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LINE FOLLOWING

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1. Introduction

Today the interpretation of aerial imagery is still reserved to trained human experts. Only for several special problems (e. g., multispectral classification without explicit definition of object boundaries) successfully working automatic methods (1,2) have been developed. On the other hand, the amount of high-quality image data is steadily increasing due to new sensors with additional spectral bands and better spatial resolution. To analyze this flood of data the support of electronic aids is necessary for the future.

Though it will not be possible to develop a general system for the automatic interpretation of image data within the next ten years, some specific tasks like the precise extraction of the representation of objects in image data (further on called object extraction) should be solved by automatic or at least semi-automatic methods in the near future.

In the following the methods for the extraction of objects are explained for the example of line shaped objects; however the extraction principles can also be applied to point-like or region-like objects.

The methods presented here extract the line shaped objects sequentially by line following. This object-guided and object-specific proceeding is the main difference from other mostly parallel methods which process the complete picture to find line segments independently from one another and which reconstruct the line shaped objects afterwards, e. g., (3 - 7).

The line following starts at locations which reliably are part of line shaped objects. Two different object-guided methods may be initialized at these starting points. The methods follow the objects by applying special operators to extract line segments.

This procedure has three main advantages:

- the calculations are not performed in parallel on the complete image but concentrate on those locations where previous results have proved a high probability for the continuation of the object (prediction),
- the confirmation of predicted object increments can always be adapted specifically to the local properties of the object which have actually been detected, so that the extraction is not affected by changes of object properties or local occlusions,
- the results are in vector representaion.

The two methods for line following basically rely on a sophisticated analysis of local grey level situations. As the continuation of the line object can be predicted, the analysis can be confined to the processing of one or more one-dimensional grey level diagrams instead of two-dimensional submatrix computations.

The following sections describe the detection of starting points, the two methods for line following, and the combination of all methods in a system for the extraction of line shaped objects from one or more discrete grey level pictures. The system originally was implemented and tested on a minicomputer DEC PDP 11/70. Later it was transferred to a DEC VAX 11/780 to process large images of up to 8192 x 8192 pixels. Detailed descriptions of the system and its components have been published; see (8-14).

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2. A Method for the Detection of Starting Points

Simple calculations yield so-called candidates which probably are part of a line shaped object. Each candidate is examined with an object-type-specific line detector to confirm line increments of a specified width and contrast as starting points.

The basic component of the methods for the detection of starting points as well as of the first method for line following is a special operator for the analysis of one dimensional profiles.

The profile analysis operator PAO is a local operator which performs a detailed analysis of the profile of a discrete function g and generates special features. By applying the PAO several times an extensive description of g can be obtained, e.g.: in the interval I, g is shaped like a valley with steep sides and a flat bottom containing one small peak. Furthermore the exact position and width of the features "valley", "side", "bottom", and "peak" are specified; "steep" can be made precise as medium grade of the slope in an interval.

Each application of the PAO yields a partition of the definition domain into intervals. All points in an interval possess the same feature, e.g., their function values form a "valley" or a "peak". Thus the substantial property of the PAO is that it expands local features of single points such as "local maximum in x" to intervals of the definition domain which contain x. The so-called profile characteristic which indicates the shape of g in I is attached to every interval I.

To detect the candidates for starting positions a grid of sample lines is spread over the whole image. The grey level diagram along each sample line is evaluated with the PAO to find intervals of correct shape and width.

Now the object-type-specific line detector designs two circular sample lines around each candidate and evaluates the grey level diagram along the lines using the PAO. The intervals with the correct shape and width, i.e., the intervals with the predicted profile, are selected on every sample line. A candidate is accepted as starting point if there exist two pairs of selected intervals on the circles, which together with the candidate, are in collinar position, and if the grey levels are nearly constant along a line connecting the selected intervals (see Fig. 1). The horizontal line marks a sample line of the grid. The candidate is denoted by a cross and the middle of the selected intervals on the outer circle is marked by asterisks. The constancy of the grey levels is tested along the line connecting the asterisks.

