AUTOMATIC COMPLETION AND EVALUATION OF ROAD NETWORKS

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ABSTRACT

Road networks automatically extracted from digital imagery are in general incomplete and fragmented. Completeness and topology of the extracted network can be improved by the use of the global network structure which is a result of the function of roads as part of the transport network. This is especially – but not exclusively – important for the extraction of roads from imagery with low resolution (e.g., ground pixel size > 1 m) because only little local evidence for roads can be extracted from those images.
In this paper, an approach is described for the completion of incompletely extracted road networks. The completion is done by generating link hypotheses between points on the network which are likely to be connected based on the network characteristics. The proposed link hypotheses are verified based on the image data. A quantitative evaluation of the achieved improvements is given.
New developments presented in this paper are the generation of link hypotheses between different connected components of the extracted road network and the introduction of measures for the evaluation of the network topology and connectivity. Results of the improved completion scheme are presented and evaluated based on the introduced measures. The results show the feasibility of the presented completion approach as well as its limitations. Major advantages of the completion of road networks are the improved network topology and connectivity of the extraction result. The new measures prove to be very useful for the evaluation of network topology and connectivity.

1 INTRODUCTION

One of the major problems of image interpretation systems, in particular for road extraction, is that the results of the extraction of primitives are incomplete (Steger et al., 1997). In order to overcome this problem, perceptual grouping algorithms are used to extract meaningful entities from segmentation results. In systems for automatic road extraction, hypotheses for the links between different parts of the segmentation result are often generated based on geometric criteria like proximity and collinearity (cf., e.g., (Vasudevan et al., 1988, Ton et al., 1989, Mayer et al., 1997, Steger et al., 1997, Baumgartner, 1998)). The hypotheses are then checked, e.g., based on the image data. Despite all these efforts, until now, no fully automatic approach is able to extract road networks complete and correct from imagery. But some approaches reach a completeness of 80% and more in open rural areas with about 95% of the extracted roads being correct (Wiedemann et al., 1998).

Completeness and topology of the extracted network can be improved by the use of the global network structure which is a result of the function of roads (Mayer, 1998). In this paper, an approach is presented for the completion of incompletely extracted road networks. In general, grouping deals with the addition of new links as well as with the deletion of old parts. The presented approach is only able to add new links. The approach is based on the function of roads as part of the transport system.

An evaluation based on quantitative measures like $completeness$ and $correctness$ only, does not capture the improvements of topology appropriately. Therefore, new measures for the evaluation are proposed, namely $mean\ detour\ factor$ and $connectivity$. These measures are calculated — similar to $completeness$ and $correctness$ — based on the comparison of the extraction result with reference data. They are intended to capture the topology of the extracted road network.

In the following section a strategy for the generation of link hypotheses is proposed which makes use of the function of roads. Section 3 deals with image based checking of the link hypotheses. In Sect. 4, new measures for the evaluation of the achieved results are introduced. Results are presented, evaluated, and discussed in Sect. 5. The paper concludes with a summary and an outlook.

2 GENERATION OF LINK HYPOTHESES

The division of labor in our modern business world demands for a transport network which allows for fast, cheap, efficient, and secure transports. The same characteristics are expected by the people for their daily ride to work, for shopping and for their trips to recreation areas (Pietzsch, 1989).

The first statement describes the more global requirements for the transport network and the second the more local ones. Besides, there are additional factors which influence the design of the transport network like, e.g., local topography, land use, and environmental conservation. All these requirements are taken into account for the development of the road network (as part of the whole transport network). Therefore they can and should be used for the extraction of road networks from images as well.

In this section an approach for the determination of link hypotheses between points on the already extracted road network is described. Links will be proposed where they are most desirable due to the above requirements.

2.1 Link hypotheses within connected components

Figure 1a) shows a part of a sample network which consists of four nodes (A, B, C, D) and three edges (AB, BC, CD). In the first step, between all possible pairs of points which lie on the network (the nodes A, B, C, and D in the example) the distance along the shortest path within the existing network (network distance, nd) as well as the distance along a hypothetical optimal path (optimal distance, od) are calculated, where, e.g., nd_{BD} is the sum of nd_{BC} and nd_{CD} (see Fig. 1b)). These distances are intended to represent the requirements for fast and cheap transports as well as the additional factors influencing the road network design mentioned above. Therefore the network distance depends on the actual length and classes of the roads along which the shortest path has been found. The optimal distance depends, besides the Euclidian distance between the two points, on factors like topography, land use, and environmental conservation.

