McKeown, 1992). Later on McKeown et al. (1996) presents an overview on image understanding and automated cartography to support efficient representation and rapid construction of virtual world databases. Topics here discussed include the use of aerial and terrestrial imagery to phototexture site models for visualization, the refinement of multi-image stereo, and experiments towards the development of methods to evaluate cartographic feature extraction systems. Mirmehdi et al. (1997) describes an optimization process for robust low level feature extraction based on genetic algorithms, and Bulwinkle et al. (1998) proposes an exchange format in order to serve as a system independent method for import and export of three dimensional object descriptions between different systems. The genetic algorithms theory can be consulted in (Goldberg, 1989).

The technological advances in the years 1980 and 1990 have demonstrated the importance of multi-sensor data fusion techniques. In (Hall, 1992) a detailed study is presented, and between the most important works in this topic are Ford et al. (1998), Ebner et al. (1999) and McKeown et al. (1999a). Also Hellwich and Wiedemann (2000) offers an approach to the combined extraction of linear as well as surface objects from multi-sensor image data based on a feature and object level fusion. In this case, data sources are high resolution panchromatic digital orthoimages, multi-spectral image data, and interferometric Synthetic Aperture Radar (SAR) data. An extension of this work is presented in (Hellwich et al., 2001).

On the other hand, Peddle and Ferguson (2002) proposes three methods for optimizing the process of data fusion, relative to the specification of user defined inputs, based on different levels of empirical testing and computational efficiency. Likewise, Fabre et al. (2001) uses pixel fusion in order to elaborate a classification method at level pixel. In this paper the evidence theory is utilized according to Kohlas (1995, 1997) and Kohlas and Besnard (1995a,b), and Bauer (1997). Kiema (2002) examines the influence of multi-sensor data fusion on the automatic extraction of topographic objects from SPOT panchromatic imagery using texture analysis. This technique also is applied, according to Cross and Jain (1983) and Gagalowicz (1987), in (Mena, 2002b). Another fusion techniques are presented in (Schenk and Csathó, 2002), where Light Detection and Ranging (LIDAR) imagery is used, and (Hellwich et al., 2002) where SAR imagery is analyzed.

A fundamental topic in automatic object extraction is the knowledge representation and modeling for computer vision. In this field, Mayer (1999a) presents a exhaustive study and detailed analysis on automatic object extraction. This paper defines criteria in order to establish a model of knowledge. In (Sowmya and Trinder, 2000) a review of the approaches used in knowledge representation and modeling for machine vision can be found. More recently Dell'Aqua and Gamba (2001) offers a fuzzy approach to the analysis of airborne SAR images of urban environments; and

in (Andersen et al., 2002) LIDAR sensing geometry is explicitly modeled in the scan space three dimensional domain.

About the phases of the general automatic object extraction process, very important is Ohlhof et al. (2000) which have been already commented, and Markov and Napryushkin (2000) which proposes a detailed and efficient sequence very interesting for many extraction systems and applications.

On building extraction, Mayer (1999a) is a basic reference. Other surveys are Shufelt (1999a,b) and, more recently, Gulch (2000) where a semi-automatic system for the extraction of buildings from digital aerial imagery with the aid of volumetric primitives in urban environment is presented. Also about buildings, Ogawa et al. (2000) develop a map based approach that enables to efficiently extract information about man made objects from aerial images. In (Gamba and Houshmand, 2000) the task of extracting significant built structure in digital surface models is analyzed. Zimmermann (2000) describes a framework for building recognition in aerial images, as well as Niederöst (2000). Later on Zhang (2001b) presents a method focusing in urban areas fusing multi-spectral with panchromatic satellite data. Other works on building extraction are: (Sohn and Dowman, 2001) where high resolution satellite images are used; (Gerke et al., 2001a) which uses digital surface models in urban environment; (Gerke et al., 2001b) where aerial color infrared images are analyzed; and (Heuel and Förstner, 2001) which discusses models for building extraction from multiple images.

Using a set of color infrared aerial photos, Knudsen et al. (2002) compares a developed neural net based clustering method with a method based on classical algorithms for automated detection of buildings. Ruther et al. (2002) presents an approach to semi-automatic extraction in informal settlement areas from aerial photographs. In (Fraser et al., 2002) a research on the application and characteristics of IKONOS satellite imagery for building reconstruction is presented. Recently Rottensteiner and Brieser (2002) presents a new method for the automated generation of 3D building models from LIDAR sensors; and Hof-

mann et al. (2002) seeks to transfer 2D building data into 3D building data.

