Delineating Road Structures on Satellite Imagery by a GIS-Guided Technique

J. Van Cleynenbreugel, F. Fierens, P. Suetens, and *A. Oosterlinck*
ESAT-MI2, Department of Electrical Engineering, Katholieke Universiteit Leuven, Kardinaal Mercierlaan 94, B-3030 Heverlee, Belgium

ABSTRACT: To solve a spatial image recognition problem like the extraction of roads and linear networks from remotely sensed (RS) imagery, human analysts rely on their expertise in combining external data sets (e.g., topographic maps and land-cover classifications). Such data are now typically stored in Geographic Information Systems (GIS). This paper outlines existing approaches to automatic road extraction on RS imagery and compares them to GIS-related knowledge sources employed by human interpreters. Methodologies to implement two of these sources using an object-oriented expert system building tool are elaborated in practical case studies on SPOT data.

INTRODUCTION

BECAUSE OF THE HIGH SPATIAL RESOLUTION of current satellite imagery, the extraction of roads and linear networks from satellite data has become a feasible – although labor-intensive and tedious – task for a human operator. This interpretation problem has many useful applications in disciplines such as cartography, landscape investigation, and planning. It relies on structural image recognition as well as on expertise in combining data sources external to (but sometimes derivable from) the image (e.g., topography, land-cover classification). In order to lighten the human effort, the appropriateness of (semi-)automated knowledge-based spatial analysis techniques has been envisaged. This paper covers the development and operationalization of multiple knowledge sources for the particular problem of road extraction from high resolution satellite imagery.

Automatic road extraction requires a multidisciplinary approach. Fields contributing to it are satellite image interpretation, geographic information systems (GIS), and knowledge-based image analysis. Currently, the possibility to integrate spatially referenced data for problem solving is emphasized as one of the main characteristics of GIS (see Cowen, 1988). However, GIS has been little used as a potential set of knowledge sources for automated spatial image analysis. Human analysts, when asked to delineate roads or rivers on satellite imagery in the presence of GIS-like data, rely on (unconscious) knowledge associated with different datasets. As a result, there is a need to extract, formalize, and code this kind of expertise into computer programs in order to automate spatial analysis. Techniques to facilitate this process of knowledge extraction and implementation are offered by knowledge-based systems. The main objectives of this paper are

- to review knowledge sources used in previous road extraction work,
- to outline GIS-related knowledge sources employed by human interpreters during road delineation, and
- to present methodologies to implement (some of) the GIS sources using an existing expert system building tool.

BACKGROUND

In general, a road is defined as a functional entity, forming a means of communication between different locations (see Bajcsy and Tavakoli, 1976). These functional requirements, as well as geophysical and engineering constraints, affect the geometrical and physical constitution of roads. Examples of such requirements are

- a road surface must be smooth and firm;
- the slope, the width, and the local curvature of a road all have an upper bound; and
- roads are usually connected to form a network.

The availability of a visual model describing the appearance of roads on satellite imagery is a prerequisite to delineate roads. This visual model should bridge the gap between the photometry of the image data and the physical and geometrical requirements mentioned above. For example, the requirement that the road surface must be smooth and firm could be translated in the image domain by stating that a road will appear as an elongated homogeneous region having spectral properties corresponding to materials of concrete or asphalt. However, not all of the above requirements (e.g., slope) can be directly linked to visual properties reflected in the image photometry. In order to overcome these problems, other models relying on data sources external to the image data (e.g., a terrain model) are mandatory. First, a visual model of roads and road networks on high resolution satellite imagery will be discussed. Second, factors affecting the complexity of the road extraction problem will be summarized. Third, existing work on extraction of roads from remote sensing (RS) data will be overviewed.

LINE IDENTIFICATION ON SATELLITE IMAGERY

The visual appearance of roads on images is mainly constrained by the spatial resolution of the imagery. Currently, civilian satellite imagery is regarded as high resolution if it has a pixel size less than or equal to 30 m^2. In general, linear structures on these images can be classified as thick and thin. Thick linear structures are made up of two parallel edges and usually represent highways, channels, large rivers, ... Thin linear structures correspond to line-elements on the imagery and are reflecting roads, rivers, railways, pipelines, ...Detailed studies on the applicability of high resolution satellite images for mapping purposes (e.g., Dowman and Peacegood, 1989) have shown that highways, most major roads, and (double-track) railways are generally 100 percent visible. Sometimes minor roads and tracks are difficult to detect because of canopy closure or field boundaries; sometimes they are very clearly defined because of their contrast with the background. Visual models for both types of structures will be discussed.