In the second step, preliminary link hypotheses are defined between each possible pair of points. A so-called "detour factor" is calculated for each preliminary link hypothesis according to the following definition:

$$\textit{detour factor} = \frac{\textit{network distance}}{\textit{optimal distance}}$$

In Fig. 1c) the detour factors for all preliminary link hypotheses are shown. For simplicity reasons both, the network distance as well as the optimal distance are set to the Euclidean distance between the respective points.

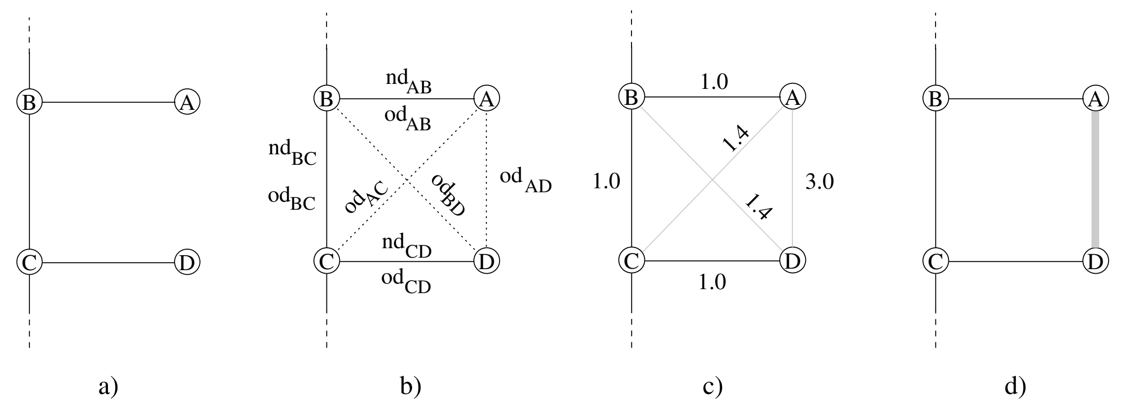


Figure 1: Hypothesis generation: a) Sample Network; b) Network distances and optimal distances; c) Detour factors for all preliminary link hypotheses; d) Link hypothesis

The third step consist of a selection of potentially relevant link hypotheses. The selection is carried out based on the assumption that only links which have a locally maximal detour factor are of any interest and that there is no preferred direction within the road network. Based on these assumptions, a non-maximum suppression (NMS) is performed on the set of preliminary link hypotheses: a link hypothesis is only kept if there is no competing link hypothesis which has a higher detour factor, otherwise it is deleted. Competing link hypotheses are preliminary link hypotheses between one end point of the preliminary link hypothesis under investigation and a point neighboring the other end point.

In the above example only the link hypothesis AD passes the NMS (see Fig. 1d)). In general more than one link hypothesis will be kept. All these link hypotheses are sorted according to their detour factor and the one with the highest detour factor is send to a module which checks the link hypothesis based on the image data. If the link hypothesis is rejected, the next one (the one with the second highest detour factor) is sent to the checking module, and so on. If a link hypothesis is accepted (and geometrically improved according to the image data), it is inserted in the road network. This changes the whole topology of the road network. Therefore, the procedure of generating link hypotheses has to be started again from the beginning. Link hypotheses already rejected are not taken into account in the following iteration. The iterative process of determining link hypotheses with maximum detour factor and checking them has to be broken off if one can expect that no further link hypothesis will be accepted by the checking module. In general, this cannot be predicted reliably, but it can be estimated roughly, e.g., based on the highest detour factor which occurs in the current iteration.

2.2 Link hypotheses between different connected components

Using the method presented in Sect. 2.1, it is not possible to generate link hypotheses between different connected components of the existing road network, because the calculation of the detour factor requires the determination of the network distance. For the generation of link hypotheses between different connected components another criterion has to be used. Having in mind that the road network consists of long roads, the following method is proposed:

In the first step, between all possible pairs of points (P_i, P_j) with P_i and P_j lying in different connected components (AB, AC, and AD in the sample network given in Fig. 2), the lengths l_i and l_j of the respective connected components as well as the optimal distance od_{ij} between P_i and P_j are calculated.