The surveys focused in other cartographic objects are less frequent in the literature. Between them, Heipke and Straub (1999) and Pakzad (2002) present methods in order to extract vegetation areas; Bacher and Mayer (2000) and Straub (2002) discuss the automatic extraction of trees; and Dillabaugh et al. (2002) proposes a semi-automatic extraction of multiple pixel width river features appearing in high resolution imagery.

General automatic systems constructed in order to extract cartographic objects are the ALFIE system and the GeoAIDA system. The first, named Automatic Linear Feature Identification and Extraction is presented in (Wallace et al., 2001). The research project uses a GIS built around an object oriented geospatial database. The second system, named Geo Automatic Image Data Analyser, is described in (Bückner et al., 2002; Gerke, 2002). This system allows an intelligent, concise and flexible control of a scene interpretation by utilizing a semantic scene description.

3. Road extraction methods: general classification

The classification of surveys and different techniques on automatic and semi-automatic road extraction methods and related works is very difficult, given the variety of existing proposals in the literature. However, we can select the principal factors in order to achieve it. These factors are the following: *the preset objective*, *the extraction technique applied*, and *the type of sensor utilized*. Schematically in Table 1 our classification of methods and works on road extraction is presented.

Evidently, in order to attend to this structure, the possibility that a same work is included at the same time in several categories of the classification have been supposed. Next, classification according to the preset objective and classification according to the extraction technique applied are developed. The classification according to the type of sensor utilized is not explicitly developed since this is implicitly included in the two other classifications.

Table 1
General classification

Classification of methods and works on road extraction	
<i>According to the preset objective</i>	
<ul style="list-style-type: none"> • Road extraction general methods • Road network reconstruction methods • Segmentation general methods • Vectorization methods • Optimization methods <ul style="list-style-type: none"> ◦ Neural networks ◦ Genetic algorithms ◦ Other optimization methods • Evaluation methods • Other objectives 	
<i>According to the extraction technique applied</i>	
Low and mid level methods	Mid and high level methods
<ul style="list-style-type: none"> • Road tracking methods • Morphology and filtrate • Dynamic programming and snakes • Segmentation and classification • Multi-scale and multi-resolution • Stereoscopic analysis • Multi-temporal analysis • Other techniques 	<ul style="list-style-type: none"> • Knowledge representation and fuzzy modeling <ul style="list-style-type: none"> ◦ Logic systems ◦ Rules based systems ◦ Blackboard systems ◦ Frames based systems ◦ Semantic networks ◦ Fuzzy logic based systems • Other methods of spatial reasoning
<i>According to the type of sensor utilized</i>	
<ul style="list-style-type: none"> • Monochromatic imagery • Infrared band • Color imagery (RGB) • Multi- and hyper-spectral imagery (HYDICE) • Synthetic aperture radar imagery (SAR) • Laser imagery (LIDAR, ...) • Other type of sensor 	

4. Classification on road extraction according to the preset objective

4.1. General road extraction and network reconstruction methods

These methods seek to obtain the detection and definition of the road network starting from original images, GIS data and context information. Normally segmentation and vectorization geometric techniques are used, as well as processes, models and patterns characteristics of the low, mid and high level of knowledge.

Different investigations related with the automatic and semi-automatic road extraction areas starting from aerial and satellite images have been achieved for some time for specialists in computer

vision (Gonzalez and Woods, 1992; Winston, 1992; Marr, 1982; Mikhail et al., 2001; Winston, 1992) and digital photogrammetry (Schenk, 2002). In the low level pioneer works appear in (Bajcsy and Tavaloki, 1976; Quam, 1978), very distant of the global extraction methods presented in (Markov and Napryushkin, 2000; Ohlhof et al., 2000). General surveys on automatic object extraction, though very related with the road extraction, are given by Brennan and Sowmya (1998) and Mayer (1999b) as well as Eidenbenz et al. (2000), Hellwich and Wiedemann (2000), Bonnefon et al. (2002) and Amini et al. (2002). In the last paper segmentation techniques and morphological algorithms are applied, followed by a skeleton extraction process based on the Wavelet transform according to Benedetto and Frazier (1994) and

Chui (1997). Previously Leymarie et al. (1996) presents a report about the investigations on automatic road extraction carried out by the French National Geographic Institute. In this paper the detection based on texture analysis is a low level visual process, while geometric recovery is a mid level visual process where contextual knowledge about roads is used. Other related works are Airault and Jamet (1995), Ruskoné (1996) and Boichis (2000). Likewise Wufeng and Qiming (1998) presents a system for road extraction which combines low and mid level techniques with artificial intelligence in the high level of knowledge.