A thick linear structure is photometrically defined as an elongated region in the image array characterized by a homogeneous grey level. Its width is substantial enough to give rise to two separate but almost parallel edges. This structure can usually be detected by multispectral analysis because its dimension relative to the image resolution reduces the influence of mixture pixels. Regions belonging to road classes can be separated by spectral inspection.

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A thin line is photometrically defined in the image array as a ridge or a valley two to three pixels wide having slowly varying grey levels. It can be obtained as a connected path of local extrema, characterized by such geometrical properties as direction, length, and curvature and by photometric properties such as average grey values and contrast with the surroundings. Due to the duality between ridge lines and valley lines, automatic extraction is usually presented only for ridge lines (light roads on dark background).

Factors Affecting Road Delineation Complexity

Three dimensions of complexity are specific for road delineation on RS data:

- *Image quality*: images vary in terms of visibility, resolution, contrast. Specifically, high resolution images tend to be very *busy*: prominent edge or textural features show up of which only a limited subset may be of interest. Roads can be invisible because of tree canopy closure or because of weak contrast between the surface material and the surroundings.
- *Road density*: depending on the scene under consideration (rural, urban, mountainous), different road densities can be expected.
- *Road complexity*: roads can have very different outlines, from piecewise straight lines (such as highways) to sinuous partially occluded line structures (such as mountain roads).

There is a need to develop models for the appearance of roads and road networks on high resolution satellite imagery for different types of land use and topography.

Existing Relevant Work

Two important sources of RS data have been used to delineate spatial structures : aerial and satellite imagery. As road extraction heavily depends on the resolution of the image data, different approaches can be expected for the two image types. This overview emphasizes computational strategies employed for the delineation of thin linear structures.

The high spatial resolution of aerial imagery (up to 50 cm^2) facilitates the extraction of so-called man-made structures. These structures (typical examples are airports and residential scenes) can be decomposed into detectable primitives such as buildings and linear elements (road pieces, driveways, runways, . . .). As a result of this inherent hierarchy, model-based systems, employing a mixture of bottom-up and context-guided hypothesize and test strategies, have emerged. Salient examples can be found in Harlow *et al.* (1986) and McKeown *et al.* (1985), among many others. They all try to refine an initial image segmentation by applying (implicitly or explicitly coded) model knowledge in order to reach a model identification. Relatively little work has been reported on the specific problems of road finding and tracking.

A low resolution tracker (suited for roads having an image width of three or fewer pixels) is discussed by Fischler *et al.* (1981). To detect road presence in the image data, pixel scores for several operators are computed. The scores of a binary operator and a numeric operator are combined in a cost array: a zero cost is given to the object pixels of the former; the other pixels are assigned a cost computed from a function of their response to the latter. A final road path is obtained by looking for a minimum cost path. Road knowledge used is mainly at the level of the line operators and general shape of roads (expressed by the form and the parameters of the function used to map scores to costs).

Groch (1982) describes a line detection system based on intensity profile analysis. A grey-level profile is constructed from the line being followed and is used to select the next line point from an arc of points or an area of interest generated in the track direction. Road knowledge used is related to road shape and assumes that roads as well as background are of constant intensity. In Groch (1983) the use of additional data (stereoscopic and multispectral images, different maps) is discussed in a cooperative extension of this method.

In Vasudevan *et al.* (1988) heuristics to aggregate line segments to larger linear structures are mentioned as part of *intermediate* level road finding for low resolution imagery. Based on measurements for alignment and proximity of pairs of segments, a segment clustering algorithm is proposed. Road knowledge is weak as it is expressed by thresholds of proximity and alignment.

Automated road extraction from satellite imagery has received attention only recently. This is partly due to the fact that satellite data of sufficient resolution (Landsat TM, SPOT) were not available until recently. An early attempt is reported in Bajcsy and Tavakoli (1976). Road knowledge used is based on intensity ranges of materials in a specific band and on constraints on width, curvature, and length. However, many features that distinguish roads from other line elements are not visible.