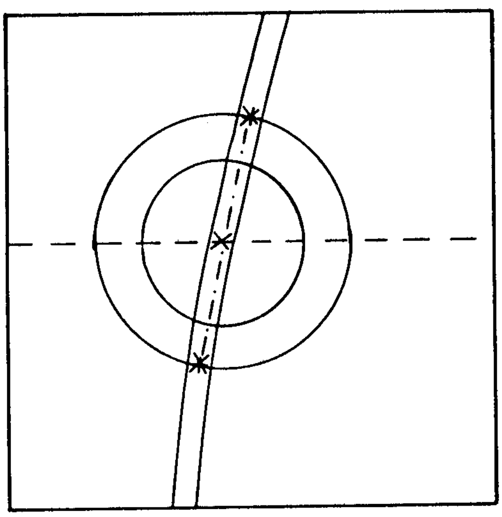

Fig. 1. Example of the detection of starting points.

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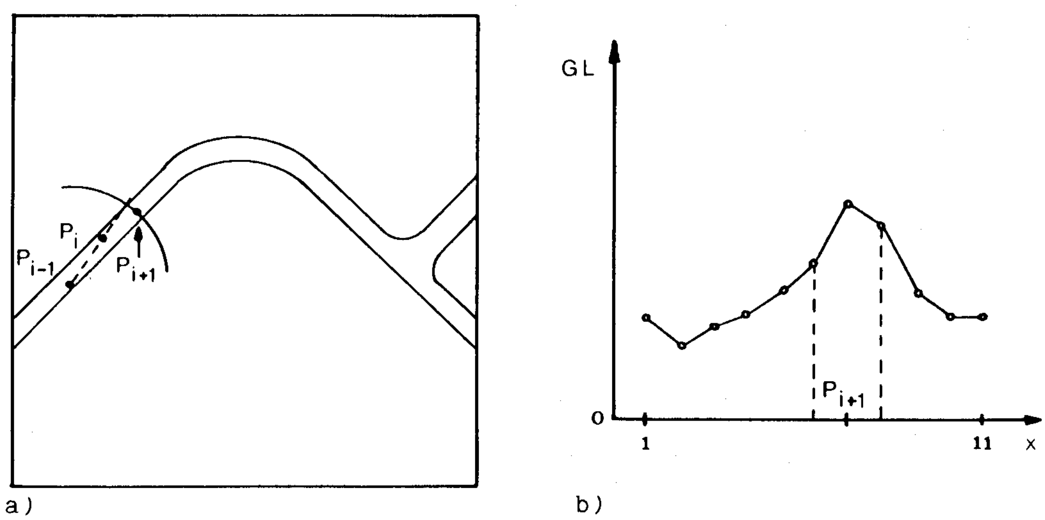
3. The Local Method for Line Following

Beginning at the given starting points the local method follows the line shaped objects incrementally using a local operator for the detection of line increments. The extraction is constantly adapted to the actual situation.

For every step of the line following the location and the direction of the next object increment are predicted using the known parts of the object (object-guided prediction). To extract the next object increment a sample line shaped like an arc is defined at the predicted position (see Fig. 2a). Regarding the last few object increments a grey level profile of the cross-section is predicted in terms of the PAO. The grey level diagram along the arc is analyzed using the PAO and compared with the expected object profile. Thus an interval of the area can be marked where the object and the arc meet (object-specific confirmation; Fig. 2b).

Besides the adaption of the object profile to the actual properties the width of the steps, i.e., the distance between two successive arcs, is chosen according to the local situation. If the representation of the object is not disturbed and its course is straight the width of the steps is increased. Vice versa the stepwidth is decreased if the appearence of the object is disturbed or if there is a bend. If the continuation of the object is covered, wide steps with additional calculations are used to bridge the gap.