In (Baumgartner et al., 1999c; Hinz et al., 2000) a scheme for road extraction in rural areas that integrates three different modules with specific strengths is presented. These modules consist in local grouping using multiple scales and context, global grouping in the road network frame, and analysis of path lengths for improving the result, respectively. Wiedemann and Ebner (2000) proposes a method based on automatic generation of link hypotheses between lines. More general is the work by Chiang et al. (2001) where road network extraction is achieved by generation of seed points, Kalman filtering (Vosselman and De Knecht, 1995), and snakes. Also on network reconstruction, Steger et al. (1997) offers an approach based on fuzzy set theory which involves selecting the correct roads from the extraction results as well as connecting them to construct the road network. The described strategy in order to reconstruct the road network also is used in (Bajcsy and Tavaloki, 1976; Fischler et al., 1981; Ruskoné et al., 1994; Trinder et al., 1999; Wang and Trinder, 2000) and more recently in (Dal Poz and Silva, 2002; Kartatzis et al., 2001; Zhang and Baltsavias, 2002a,b).

The support on GIS information is a common characteristic in many works on road extraction. Besides the already mentioned, we could highlight: (Guérin et al., 1994) because it is one of the first in trying the considered topic; (Agouris et al., 1998) where the road extraction is governed for a fuzzy system; (Jeon et al., 2000) which analyzes curvilinear structures in SAR images together with a digital map; (Dal Poz and Agouris, 2000b) because it uses the GIS database in order to formulate and validate extraction hypotheses; and (Hinz and

Baumgartner, 2002) where evaluation models on road extraction in urban areas are employed.

The use of context information is another important aspects in many methods. Although the most indicative works are Ruskoné et al. (1994, 1995), Ruskoné (1996), Ruskoné and Airault (1997), other important surveys are the following: Vosselman and De Gunst (1997), because only context information for reasoning in the digital road maps update is used; Baumgartner et al. (1997, 1999a,b), where context information, edges analysis and multi-resolution techniques are combined; McKeown et al. (1999b) and Fabre et al. (2001) because they use context information into the study of data fusion in hyperspectral (HYDICE) image processing; Mayer et al. (1997, 1999a) and Hinz et al. (2001b) because they propose the generation of models in the context information analysis; and finally Wallace et al. (2001) where the context information is exploited through an object oriented database.

4.2. *Segmentation general methods*

Although image segmentation general methods have multiple applications, in the road extraction topic they are a great importance. In fact, many segmentation techniques can be used for road extraction in order to obtain a binary image where the road network is depicted. Therefore, many researchers have opted for including these techniques in their road extraction methods.

Under a general view point, the literature presents a great amount of segmentation works based on different theories and principles which are analyzed in many texts like Van Der Heijden (1995); Richards and Jia (1999) and Duda et al. (2001). In this field, Cheng et al. (2001) presents multiple references about the main segmentation supervised and unsupervised techniques. Comaniciu and Meer (2001) proposes a general technique for the recovery of significant image features based on the mean shift algorithm and density gradients analysis. Yu and Bajaj (2002) achieves the image segmentation using existing active snake model and region merging. This last technique is also used in (Cheng et al., 2002). Mukherjee (2002) applies Markov Random Field (MRF) processing

according to Chellappa and Jain (1993) in order to improve an initial segmentation based on growing regions. Another version of MRF processing appear in (Kim and Zabih, 2002).

On the other hand, Chen and Lu (2002) develops a fuzzy clustering algorithm that iteratively generates color clusters using a uniquely defined fuzzy membership function and an objective function for clustering optimization. The unsupervised segmentation through clustering, also can be found in (Hermes et al., 2002; Yang et al., 2002). In the first paper the search for good grouping solutions is posed as an optimization problem, which is solved by deterministic annealing techniques according to Kirkpatrick et al. (1982).

About the segmentation techniques focusing on texture analysis, Cross and Jain (1983) already describes a texture model as a mathematical procedure capable of producing and describing a textured image. Supported in this work, Gagalowicz (1987) presents a technique by which realistic textures can be constructed from a statistical model. In (Campbell and Thomas, 1996) texture and color information are combined using a neural network. Also, Dubuisson et al. (1996) describes an algorithm for combining color and texture information for color images segmentation. Zhu and Yuille (1996) proposes a statistical and variational approach to image segmentation based on an algorithm named *region competition*. On the other hand, Clark et al. (1999) uses the Fourier analysis according to Bracewell (1986) to allow the extraction of texture information from image data. Mirmehdi and Petrou (2000) presents an approach to perceptual segmentation of color textures based on multi-scale representation. Recently Chen and Pappas (2002) presents another algorithm for combining color and texture information. Likewise, in (Monadjemi et al., 2002) methods for extracting features and classifying textures in high resolution color images are proposed.