The advent of the SPOT satellite has raised the interest in satellite data as a source to extract topographic elements for various purposes. In Destival and Le Men (1986) and in Berthod and Serendero (1988), methods are described to detect, link, and follow line elements mainly based on operators from mathematical morphology. Results are shown on SPOT images. These systems rely on the fact that a road is photometrically represented as a ridge or valley line. In Yee (1987) an expert system approach to planimetric feature extraction is discussed. Extracted line elements are represented symbolically and used to match conditions of rules describing general and feature specific knowledge. A sample rule states that **if** side 1 of a road segment is adjacent to water **and** side 2 is adjacent to water, **then** the road segment is a bridge. The knowledge used is represented symbolically and no need for an iconical representation is mentioned.

Also, the extraction of highway networks from Landsat TM data has attracted research efforts. In Guindon (1988), multitemporal coregistered TM data (band 2) are used to delineate line-like features that show a level of temporal consistency. Highways are typical examples (unlike transient line elements such as field boundaries). Road knowledge used relies on assumptions on width and on photometry and on the fact that roads are lasting objects. In Wang and Newkirk (1988), a method is detailed to derive a highway network description from one multispectral TM image. Knowledge used assumes that roads are lighter than the background and relies on shape and expected outline. In Ton *et al.* (1989) a road identification system for TM imagery is proposed consisting of a new line detection algorithm, a conceptually parallel road growing method, and a segment-labeling and merging phase. The line detector is designed to find lines that are one or two pixels wide. Knowledge used relies on the appearance of the roads with regards to the image resolution and on geometric properties (shape, length) of the extracted segments.

METHODOLOGY

Two main knowledge sources are employed in previous work on road extraction from satellite imagery:

- *Photometry* is used to derive candidate line primitives from the (multispectral) images(s) (by assuming a general model of the appearance of roads as line elements).
- *Perceptual grouping* rules are used to select, to combine, and to extend line primitives in order to construct a network (mostly by heuristic **if-then** rules).

In general, this knowledge is shallow as it is not (or it is weakly) based on any theoretical model from (physical) geography or landscape investigation that explains the possibility to find roads in particular areas. To use these theories, additional data are required. Also, the domain of applicability of previous attempts is not specified or seems to be very restricted. The usage of additional data can be helpful here to investigate road extraction for different types of land use and topography.

By discussing the problem of road network extraction with RS experts, it becomes clear that non-trivial cases on high resolution satellite images cannot be solved unless diverse knowledge sources are tapped and integrated. In this context, a knowledge source (KS) is defined as being the combination of a data source and the accompanying expertise to maximally exploit these data. For example, a photointerpreter classifies a visible line segment as a road piece if it is connecting two meaningful *features* (e.g., crossroads,villages) and if it satisfies a number of external constraints. These constraints can be obtained from existing external datasets, as a typical part of the analyst's expertise. The following data sources, likely to be found in a GIS, are important to human experts to delineate linear networks : global land-cover classifications, existing roadmaps and hydrographic maps, and terrain (elevation) models. Depending on the complexity of the task in terms of road density, road complexity, and image quality, experts can decide what KSs must be involved. The hypothesis advanced in this paper is that GIS-related knowledge makes the process of road extraction less shallow. First, applicable KSs will be treated in more detail. Second, the implementation environment will be discussed. In the next section our hypothesis will be tested for two case studies.

Knowledge Sources for Road Delineation

Land-cover related expertise can be associated to the specificity of given types of land cover as well as to the shape and position of actual regions. Different types of land cover correspond to different types of road network topology. For example a network in an urban area and a network in an agricultural area are likely to be structured differently (many crossroads connected to many road segments, one central lane and many branches, respectively). These generic models imply typical ways to instantiate road network extraction. To handle problems such as delineating new roads that do not exist in maps and extend over more than one region, the former models are insufficient. Inter-region knowledge can be applied here : as new roads tend to be situated on the boundaries of two or more regions, evidence obtained from photometry and/or perceptual grouping can be adjusted depending on the spatial position of a linear element with regard to landcover regions.

The terrain model can be used to indicate plausible road tracks in the image data. For example, in a mountainous area, a road between villages having almost equal altitude usually follows a line of the same altitude. As a consequence, a contour line can be used to guide the photometric extraction of a road. Lines can only have slope values in a limited interval in order to be maintained as road candidates. On the other hand, line elements such as fire lanes in forestry are known for their slopes perpendicular to the relief.