Abrupt increases of the width of the object profiles or the existence of two neighboring profiles on one arc yield a hint of a branching of the object. The surroundings of the supposed branching is examined in a manner similar to the detection of starting points. Two concentric circular sample lines are analyzed using the PAO to detect object profiles. Every pair of profiles on both sample lines which is in collinear position with the center and which has nearly constant grey level along a line connecting the center and the outer profile is accepted as segment of a line shaped object. If there exist two or more "new" segments the branching is confirmed and the different objects are extracted one after another as described above. The extraction stops if all branchings and starting points are evaluated.



a) b)

Fig. 2. (a) Example of the definition of an arc. (b) Example of the grey level diagram along an arc.

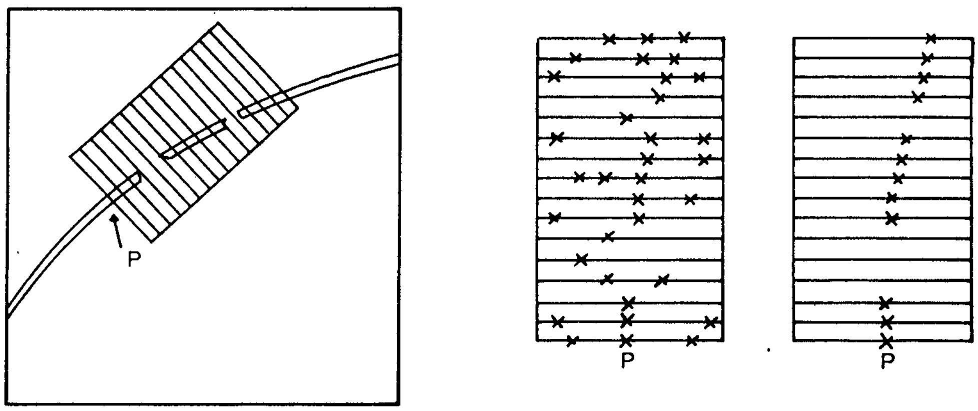
4. The Regional Method for Line Following

Beginning from given starting points the regional method follows the line shaped objects by applying a regional line detector to confirm a predicted line segment at each step. In contrast to the local method more than one grey level diagram is evaluated at each step to confirm a line increment.

For every step a rectangular area of interest AoI is defined straight in front of the last object increment (object-guided prediction).

The AoI contains n samples which are perpendicular to the predicted continuation of the object (see Fig. 3a). The evaluation of the AoI, i.e., the confirmation of a line increment, consists of three stages. In the first stage the grey level diagrams along the n sample lines are evaluated separately. For every point of the grey level diagrams a confidence measure is calculated, which indicates if the point probably contributes to a profile representing an object cross-section or not. The calculation comprises the comparison of the grey level of every point with the grey levels of several points in its surroundings. If this comparison indicates the correct shape for the profile of the object's cross-section the point yields a high confidence measure. In every sample line the points with high confidence measure are selected as candidates for object points (see Fig. 3b).

In the second stage the candidates on every sample line are compared with the candidates of the lines above and below. If the points are in a local collinear position the confidence measure of these candidates is increased, otherwise it is decreased. For every candidate two directions are calculated which point to the next candidates in the sample lines above and below.



a) b) c)

Fig. 3. (a) Example of the definition of an area of interest (AoI). (b) Example of candidates on every sample line of the AoI. (c) Example of the selected object points.

In the third stage the object points are finally selected. Due to the definition of the AoI the point in the first sample line is known to be part of the object. Using this point, the confidence measures of the candidates, and their two directions, the chain of object points is chosen as continuation of the line shaped object in the AoI (see Fig. 3c).

5. Combinations of the Three Methods

To extract a complete network of line shaped objects from an image the three methods described above are combined. At first the method for the detection of starting points is used to calculate at least one starting point on different parts of the network of lines. As both methods for line following complement each other perfectly, a combination which incorporates the advantages of both mostly proves to be able to extract the complete network of line shaped objects with these starting points.