About the evaluation of segmentation methods, in (Everingham et al., 2002a,b; Kanatani, 2002) interesting approaches are proposed. Finally, Mathiassen et al. (2002) presents a texture similarity measure based on the Kullback–Leibler divergence between gamma distributions; and

Soundararajan and Cross (2002) proposes the application of texture analysis through fractal geometry techniques.

4.3. Vectorization methods

The raster vector conversion is a serious problem as regards automatic road extraction. The vectorial definition of the road network represented in a binary image, in order to obtain automatically the numerical and topological definition of the different components, is very difficult. However, some interesting references relative to this topic can be found. These are the following.

Tanaka and Kamimura (1993) presents a vectorization method based on the energy minimization principle for skeleton extraction. In (Sanniti Di Baja, 1994) the skeleton of a digital pattern is extracted from the distance transform of the pattern, computed according to a quasi-euclidean distance function according to Borgefors (1988). The main advantage of this method is that the pattern can be reconstructed starting from the skeleton. In (Zhu et al., 1995) contour vectorization is applied to convert the binary image of drawings from raster form to vector form. Miravet et al. (1998) presents a system for semi-automatic vectorization of linear networks on scanned cartographic maps. And Yin and Huang (2001) proposes another method in the same line.

On the other hand, McGlone (1998) describes experiments in the block adjustment of linear pushbroom sensor imagery incorporating object space straight line constraints. Other techniques about the adjustment topic can be found in (De Boor, 1978), where the use of splines is described; and Mena (1992), where the application and description of a vectorial format is considered. In (Doucette et al., 2001) an approach of elongated region based on analysis for 2D road extraction from high resolution imagery is presented. Likewise, Mena (2002a) presents a practically automatic method in order to extract the skeleton and the basis topology of a binary image using the *K*-means technique and a new method based on Voronoi diagram construction and Delaunay triangulation degeneration. Other references on vectorization topic are the following: (Tang et al., 2002)

because it describes a system for skeleton extraction based on the digital processing of photo-elastic image; (Amini et al., 2002); (Huggins and Zucker, 2002) where edge models representation by means of the principal components analysis is proposed; and (Tam and Heidrich, 2002) because it presents a novel technique for medial axis noise removal.

4.4. Optimization methods and road optimized extraction methods

Neural networks and genetic algorithms are techniques much used in the optimization topic. Subsequently, in the automatic road extraction methods these techniques are also employed. Although other optimization techniques exist, like simulated annealing, here only neural networks and genetic algorithms are considered.

Along this writing some works which utilizing neural networks have been mentioned such as Campbell and Thomas (1996), Doucette et al. (1999) and Petersen et al. (2002). Also in (Barsi et al., 2002) a technique based on neural networks is applied, in this case within a junction extraction system. About the genetic algorithms topic, Mirmehdi et al. (1997) presents an optimization process for robust low level feature extraction based on this technique. In (Shanahan et al., 2000) genetic algorithms are used to generate probabilistic models for high level road classification. And Jeon et al. (2002) uses this technique for road detection in spaceborne SAR images.

4.5. Evaluation methods

External evaluation and internal self-diagnosis of the obtained results are of major importance for the relevance of automatic road extraction systems for practical applications. Getting a correct evaluation of different methods on road extraction is the objective of the works here commented.

Frequently, the evaluation is achieved by comparison between the automatic result and the manually plotted used as reference data. In (Heipke et al., 1998; Wiedemann et al., 1998; Wiedemann and Ebner, 2000) this criterion is applied, so that the authors propose to evaluate two main aspects

in the road network extracted: the completeness and the correctness. Hinz et al. (2002) presents an approach for self-diagnosis which is a part of an existing road extraction system. In this paper, fuzzy set theory is used as theoretical framework for knowledge representation for evaluation. In (Wiedemann, 2002) an approach for the improvement of extracted road crossings is presented as well as a method for the external evaluation of the extraction results. Other evaluation methods can be found in (Barsi et al., 2002; Harvey, 1999; Shufelt, 1999a).

4.6. Other methods and objectives

Many references on road extraction are supported in the GIS available information. Therefore, works about the quality of digital geodata in the GIS databases are very important for us. Between them, Rellier et al. (2002) proposes a new method based on MRF to locally register cartographic road networks on SPOT satellite images. In (Busch and Willrich, 2002; Willrich, 2002) a method in order to know how good the data are and if the data are up to date is also presented. This work develops a concept for automated quality control of the area wide available topographic vector data set ATKIS using images. On the other hand, Elberink and Vosselman (2002) presents an approach for the automatic reconstruction of 3D object lines from airborne three line scanner data. And finally, in (Toth and Grejner-Brzezinska, 2002) a new GPS/INS/CCD integrated system for precise monitoring of road center and edge lines is presented.