Hydrography is related to the terrain. It is a more or less stable factor for the areas under analysis. It has influences on the appearance of road structures. Roads often follow contour lines in valleys and are less curved than rivers. Such principles as minimizing the number of road-river crossings (bridges to be built) are important in road construction.

Also an existing roadmap contains cues to be used in two ways: as a guide for image analysis to find analogous roads (based on photometry, structural properties, etc.) and as a logical framework : new roads are usually connected to existing ones. However, the first utilization is only appropriate for those images where newly constructed and longer existing roads show equivalent photometric properties. Often this is not the case due to canopy closure.

Implementation Environment

To exploit the various data sets for image analysis purposes, not only do ways to operationalize iconic descriptions (maps) need to be developed, but also task-specific expertise must be implemented. In this paper a GIS is regarded as a digital raster database consisting of layers of cartographic maps and RS data. It is assumed that the different data layers are registered in such a way that any two of them can be exactly (pixel-by-pixel) superimposed. To provide a smooth link between GIS and knowledge-based programming, an object-oriented environment for image understanding is used, presented in Fierens *et al.* (1989). It is implemented on top of the existing hybrid tool KEE (see, e.g., Tello (1989)). In this way, data sets from the GIS can be directly mapped to object classes in a KEE knowledge base. Possibilities to utilize iconic structures are provided by the environment. Expertise about road delineation can be added using several paradigms, as will be shown in the next section.

RESULTS AND DISCUSSION

Two case studies are detailed. The first makes use of land-cover-associated knowledge, while the second relies on knowledge extracted from the terrain elevation model. Multispectral SPOT data (acquired in August 1987) from the northern part of Portugal (see Figure 1) are used in these examples.

Delineating Forest Path Networks

Forests in flat terrain show typical patterns of path networks. These paths are visible as line-like structures on high resolution satellite imagery and appear in many respects equivalent to roads. Network expertise for this kind of land cover is related to practical considerations. A generic model was obtained by observing and interviewing two experienced cartographers during manual delineation. The model has the following characteristics:

- forest paths are normally straight,
- forest paths very often intersect perpendicularly,
- the forest is subdivided into repeating geometrical structures (rectangles) by the paths, and
- there are usually chains of roads or paths near the border of a forest region.

In Figure 2, a part of an image containing a coniferous forest is shown. One road is known to exist from the roadmap (shown in white). Figure 3 shows a symbolic representation of the input data as implemented in our environment. It contains three main

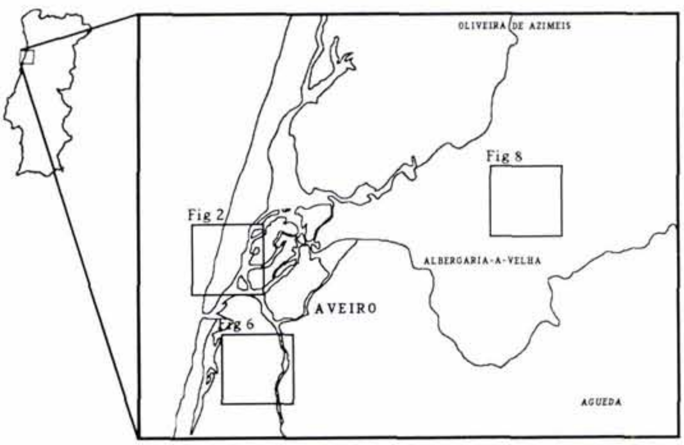

FIG. 1. Orientation map showing part of northern Portugal. The location of the images used in the following examples has been indicated.

FIG. 2. Part (5 km²) of a SPOT image, band XS1. © *SPOT Image 1987.* Existing roadmap overlayed in white.