The extraction begins at the starting points with the local method. This method produces excellent results for line objects with little or no occlusion; bends, intersections, and changing

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appearance of the line shaped objects are accepted without problems. At locations where large gaps interrupt the continuation of an object the regional method is applied to bridge the gaps. Due to the regional field of view this method can interpolate the gaps if the AoI completely contains the occlusion. Within the AoI the regional method is not affected by noise or changing appearance of the object. As the regional method might miss intersections of lines and is not suitable to follow sharp bends the local method continues with the extraction when the gaps are bridged. The extraction stops when all starting points are evaluated.

If the results are incomplete a continuation of the extraction is possible by integrating additional knowledge into the extraction process. This is the a priori knowledge about the network of lines to be extracted. Man made objects for example like roads or railways will normally not start out of nowhere and stop in a dead end. So the dead ends of the extraction process where neither method could continue will be analyzed if they can be connected to other dead ends, object crossings or sharp curves of objects already extracted. If candidates for a connection are detected an examination is performed using the regional method where the thresholds for the acceptance of an object segment can significantly be decreased compared to the normal line following mode.

The system for the extraction of line shaped objects consisting of the three methods described above can also be applied to more than one image of the same area (e.g., stereo images, multitemporal images, multispectral images, or multisensor images). The results of the cooperative extraction from more than one image will be more complete because often a part of an object which is occluded or of bad visibility in one image can easily be detected in an image taken from another point of view or recorded in another spectral band respectively. Instead of a second image there can also be used a map or a digital elevation model (e.g., for the extraction of rivers).

If the rivers have different geometries (e.g., different points of view or different sensors) an image registration is required. The extraction methods do not demand a pixel to pixel registration so that a rough projective transformation given by four pairs of control points will suffice normally.

For the cooperative extraction in two (or more) images two extraction modes are available: the supporting and the verifying mode. The extraction is performed in the first image as long as new results can be found then the results are mapped into the other image. In the case of the supporting mode the results are accepted as final results for both images. Before continuing the extraction the dead ends are centered (shifted to the correct location) if necessary. The extraction stops, if an object part of a predefined length has been extracted. The results are mapped back into the first image, the extraction is continued, etc.

If the verifying mode is chosen, the results mapped to the other image are taken as preliminary results for both images. The verification process tries to find the respective object parts by means of a modified regional extraction method. Therefore chains of areas of interest are positioned along the mapped results. Only objects which can be found in both images are accepted as final results. Objects which can be found only in one image are presented to the human interpreter as possible changes. Starting from the dead ends which have been produced by the verification process the extraction can be continued. Thus extraction and verification are performed alternately in both images until no continuation can be found in either image.

6. Results

The following figures show results of the different methods extracting line shaped objects (roads, rivers, etc.) from black and white aerial images at scales between 1 : 20 000 and 1 : 74 000. Parts of image transparencies are digitized to produce image matrices of 512 x 512, 1024 x 1024, 2048 x 2048, 4096 x 4096 or 8192 x 8192 pixels depending on the scale of the image. For visual control reductions of the image, matrices are displayed on a color display and the results are overlayed on-line.

Fig. 4a shows an image matrix of 512 x 512 pixels which contains one river and a network of roads. The side-length of the image corresponds to approximately 1.5 miles. In Fig. 4b the results of the starting point method are displayed. The white bars at the sides of the image mark the horizontal sample lines which were evaluated to detect hints for starting points.