5. Classification on road extraction according to the applied extraction technique

5.1. Road tracking methods

The methods of road tracking seek to obtain the road network starting from a set of seed points automatically or manually selected. In this way, while in (Sakoda et al., 1993) the seed points are defined for the user, in (Zlotnick and Carnine, 1993) an automatic algorithm in order to select

these points is presented. Another references where the edges analysis is also applied are Nevatia and Babu (1980) and Dal Poz et al. (2000). In (Quam, 1978; Vosselman and De Knecht, 1995) the road tracking is performed according to profiles taken perpendicularly to the road axis. In other works, like McKeown and Denlinger (1988), a combination of several techniques for road tracking is used. Geman and Jedynak (1996) offers a general computational strategy for tracking of linear structures and other recognition tasks in computer vision. In (Barzohar and Cooper, 1996) a combination of geometric and stochastic methods of road tracking can be found. Ruskoné and Airault (1997) proposes an automatic detection method of road network from aerial images using low level of knowledge and semantic information for solving interpretation problems. In (Wufeng and Qiming, 1998) automatic search of seed points is achieved by superficial analysis in the road tracking phase and using an expert system for the road network reconstruction. Tesser and Pavlidis (2000) proposes the Road Finder Front End System: a fully automated system that identifies roads in high altitude imagery. Recently, in (Yoon et al., 2002) a semi-automatic road extraction method which utilizes IKONOS imagery Dial et al. (2001) is presented. Also recently, Baumgartner et al. (2002) and Zhao et al. (2002) propose another prototypes for semi-automatic extraction of road axes. Finally, in (Bonneton et al., 2002) the road and linear object extraction is achieved starting from a set of directional seed points and utilizing the radiometric values of pixels in the road tracking process.

5.2. Morphological methods and filtrate techniques

Mathematical morphology is a set theory approach developed by Matheron (1975) and Serra (1982). Based on a formal mathematical framework, it provides an approach to the processing of digital images that is based on geometrical shape. It uses set operations such as union, intersection and complementation as well as dilation, erosion, thinning and other derived operations.

In (Zhang et al., 1999) an approach on road network detection from digital images can be

found. This method firstly classifies image to find road network regions, and then morphological trivial opening is adopted to avoid noise including objects that have similar spectral characteristics as road surfaces. In (Chanussot and Lambert, 1998; Katartzis et al., 2001) mathematical morphology is also applied. The second work describes a model based method for the automatic extraction of linear features from aerial imagery, combining and extending two earlier approaches for road detection in SAR satellite images. In (Amini and Saradjian, 2000; Amini et al., 2002) gray scale morphological algorithm for image simplification is used.

Between the works in filtrate techniques supported, Oliveira and Caeiro (2000) proposes the application of an isotropic filter according to Cressie (1991) which is constructed starting from the Gauss function according to Canny (1986) and Chiang et al. (2001) also presents a road extraction method based on edge detection and filter usage. In this case Kalman filtering for snaxel generation is applied.

5.3. Snake applications and dynamic programming methods

Deformable contour models (snakes) is an approach analyzed in (Kass et al., 1987), which have lately been used extensively for detection and localization of boundaries for facilitating the image segmentation problem, and also for the extraction of man made structures such as roads and buildings from gray level imagery. Snakes are utilized in (Cohen, 1991) as well as in (Gruen and Li, 1997; Li, 1997) where semi-automatic methods on linear object extraction and road extraction are, respectively, presented. Later on Zafiropoulos and Schenk (1998) tackles the problem of embedding color image information, coming from different channels in deformable models of contour type for the extraction and localization of road structures of small width. In (Jeon et al., 2000) snakes are used to extract roads accurately. Mayer et al. (1997, 1998) and Laptev et al. (2000) also present the snake application in the cartographic object extraction. The last paper proposes an approach for automatic road extraction from aerial imagery

with a model and a strategy mainly based on the multi-scale detection in combination with geometry constrained edge extraction using snakes. We also find snakes in (Chiang et al., 2001) and other energy model in (Ferraro et al., 1999). A modification of classic concept of snakes is presented in (Agouris et al., 2001b,d). In these papers a novel framework, comprising change detection and versioning, is introduced.