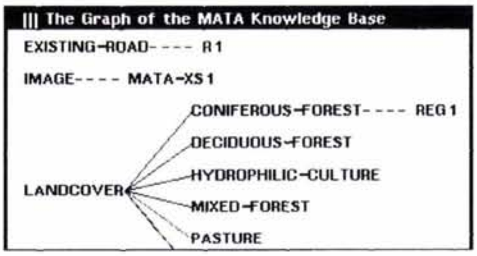

FIG. 3. Symbolic description of the GIS data employed in the first example.

classes: EXISTING-ROAD, IMAGE, and LANDCOVER. Each class contains slots to store attribute values and applicable procedures. The LANDCOVER class has subclasses describing different types of land cover. The considered forest region is represented by the member REG1 of the CONIFEROUS-FOREST class. The EXISTING-ROAD class has one member R1 corresponding to the existing road. The IMAGE class has one member MATA-XS1 corresponding to the part of the XS1 band shown in Figure 2. Members inherit the frame description of their parent classes but have local values assigned to the attributes. For example, R1 inherits a slot called *pixels* from EXISTING-ROAD to store the list of its pixels. Procedures are invoked by sending messages. For example, when the message *existing-roads-in-region* is sent to REG1, REG1 searches itself and returns the known roads found (R1 in this case).

To each land-cover subclass a specific knowledge base (KB) can be associated implementing a typical road network model for this type of land cover. Control is passed to this knowledge base by sending an *instantiate-road-network* message to an actual member of the subclass. In this particular problem this message is sent to REG1, activating the KB partly displayed in Figure 4. This KB contains the appropriate data structures and procedural and declarative knowledge to cope with the delineation of path networks in coniferous forest regions.

An initial network is obtained by tracking a thinned thresholded result of applying a line detector to MATA-XS1 within the region REG1 (currently we use the detector of Ton *et al.* (1989)). This network is represented by members of the LINE and the CROSSING

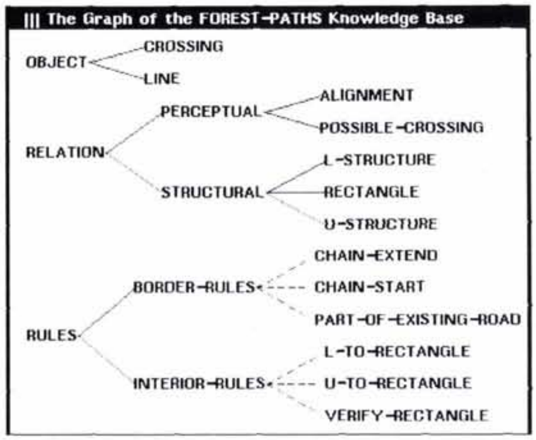

FIG. 4. Part of the KB used to extract forest paths.

classes. A LINE instance represents a linear element having high photometric evidence to be a part of a trail. A CROSSING corresponds to the crossing of at least two lines.

Relations are calculated from this initial network. Because the generic model stresses the importance of rectilinear groups of lines, a RELATION subclass STRUCTURAL is included. It has itself subclasses to describe L-shaped, U-shaped, and rectangle structures. Simple heuristics are used to obtain related objects: for example, a line connecting two crossings will generate a U-structure if at both crossings lines can be found, parallel to one another and on the same side of the former: as a result, a new member of the class U-STRUCTURE will be created having a *related-objects* slot containing the three lines. The class PERCEPTUAL has subclasses to describe relations between not connected, but neighboring, objects. For example, if an end of line 1 is very near an end of line 2 and if both lines are collinear, an instance of the relation ALIGNMENT is created to relate line 1 and line 2. Iconical exploration (instead of symbolic matching) is used to focus attention by scanning search-environment constructed around the objects.

Two sets of rules are used to complete the description to a final network. The BORDER-RULES select chains of segments near the border of the region. The INTERIOR-RULES handle structures in the interior of the region. For example, the L-TO-RECTANGLE rule tries to extend an L-structure of lines by matching it with one of the previous extracted rectangles. If evidence can be found for the missing lines, a new RECTANGLE member is created. The VERIFY-RECTANGLE rule verifies these new rectangles by context generated resegmentation. A final result for Figure 2 is shown in Figure 5. Another example of delineating forest paths is shown in Figure 6 and Figure 7.

DELINEATING MOUNTAIN ROADS

Generally, roads in mountainous areas follow contours in order to minimize construction and traveling effort. As a generic model for delineating mountain-roads, the following geophysical and engineering constraints were obtained by interaction with the two cartographers:

- in general, mountain roads are serpentine;
- mountain roads usually follow ground contours;
- if contours are not followed, then altitude differences are minimized;
- the slope along the track of a road has a maximal value; and
- older roads are almost invisible due to canopy closure.