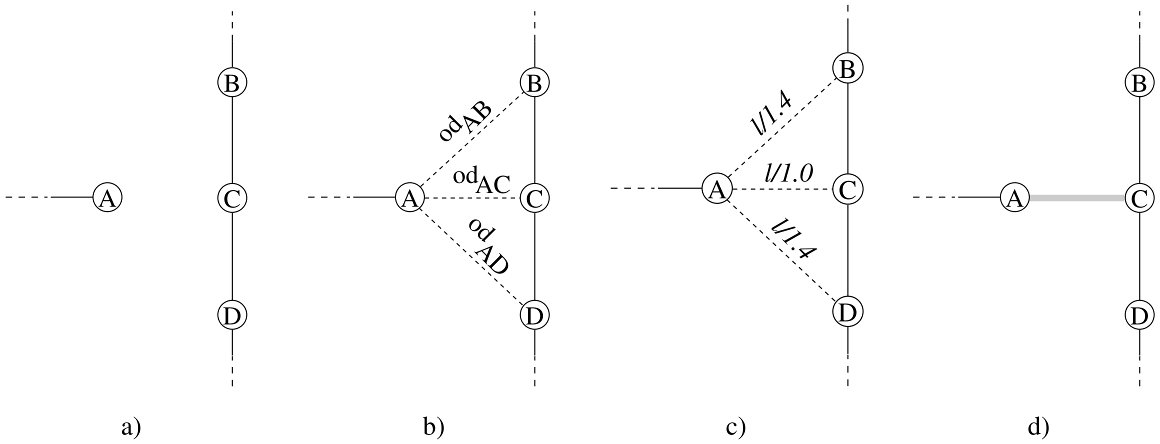


Figure 2: Hypothesis generation between different connected components: a) Sample Network; b) Optimal distances; c) Connection factors for all preliminary link hypotheses (with: $l = l_i + l_j$); d) Link hypothesis

In the second step, preliminary link hypotheses are defined between each possible pair of points. A so-called "connection factor" is calculated for each preliminary link hypothesis according to the following definition:

$$\textit{connection factor} = \frac{l_i + l_j}{\textit{optimal distance}}$$

with:

$$l_i, l_j = \text{length of the connected components } i \text{ and } j\text{, respectively}$$

This *connection factor* is further processed similar to the *detour factor* defined in Sect. 2.1, i.e., a NMS is applied to select potentially relevant connection hypotheses from all preliminary connection hypotheses. The connection hypothesis having the highest *connection factor* is sent to the checking module, which again checks the link hypothesis based on the image data. If the link hypothesis is rejected, the next one is sent to the checking module. If a link hypothesis is accepted, it is inserted in the road network.

2.3 Combination of the generation of link hypotheses within and between connected components

Since the *detour factor* is more meaningful than the *connection factor*, the generation of link hypotheses within and between connected components is organized as follows: First, all relevant link hypotheses within connected components are generated, checked, and — if verified — inserted into the road network (see Sect. 2.1). Then, link hypotheses are searched for between connected components. Again, these link hypotheses are checked based on the image data. The insertion of an accepted link hypothesis connecting two different connected components of the extracted road network changes the topology of the network. Therefore, if such a link hypothesis has been inserted, the search for link hypotheses is repeated within the resulting new connected component. If no further link can be inserted within this connected component, again, link hypotheses are generated and checked between different connected components. This is done iteratively, until no further link — neither within connected components nor between them — can be inserted.

2.4 Implementation Issues

In order to achieve better link hypotheses, equally spaced auxiliary nodes are inserted along the edges of the road network graph.

The calculation of the detour factor for all possible preliminary link hypotheses is computationally expensive due to the search for the best path between their endpoints in the network. In general, it is not necessary to check links between points which are far away from each other. Therefore, preliminary link hypotheses are only generated if the optimal distance between their endpoints does not exceed a given threshold (maximum optimal distance).

3 CHECK OF LINK HYPOTHESES

The check of the link hypotheses should be done based on the image data. It should provide the information whether the link hypothesis can be accepted or not, and, in the case of acceptance, it should return the exact geometry of the connecting road. Due to the modular design of the approach every road extraction tool can be used which is able to extract a road between two given points — the end points of the link hypotheses — and which provides some kind of self-diagnosis in order to decide whether the connection can be accepted or has to be rejected.