In (Dal Poz and Agouris, 2000a) a semi-automatic method on road extraction using dynamic programming is presented. Basically, a generic road model is formulated, which is solved sequentially by a dynamic programming algorithm in order to GIS update starting from aerial and satellite images. In this work a few seed points describing coarsely the road need to be provided by the operator. Likewise, this job proposes a solution for the optimization problem which consist in the search of the most short path between two points of an object (Ballard and Brown, 1982). Dal Poz and Agouris (2000b) addresses the problem of extracting georeferenced roads from images and formulating hypotheses for the presence of new road segments. In (Amini et al., 1990; Stoica et al., 2000) dynamic programming is applied by means of physical techniques. In the last case the method is based on geometric and stochastic processes using Markov dynamic chains according to Puterman (1994) in the segment grouping phase.

The use of dynamic programming and snakes at the same time, can be found in (Agouris et al., 2001a; Gruen and Li, 1997).

5.4. Segmentation and classification methods

This methods seek the supervised or unsupervised segmentation and classification of an image in order to extract the road network. Frequently the segmentation process is based on texture analysis which can offer a binary image clean enough in order to serve as input in a posterior vectorization process. In connection with the road extraction topic, Benjamin and Gaydos (1990) presents a system for segmentation of an infrared image using maximum likelihood decision techniques. In (Haala and Vosselman, 1992) classification methods based on region growing from

infrared and visible spectral bands can be found. More recently, Faber and Förstner (1999) proposes the texture analysis for the image segmentation in urban areas on high resolution multi-spectral imagery. In this work the texture is defined by means of three parameters: energy, direction and anisotropy (Haralick, 1979). In (Agouris et al., 2001c) a technique of spatio-spectral cluster analysis for road extraction is introduced. Unsupervised segmentation is also applied in (Chen et al., 2002a).

Roggero (2002) tackles the problem of object segmentation and shape recognition in discrete noisy data. Here, two different algorithms combine region growing techniques with principal component analysis from airborne laser scanners in urban areas. A new method where the texture analysis is the main factor in the segmentation process on road extraction, can be found in (Mena and Malpica, 2003; Mena, 2002b). In these two last papers the binary segmentation is achieved using a novel technique named Texture Progressive Analysis (TPA) in the framework of Dempster–Shafer Evidence Theory. Segmentation methods are also applied in (Amini et al., 2002).

5.5. Methods based on multi-scale and multi-resolution analysis

The road extraction by means of multi-scale analysis offers a control about the width of roads in the image. Thereby an efficient tool for narrow road detection in high resolution images (big scales) will also serve in the freeways recognition in low resolution images (small scales). In (Heipke et al., 1995) different characteristics of objects such as roads are detected in different scales. Baumgartner et al. (1996) proposes the multi-scale analysis based on the analysis of profiles taken perpendicularly to the axes of roads. Similar study appears in (Baumgartner et al., 1997). Here, roads are modeled as a network of intersections and links between the intersections. Interesting and exhaustive works about the model pattern in road extraction through multi-scale analysis is presented in (Mayer et al., 1997, 1998). These works are complemented with Mayer and Steger (1998) where the abstraction concept is presented. This

concept is defined as the increase of the degree of simplification and emphasis in road extraction methods. The multi-resolution analysis is also applied in the following papers: Baumgartner et al. (1999a) which is based on the topological relations between roads and other cartographic objects; Hinz et al. (2000) which is a method of road network reconstruction; Laptev et al. (2000) which presents an automatic road extraction system based on snakes; and Hinz et al. (2001a) where lines, segments and edges are extracted by means of texture analysis.

In (Couloigner and Ranchin, 2000) a method to hierarchically extract urban road networks from very high spatial resolution spaceborne imagery using the Wavelet transform imagery is presented. Also in (Chen et al., 2002b) the Wavelet transform for extracting road networks from high resolution images is applied. Finally, other references about the multi-scale analysis for road extraction can be found in (Förstner, 1997; Baltsavias et al., 2001) editions.

5.6. Stereoscopic analysis methods

The technique mainly utilized in order to obtain the Digital Terrain Elevation Data (DTED) is the stereoscopic analysis. About the automatic road extraction topic, methods based on this technique always have the advantage of adding at the plane characteristics of the image their properties in altitude. In this way, upon considering the inclination in each zone of the image, the extraction of the cartographic objects is simplified. However, though Photogrammetry and Teledetection are very developed (Mikhail et al., 2001; Schenk, 2002), many difficult problems still exist in order to solve completely the automated object extraction. The most important works in the stereoscopic analysis for road extraction appear in (Baltsavias et al., 2001; Förstner, 1997) editions as well as in (Zhang, 2001a; Zhang and Baltsavias, 2002a,b). Other additional works are the following: the global extraction process presented in (Leymarie et al., 1996); the works in multi-sensor and hyper-spectral imagery presented in (McKeown et al., 1996, 1999a); and also, the surveys (Niederöst, 2000; Fraser et al., 2002) focused on buildings.