Fig. 4c demonstrates a step of the local method for line following. Beginning from a starting point (see cursor) a part of the road is extracted advancing from left to right. At the left side of the extracted road the arc is shown which is used to select the next object increment. In the left half of the figure the grey level diagram along the arc is displayed. Fig. 4d shows the result of the local method extracting from two starting points. In the left of the cross-road the extraction stops because the road is partly occluded. The extraction is automatically continued by the regional method (see Fig. 4e where the first AoI to be processed is displayed). In the second AoI (see Fig. 4f) the road again is of good visibility and control is automatically switched back to the local method which extracts the rest of the network of roads (see Fig. 4g). Figs. 4h to k show the result of extracting the river. In Fig. 4l the results of road extraction and river extraction are overlaid.

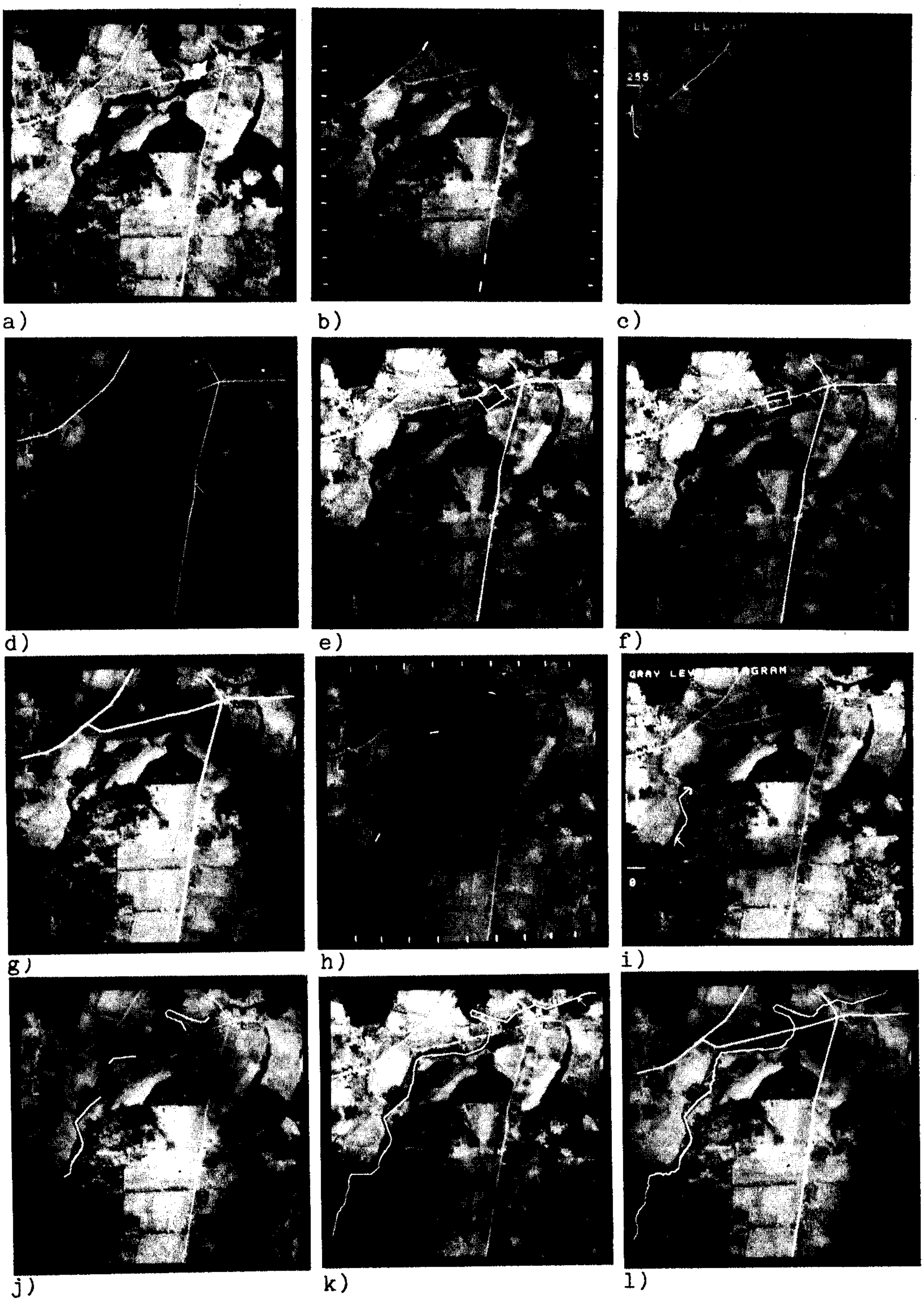

Fig. 4. Example of the extraction of a network of roads and of a river.