Figure 8 shows a part of a mountainous country SPOT image. In Figure 9, a digital terrain model corresponding to this area is displayed. It is compiled by manually digitizing contour lines from an existing topographic map. In Figure 10 the existing

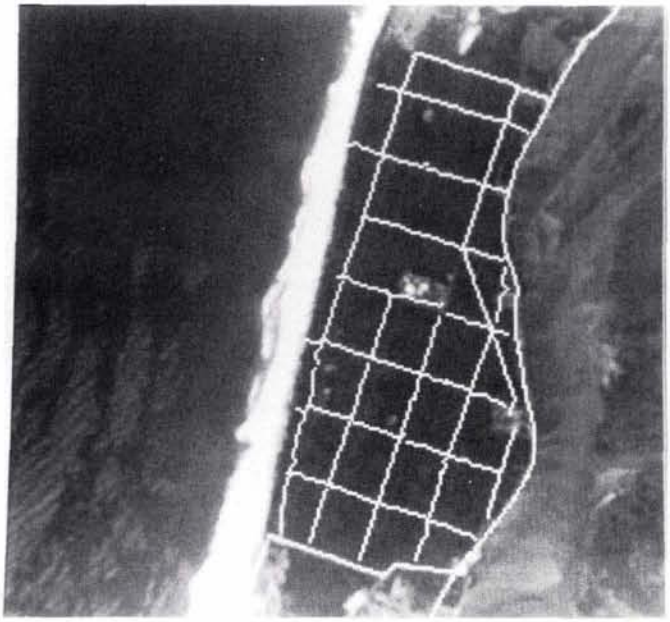

FIG. 5. Extracted network from Figure 2.

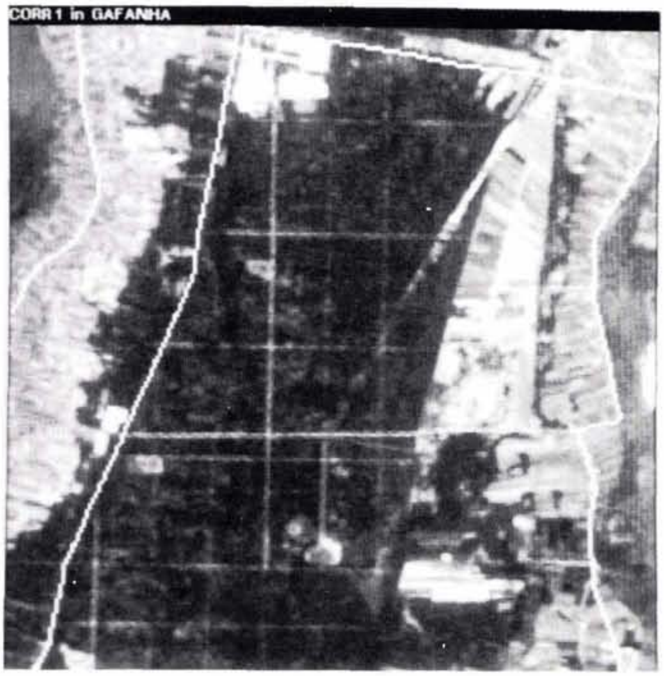

FIG. 6. Another part (5 km^2) of a SPOT image showing a coniferous forest, XS1 band. © *SPOT Image 1987.* Existing roadmap overlayed in white.

roadmap has been overlayed in black and extracted road pieces are shown in white. These road pieces result from combining line elements.

Again, line elements are found by a line detector. Only those satisfying the constraint on the maximal tolerable slope are maintained. The image photometry and the DTM data are employed to connect lines. A typical result of this analysis is shown by the sinuous roads in the lower right part of Figure 10. Here, line elements were combined by a global optimization technique maximizing photometric evidence and minimizing altitude differences: when two line segments are found with a gap in between, an average line of equal altitude is used as a hypothesis for the connecting segment; this line will be elastically deformed under influence of photometric force fields to obtain an optimal road outline. This procedure is not unlike SNAKES (see Kass *et al.*, 1987). The force field used in this case is the response for the line detector.

Figure 10 also shows that existing roads can be difficult to recognize but are useful as a *logical framework*. Relations between extracted road pieces and roads from the roadmap are once again established by iconical exploration.