5.7. Methods of multi-temporal analysis

These processes analyze the different variability in the time between the man made objects and the natural objects, comparing several images corresponding at the same zone. The road extraction methods through multi-temporal analysis are the scarcest in the scientific literature. In fact, in the generic study realized in (Ruskoné, 1996) only the reference Van Cleijnenbreugel et al. (1991) is cited. More recently, Heipke et al. (2000) presents a method whose primary goal is the automatic extraction of visible and spatial topographic objects from imagery. In this paper, different aspects of image analysis are discussed and a framework for scene interpretation is provided. In (Growe et al., 1999, 2000) the multi-temporal analysis is also applied. The second paper presents an analysis of multi-sensor and multi-temporal images by the use of structural, topological, and temporal knowledge about the objects expected in the scene.

5.8. Surveys on knowledge representation and fuzzy model

The second block of our classification comprises the existing techniques for road extraction in the mid and high level of knowledge. Most of these methods can be included inside fuzzy logic (Zadeh, 1965), since this framework constitutes a generalization of the probabilistic studies when the variable uncertainty is considered, the same as the probability theory generalizes the classical methods of the Mathematics when the relativity in the success occurrence is considered. The main characteristic of the high level methods is that they seek an analysis and interpretation of the image similarly at how this is realized by a human operator. In this way, the road extraction is not yet achieved through the analysis of the pixel radiometric values, but rather for a reasoning based on rules and models which permits to the computer to operate such as a human being would make it. In order to achieve this reasoning it is necessary to dispose of an efficient structure of knowledge, as well as of an intelligent algorithm which facilitates a correct, flexible and effective knowledge manipulation.

Since the experience confirms the necessity of including knowledge in the automatic processes for cartographic object extraction, many researchers have directed their investigations for this way. Nevertheless the advances achieved in this topic from Fischler et al. (1981) so far are still under development. Subsequently, the methods of knowledge representation and modeling still require exhaustive studies in terms of their ability to match the performance of humans in extracting and recognizing features in images. According to Sowmya and Trinder (2000), apart from possible comparison of the different methods, it is not possible to make firm conclusions on the most appropriate approach that should be used for the automation of information extraction from aerial and satellite images. Although the automatic implementation of these methods and techniques is very difficult, next a classification inspired in (Sowmya and Trinder, 2000) is proposed and progressively commented and discussed.

The oldest systems for knowledge representation are those that use the named first-order logic through programming logic languages. Between the *logic systems*, we find the work Reiter and Mackworth (1989) where a logical framework for depiction and interpretation of image and scene knowledge is proposed.

The *rule based systems* have demonstrated their utility under certain conditions and for this they have been much used. Between them McKeown and Harvey (1987) proposes a system for aerial image interpretation where rules are automatically generated. Likewise, Strat and Fischler (1991) presents the system of recognizing Condor, where the information is modeled through rules arranged according to several knowledge levels. In (Vosselman and De Gunst, 1997) rules are also used. Another surveys where rules are applied are Straub and Weidemann (2000), Hellwich and Wiedemann (2000) and Zhang and Baltsavias (2002a).

Between the *blackboard systems* we only have found a few references which are cited in (Sowmya and Trinder, 2000). One of them is Nagao and Matsuyama (1980) which is forerunner of the NAGAO system described in (Ruskoné, 1996). Also, in (Füger et al., 1994; Stilla, 1995) a black-

board system for analysis of man made objects in aerial images is presented.

In the *knowledge based systems* the objects are represented by means of classes and frames. Here, the knowledge is manipulated for a symbolic program which tries to demonstrate events using forwards reasoning and backwards reasoning. The result is an progressive increment of knowledge in the system. A pioneer work in this topic is (Hanson and Riseman, 1978) which is guided to the image generic interpretation. More recently, Wufeng and Qiming (1998) presents a road extraction method that combines image processing techniques with this artificial intelligence methodology.