Figs. 5 and 6 demonstrate the extraction of a network of lines from a large image matrix of 4096 x 4096 pixels. The side-length of the image corresponds to approximately 5 miles. Fig. 6 shows the results of the automatic extraction of roads from Fig. 5.

The following examples show results of the cooperative extraction from two patterns. In Fig. 7 the extraction from multispectral data is demonstrated. Figs. 7a and b show channel A and channel B of the eleven channels of a MSS-recording. Fig. 7c shows the result of the extraction of the railway-track from channel A by the local method. Instead of calling the regional method the extraction is continued in channel B by the local method (see Fig. 7d).

In Fig. 8 the cooperative extraction is applied to a pair of stereo images. Stereo partners can also be used to calculate the relative terrain elevation along the lines extracted from both images. To do so the verification mode of the cooperative extraction is chosen. Figs. 8a and b show the left and the right stereo partner. In Fig. 8c the network of lines extracted from the right image is displayed. The lines are transferred to the left image using an exact projective transformation (see Fig. 8d). The cursor indicates a position where the lines transformed from the right image deviates from the road in the left image due to differences in terrain elevation.

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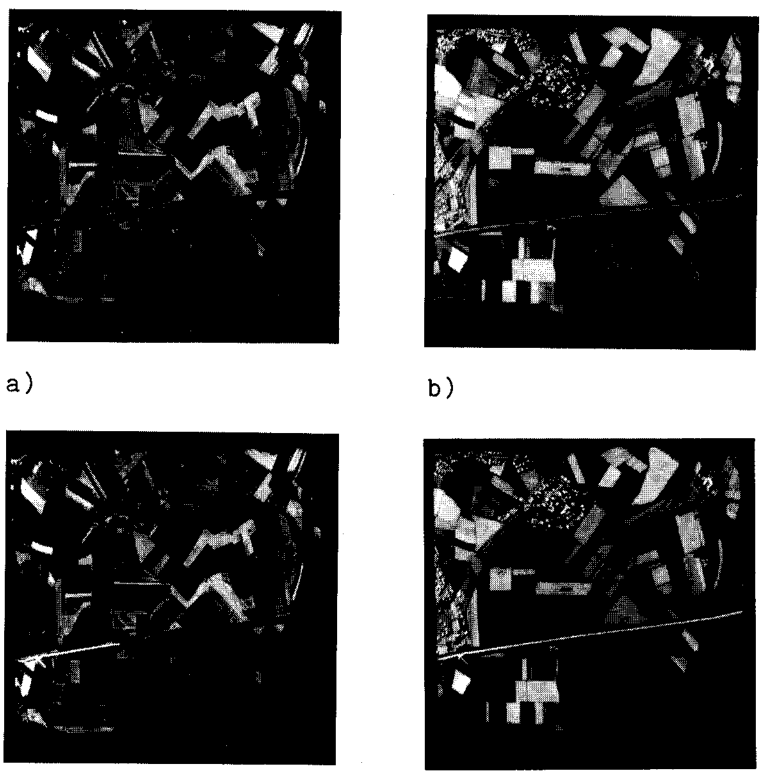
Fig. 6. Plotted results of the extraction from Fig. 5.