3.1 Road extraction

In this work, the extraction algorithm described in (Wiedemann and Hinz, 1999, Wiedemann, 1999) was used. This approach has been designed for the extraction of road networks from satellite imagery. Nevertheless, it can also be applied to aerial imagery which is down-sampled to a ground pixel size of, e.g., 2 m. Due to the limited ground resolution of traditional satellite images a road model purely based on local characteristics is rather weak. For this reason, network characteristics of the roads are also taken into account, and regional and global properties are incorporated into the road model:

Locally, radiometric properties play the major role. The road is modeled as a line of a certain width. It can have a higher or lower reflectance than its surroundings. On the regional level, geometric and radiometric characteristics of roads are introduced. These incorporate the assumption that roads mostly are composed of long and straight segments having constant width and reflectance. Globally, roads are described in terms of functionality and topology: The intrinsic function of roads is to connect different — even far distant — places.

3.2 Insertion of verified link hypotheses into the road network

If a road has been found which connects the two end points of the link hypothesis, this new link has to be inserted into the whole road network.

First, all parts of the new link which are redundant with respect to the already extracted road network are eliminated. In most cases, one large part of the new link will remain. This part is then inserted into the network by connecting its two end points directly with the respective nearest points of the road network. If this point is not an end point of a road, a new junction is inserted into the road network. In cases where more than one remaining part of the new link exist, all these parts are inserted into the network as described above. If the whole new link has been eliminated no part can be inserted into the road network, i.e., the respective link hypothesis is rejected.

4 EVALUATION

Besides the intuitive measures completeness, correctness, and RMS (Wiedemann et al., 1998), an evaluation of the topology of the extracted network is carried out. To this end, two new measures are introduced: *mean detour factor* and *connectivity*.

For the evaluation of the topological correctness within connected components of the extracted network, the mean detour factor with respect to the reference network is calculated: the distance along the reference network ($network\ distance^{ref}_{i,j}$)

and the distance along the extracted network (*network distance*$^{extr}_{i,j}$) are calculated between all pairs $(i, j), i \neq j$, of points which are connected in both networks. The ratio $r_{i,j}$ between these two distances is calculated for each pair (i, j):

$$r_{i,j} = \frac{\textit{network distance}^{extr}_{i,j}}{\textit{network distance}^{ref}_{i,j}}$$

If $r_{i,j}$ is larger than one, the distance between points P_i and P_j along the extracted network is larger than the respective distance along the reference network. In this case it is referred to as *detour factor*$^{ref}_{i,j}$ (detour factor with respect to the reference network). The *mean detour factor* is defined as the mean of all values *detour factor*$^{ref}_{i,j}$.

The optimum value for the *mean detour factor* is 1.0. The *mean detour factor* increases with the amount of missing connections within connected components of the extracted network and with the degree of "wiggling" extraction (see Fig. 3).

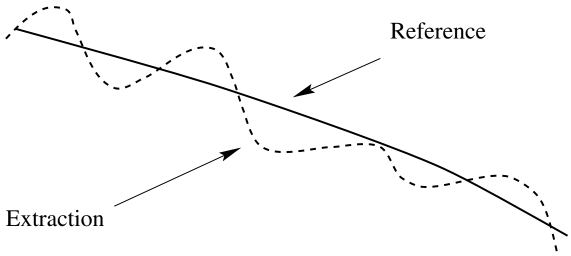


Figure 3: Wiggling extraction

For the evaluation of the connectivity of the extracted network, a number of points P_i are defined equally distributed within the reference network. All possible pairs of these points are examined if they are connected in the reference network, i.e., if they lie within the same connected component. For these **CR** pairs **c**onnected in the **r**eference it is checked whether they are connected in the extracted network as well. This yields **CB** pairs which are **c**onnected in **b**oth networks. Based on **CR** and **CB**, *connectivity* is defined as

$$\textit{connectivity} = \frac{CB}{CR} = \frac{\textit{\# of pairs connected in both networks}}{\textit{\# of pairs connected in reference network}}$$

The optimum value of the *connectivity* is 100%. The *connectivity* decreases with an increasing fragmentation of the extracted network with respect to the reference network.

The *mean detour factor* can be used to quantify the improvements achieved by the completion *within* connected components, whereas the *connectivity* quantifies the improvements achieved by the completion *between different* connected components.