Nowadays, it seem to be that the *semantic network based systems* are the most utilized in knowledge applications. In fact, many researchers have opted for this technique in their investigation tasks on cartographic object extraction. An example is Nicolin and Gabler (1987) where a system to analyze aerial images is proposed. This system uses semantic nets to represent and interpret the image. Later on Mayer (1994) develops a system based on semantic networks in order to extract cartographic objects starting from digital maps. Tönjes and Growe (1998) and Growe and Tönjes (1998) present a system in order to evaluate 3D scenes observed from different sensors and to reconstruct the 3D geometry. This work is enlarged in (Tönjes et al., 1999) where the definition of a network language allows to exploit the knowledge base by a set of application independent rules which provide data and model driven control strategies. Hinz et al. (1999) is an initial work on roads in rural and urban areas, which is subdivided in two ones: Hinz et al. (2000) where only rural areas are considered, and Hinz et al. (2001a) where road extraction in urban areas is analyzed. Nevertheless, in they all semantic nets for knowledge representation and manipulation are applied. More recently, Hinz and Baumgartner (2002) also presents a semantic object model, but it is divided into two different types. The model components of the first type are used for extracting features, and the components of the other type serve as criteria for evaluating the quality of the extracted features. Other studies about semantic nets in object ex-

traction can be found in (Baumgartner et al., 1997; Förstner, 1997; Bückner et al., 2002).

Finally, the *systems based on fuzzy logic* are specially important since they are acquired a great attention recently. Some of them are Agouris et al. (1998), Shanahan et al. (2000); Dell'Aqua and Gamba (2001), Knudsen et al. (2002) and Yang et al. (2002).

6. Main teams of research on automatic methods of road extraction

Finally, a schematic relation about some of the main researcher centers on automatic road extraction methods is presented. They are the following:

- *Asian Countries.* Korea Advanced Institute of Science and Technology; University of Tokyo.
 - Application of least squares correlation in the IKONOS image processing (Yoon et al., 2002).
 - Semi-automatic methods of road tracking (Zhao et al., 2002).
- *Australia.* University of New South Wales, Sydney.
 - Knowledge representation and manipulation (Sowmya and Trinder, 2000).
 - Image segmentation methods (Chen et al., 2002a).
- *Brazil.* São Paulo State University.
 - Geometric methods and dynamic programming (Dal Poz and Agouris, 2000a).
- *France.* Institute Geographique National, Paris; University Paul Sabatier, Toulouse.
 - Network extraction by context, seed points and semantic nets (Ruskoné and Airault, 1997).
 - Geometrical and filtrate techniques (Bonneton et al., 2002).
- *Germany.* Technische Universität München, Institute for Photogrammetry and Cartography University of the Federal Armed Forces, Munich; University of Bonn; University of Hannover; Technical University, Berlin.
 - Stereoscopic analysis and evaluation methods (Förstner, 1996).
 - Texture analysis for image segmentation (Faber and Förstner, 1999).
 - Multi-scale analysis combined with contextual information in the 3D space (Mayer, 1999a).
 - Automatic image interpretation and knowledge model generation (Straub and Weidemann, 2000).
 - Multi-temporal image analysis (Heipke et al., 2000).
 - Geometrical and topological methods of network reconstruction (Wiedemann and Ebner, 2000).
 - Road extraction methods based on snakes (Laptev et al., 2000).
 - Object extraction from multi-sensor and radar images (Hellwich and Wiedemann, 2000; Hellwich et al., 2001).
 - Result evaluation methods (Wiedemann, 2002).
 - Semi-automatic methods of road tracking (Baumgartner et al., 2002).
- *United Kingdom.* University of Bristol.
 - Optimized extraction by genetic algorithms (Mirmehdi et al., 1997).
 - Fuzzy models in the high level (Shanahan et al., 2000).
- *USA.* Carnegie Mellon University; University of Maine, Orono.
 - Data fusion techniques (Ford et al., 1998).
 - Automatic extraction methods from hyperspectral imagery (McKeown et al., 1999a).
 - Extraction techniques based on fuzzy logic (Agouris et al., 1998).
 - Extraction methods based on dynamic programming and snakes (Agouris et al., 2001a).
 - Vectorization methods through clustering (Doucette et al., 2001).
- *Switzerland.* Institute of Geodesy and Photogrammetry, Zurich.
 - Morphological methods for object extraction (Zhang et al., 1999).
 - Multi-resolution and multi-scale methods supported on GIS information (Baltsavias et al., 2001).
 - Road network reconstruction through databases and stereoscopic analysis (Zhang and Baltsavias, 2002a).

7. Conclusions

We are presented an analysis about the state of the art on automatic road extraction. This study can serve as a detailed resume in order to collaborate in the research task on this topic. Multiple methods, works and proposals have been considered, including a comment in many of them. About the classification realized for road extraction methods according to three concepts we estimate that it is the most appropriate because it allows to obtain quickly a correct global idea about the advances in different matters. However, given the amount of existent works and references, it is possible that some interesting studies have been forgotten for us. For this reason the reader should consider our work only as a subjective interpretation of the actual research state on automatic road extraction.

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