FIG. 7. Network extracted from Figure 6.

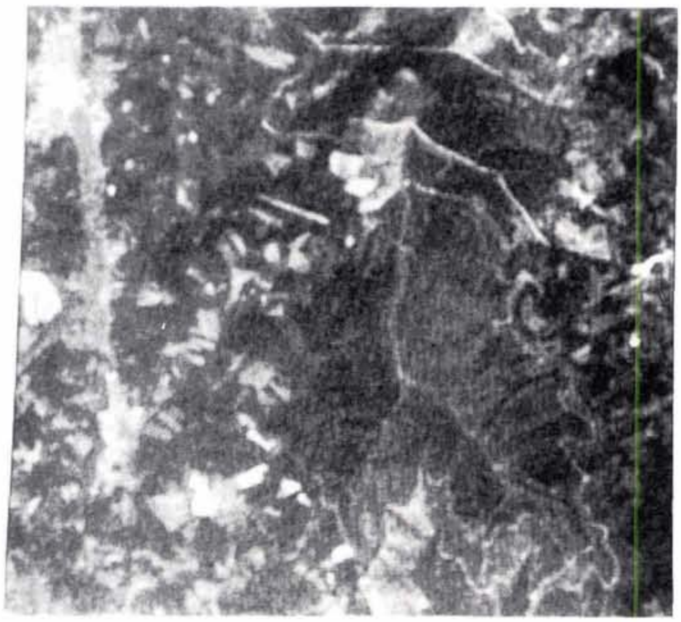

FIG. 8. Part (5 km^2) of a mountainous SPOT image, band XS1. © *SPOT Image 1987.*

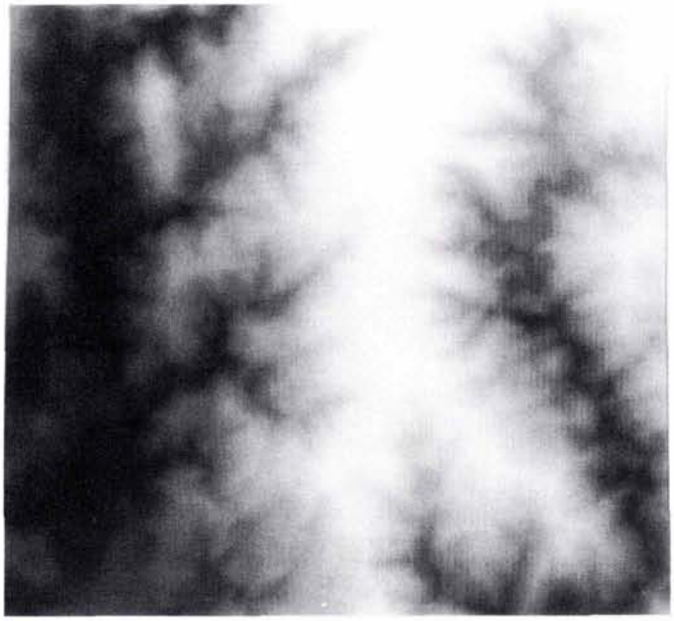

FIG. 9. Digital terrain model for the scene of Figure 8.

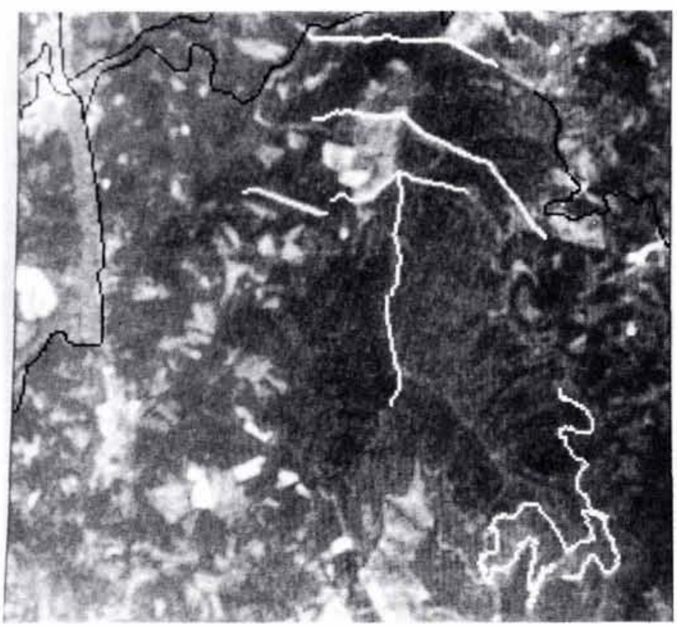

FIG. 10. Existing roadmap (black) and extracted roads (white) overlayed on scene of Figure 8.