5 RESULTS

In this section, results of the approach proposed in this paper are presented. The calculation of the network distance is performed based on the actual length of the road segments along which the shortest path has been found. No weighting of the roads according to their class or width is done. The optimal distance is calculated simply as the Euclidean distance between the respective points, i.e., no additional information like topography, land use or environmental conservation is taken into account until now. The check of the link hypotheses is performed automatically as described in Sect. 3. In this step, the geometry of the accepted hypotheses is improved according to the image data. To reduce the amount of computation time, the search for a road which connects the two end points of a link hypothesis is performed only in a restricted region of interest (ROI) which contains both end points and which is assumed to contain the connecting road as well. The following results were obtained using an elliptical ROI with the two end points as focuses and a numerical eccentricity of 0.75. The iterative process of determining link hypotheses and checking them is broken off automatically if no unchecked link hypothesis has a detour factor higher than the mean plus three times the standard deviation of the detour factors of the whole network.

The distance between the equally spaced auxiliary nodes (see Sect. 2.4) was set to 100 m. The maximum optimal distance was set to 300 m.

In Fig. 4a) and b) the reference network and the extraction result, respectively, are shown for a scanned aerial image with a ground resolution of about 0.5 m. The extraction was carried out using the road extraction system presented in (Baumgartner, 1998). Due to different parameter settings, these results are slightly different to results presented in earlier publications, e.g., in (Wiedemann, 1999). The link hypotheses which were sent to the checking module are displayed in Fig. 4c) (accepted link hypotheses are drawn broad and in dark gray, rejected hypotheses thinner and lighter; the numbers refer to the respective examples shown in Fig. 4d)-f)). 64 hypotheses were sent to the checking module. The check was carried out based on the image which was down-sampled to a ground pixel size of 2 m. 38 hypotheses were accepted and 26 were rejected. As can be seen, most of the gaps within connected components were closed as well as many links between different connected components could be inserted.

The first example (see Fig. 4d)) shows the link hypothesis in the upper right corner. It has been wrongly rejected. The reason for this failure is that the missing road is hardly identifiable. A more sophisticated road extraction algorithm, e.g., based on context as well as on additional data like high resolution multi-spectral image data, height data, etc. would be necessary to extract this kind of (partly occluded) roads. The link hypothesis in the middle of the image is displayed in Fig. 4e). In this case, the varying road width prevented the extraction of the missing part. This link hypothesis was accepted correctly. In the final result, many accepted as well as rejected link hypotheses lie in the region above and to the right of the image part displayed in Fig. 4e). Some of them are wrongly accepted/rejected due to the high complexity of this region and the fact that the road extraction algorithm used for verification was designed for the extraction of roads in open rural areas only. The third example (see Fig. 4f)) shows the correctly accepted link hypothesis from the lower left of the image. It connects two different connected components of the initial road network.

The evaluation of the initial road network and of the automatically completed one is given in Tab. 1. The completeness increases whereas correctness and RMS decrease slightly. This means, most of the added links were correct, but geometrically not as accurate as the initial result. This was to be expected because the check was performed on imagery with a ground resolution which was worse by a factor of four. The decrease of the mean detour factor signalizes that a lot of important gaps within connected components could be closed. The connectivity increases significantly, i.e., most of the different connected components could be connected by new links. Altogether, the results show that the main improvements could be achieved in the topology of the road network.

	initial	completed
Completeness	80.7%	85.8%
Correctness	92.7%	90.5%
RMS	1.05 m	1.33 m
Mean detour factor	1.44	1.04
Connectivity	78.5%	97.9%