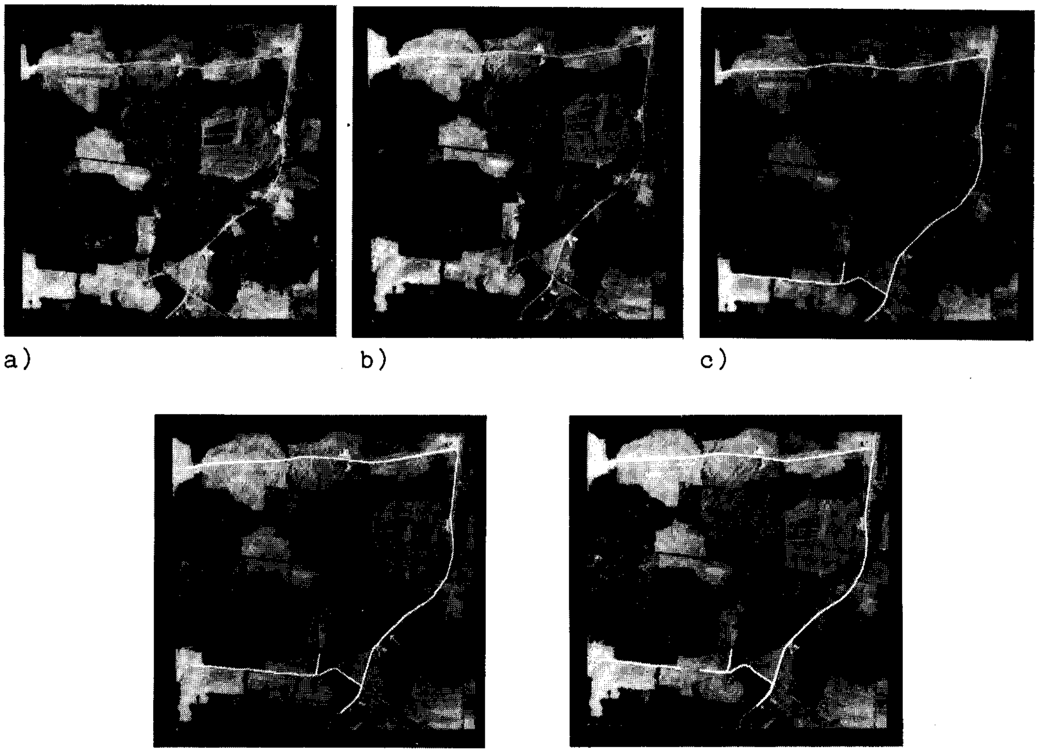


a) b)

c) d)

Fig. 7. Example of line following in multispectral image data.

To obtain the displacement of the line the road is extracted from the left image by the verification mode (see Fig. 8e). The differences in the terrain elevation corresponding to the displacements have not been calculated explicitly.



a) b) c) d) e)

Fig. 8. Example of the cooperative extraction from stereo images.

The next example demonstrates the use of additional knowledge: the extraction of a river is guided by the valleys extracted from a digital terrain elevation model. Figs. 9a and b show an aerial image and a corresponding part of the terrain elevation model. In Fig. 9c the starting points detected in the (dark) valleys of the terrain elevation model are displayed. Fig. 9d shows the valleys extracted automatically, and in Fig. 9e these lines are transferred to the aerial image. Fig. 9f shows the result of the verification process and a continuation of the extraction at dead ends.

a) b) c)