CONCLUSIONS

In this paper the delineation of road networks on satellite data has been approached from the viewpoint of guiding an image analysis problem by knowledge related to an external database. First, previous work in the field has been reviewed. It is hardly based on any knowledge of this kind. Second, different knowledge sources, corresponding to different GIS datasets, have been tapped. Third, road network models for two case studies have been described and implemented in an object-oriented programming environment. Due to the availability of generic road models, the extraction process becomes less shallow.

Additional effort is required to encode other generic road network models and to incorporate other KSs. The error prone nature of GIS data has to be carefully investigated in this process.

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REFERENCES

Bajcsy, R., and M. Tavakoli, 1976. Computer recognition of roads from satellite pictures. *IEEE Transactions on Systems, Man and Cybernetics*, 6(9):623–637.

Berthod, M., and M. A. Serendero, 1988. Extraction of thin networks on satellite imagery. *Proceedings of the Ninth International Conference on Pattern Recognition*, pp. 456–458, IAPR, Rome, Italy.

Cowen, D. J., 1988. GIS versus CAD versus DBMS: what are the differences? *Photogrammetric Engineering and Remote Sensing*, 54(1):1551–1555.

Destival, I., and H. Le Men, 1986. Detection of linear networks on satellite images. *Proceedings of the Eighth International Conference on Pattern Recognition*, pp. 856–858, IAPR/AFCET, Paris, France.

Dowman, I. J., and G. J. Peacegood, 1989. Information content of high resolution satellite imagery. *Photogrammetria*, 43(5):295–310.

Fierens, F., J. Van Cleynenbreugel, P. Suetens, and A. Oosterlinck, 1989. I-see : an AI-tool for image understanding. *Proceedings Workshop on Tools for AI*, pp. 314–320, IEEE, Fairfax, Virginia.

Fischler, M., J. Tenenbaum, and H. Wolf, 1981. Detection of roads and linear structures in low-resolution aerial imagery using a multisource knowledge integrating technique. *Computer Graphics and Image Processing*, 15:201–223.

Groch, W. D., 1982. Extraction of line shaped objects from aerial images using a special operator to analyze the profiles of functions. *Computer Graphics and Image Processing*, 18:347–358.

———, 1983. *Line Following*. Technical Report, FIM, Ettlingen, BRD.

Guindon, B., 1988. Multi-temporal scene analysis: a tool to aid in the identification of cartographically significant edge features on satellite imagery. *Canadian Journal of Remote Sensing*, 14(1):38–45.

Harlow, C. A., M. M. Trivedi, R. W. Conners, and D. Phillips, 1986. Scene analysis of high resolution aerial imagery. *Optical Engineering*, 25(3):347–355.

Kass, M., A. Witkin, and D. Terzopoulos, 1987. Snakes: active contour models. *International Journal of Computer Vision*, 1(4):321–331.

McKeown, D. M., W. A. Wilson, and J. McDermott, 1985. Rule-based interpretation of aerial imagery. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 7(5):570–585.

Tello, E. R., 1989. *Object-Oriented Programming for Artificial Intelligence*, Addison-Wesley Publishing Company, Inc., pp. 196–214.

Ton, J., A. K. Jain, W. R. Enslin, and W. D. Hudson, 1989. Automatic road identification and labeling in Landsat 4 TM images. *Photogrammetria*, 43(5):257–276.

Vasudevan, S., R. L. Cannon, and J. C. Bezdek, 1988. Heuristics for intermediate level road finding algorithms. *Computer Vision, Graphics and Image Processing*, 44:175–190.

Wang, F., and R. Newkirk, 1988. A knowledge-based system for highway network extraction. *IEEE Transactions on Geoscience and Remote Sensing*, 26(5):525–531.

Yee, B., 1987. An expert system for planimetric feature extraction. *Proceedings of IGARSS 87*, URSI, Ann Arbor, Michigan, pp. 321–325.

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