Table 1: Evaluation results

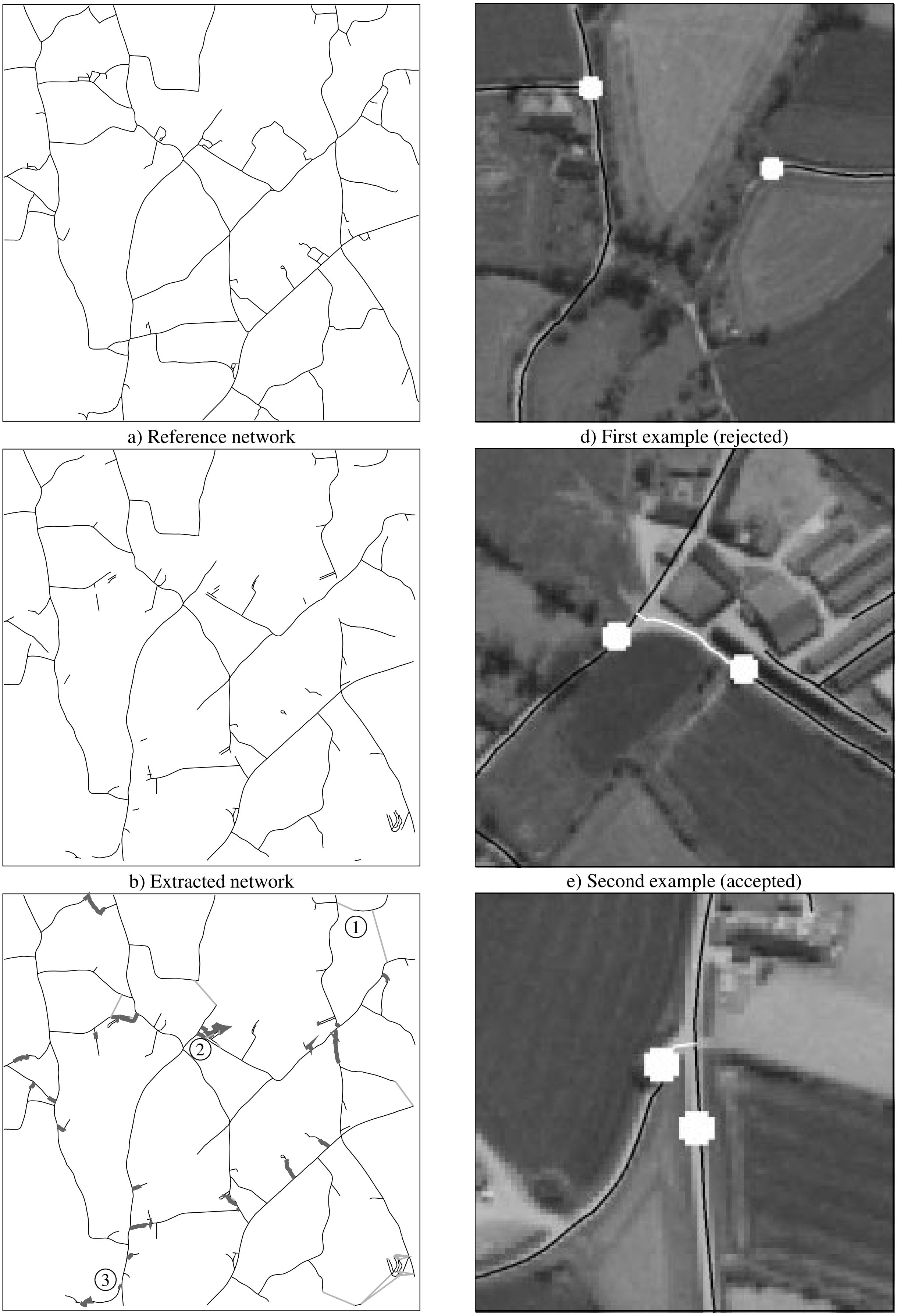
6 SUMMARY AND OUTLOOK

The paper deals with grouping based on functional characteristics of the road network. This is useful to improve the results of automatic road extraction where – until now – grouping is mostly performed on a geometric and often local level. Major requirements for the road network are to allow for fast, cheap, efficient, and secure transports. The presented approach is able to determine hypotheses for new links based on these requirements and to check them using image data. Results are presented for a road network extracted automatically from digital imagery. The results are evaluated using existing as well as newly defined quality measures. The evaluation demonstrates the feasibility of the presented approach. The new quality measures prove to be very useful.

Future work will be directed towards improvements and extensions of the presented approach. The use of knowledge about the scene, e.g., in the form of a digital terrain model or information about land use will improve the calculation of the optimal distance.

The current approach can only propose new links, it cannot be used for the deletion of parts of the road network. Also this should be done, based on the function of the roads. A basis might be the approach presented in (Morisset and Ruas, 1997) which uses multi-agent modeling to determine the importance of roads based on the amount of “road-use”. This approach has been developed for generalization tasks, but it could possibly be modified for the task of determining parts of the network which can be deleted.

Evaluation is an important research topic, because the quality (geometric as well as topologic) is a decisive factor in the introduction of automatic road extraction into practical work. Further investigations will be undertaken to improve the proposed quality measures.



a) Reference network
d) First example (rejected)
b) Extracted network
e) Second example (accepted)
c) Extracted network with link hypotheses
f) Third example (accepted)

Figure 4: Results for a road network extracted from an aerial image

7 ACKNOWLEDGMENTS

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