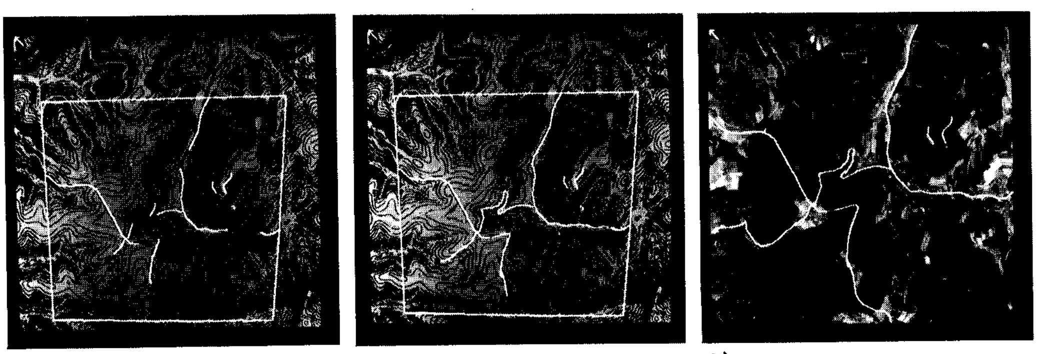
d) e) f)

Fig. 9. Extraction of a river guided by a digital terrain elevation model.

The last example demonstrates the extraction from an aerial image supported by map information. As the digital (interpreted) map where objects are stored related to their coordinates and vice versa is not available up to now the map information is used as (not interpreted) digitized matrix. Figs. 10a and b show the aerial image and a corresponding part of the topographic map 1 : 50 000 (TK 50). Due to the high density of information and the complexity of several signatures an extraction from the compound map is not very successful. Therefore the map master folios made for the color print are used for the extraction. If these folios are not available, similar folios can be produced artificially from the compound map: e.g., red color folio in Fig. 10b.

In Fig. 10c the result of the extraction from the aerial image is displayed. The result is mapped into the folio (Fig. 10d). Then the extraction is continued for a predefined distance (Fig. 10e). The two lines which have been found on walkways in the aerial image on the right-hand side have the same appearance as the roads, but they are not contained in the red color folio and therefore not continued. Fig. 10f shows the final result obtained from the aerial image after mapping back the intermediate results extracted from the map.

a) b) c)



d) e) f)

Fig. 10. Example of a cooperative extraction from an aerial image supported by cartographic information.

7. Conclusions

The system presented comprehending the method for the detection of starting points and the extraction of line shaped objects provides an essential step towards the automation of object data extraction.

The three methods and their combination with the integration of additional knowledge have proved to be successful with different kinds of images containing line shaped objects. Applications exist in image interpretation systems, especially in map data processing or image information reduction for automatic navigation updating.

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Abstract

The extraction of object boundaries from images is a basic component of numerous applications. Today the extraction is carried out manually mostly with little support of electronic aids. This paper describes how the extraction of line shaped objects from grey level pictures can be performed automatically. In contrast to the well-known parallel procedures, the objects are extracted sequentially by prediction and confirmation of neighboring object increments. To improve its performance the system presented can evaluate additional information. For example for the extraction of objects from aerial images terrain elevation models or other map knowledge or other images of the same area (e. g., stereo images, multispectral, multisensor or multitemporal images) can be included in the evaluation process.

Zusammenfassung

LINIENVERFOLGUNG

Die Extraktion von Objekträndern aus Bildern ist elementarer Bestandteil bei zahlreichen Anwendungen. Heute wird die Extraktion meist manuell und mit wenig elektronischen Hilfsmitteln durchgeführt. Dieser Bericht beschreibt, wie die Extraktion linenhafter Objekte aus Grauwertbildern automatisch vorgenommen wird. Im Gegensatz zu den bekannten Parallelverfahren werden die Objekte sequentiell durch Prädiktion und Bestätigung durch benachbarte Objektinformationen extrahiert. Um seine Leistungsfähigkeit zu verbessern, kann das vorgestellte System zusätzliche Informationen nutzen. Für die Extraktion von Objekten aus Luftbildern können z. B. Geländehöhenmodelle oder andere Karteninhalte oder andere Bilder aus derselben Region (z. B. Stereobilder, multispektrale, multisensor oder multitemporale Bilder) mit in den Auswerteprozess einbezogen werden.

Anmerkung: Alle Luftbilder freigegeben durch Reg.-Präs. Karlsruhe

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