EuroSDR-Project

Commission 2 “Image analysis and information extraction”

“Automated Extraction, Refinement, and Update of Road Databases from Imagery and Other Data”
Final Report

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Abstract

Roads are important objects for many applications of topographic data such as car navigation systems. They are often acquired manually and as this entails significant effort, automation is desirable. Deficits in automation, particularly linked to human interaction have led to the formation of this EuroSDR working group on the automated extraction, refinement, and update of road databases from imagery and other data. In the introductory part of this report we give a short account of the working group's motivation and the actual implementation in terms of actions. After showing why and how we limit the scope of the report we present an analysis of questionnaires to producers of road data as well as researchers and manufacturers. Based on it, the main focus has been the setup of a test comparing different approaches for automatic road extraction. After describing the data and the evaluation criteria used, we briefly present the approaches of a number of groups which have submitted results and give the outcome of the evaluation of these results. Finally, after thoroughly analyzing the evaluation results, we present conclusions and recommendations.

1 Motivation and Implementation

The original proposal for the project leading to the working group including an exhaustive account of background, motivation, and planned implementation can be found in Appendix 1. Here we give a short motivation and list the most important points reached in the actual implementation before finally limiting the scope of the report.

1.1 Motivation

The need for accurate, up-to-date and increasingly detailed information for roads has rapidly increased. They are needed for a variety of applications ranging from provision of basic topographic infrastructure, over transportation planning, traffic and fleet management, car navigation systems, location based services (LBS), tourism, to web-based applications. While road extraction has been sometimes performed by digitizing maps, road update and refinement can mainly be performed only from aerial imagery or high resolution satellite imagery such as Ikonos or Quickbird. Additionally, terrestrial methods, particularly mobile mapping are also of significant importance.

Because road extraction from imagery means large efforts in terms of time and money, automation of the extraction is of high potential interest. Full automation of the extraction of topographic objects is currently practically impossible for almost all applications and thus a combination with human interaction is necessary. An important factor hindering the practical use of automated procedures is the lack of reliable measures indicating the quality and accuracy of the results, making manual editing lengthy and cumbersome. Manufacturers of commercial systems have developed very few tools for semi-automated extraction and their cooperation with academia has been minimal. Thus, users and producers of such data, including national mapping and cadastral agencies (NMCAs) and large private photogrammetric firms, have been left with many wishes to be fulfilled.

NMCAs in Europe increasingly plan to update their data in shorter cycles. Their customers have increasing demands regarding the level of accuracy and object modeling detailedness, and often request additional attributes for the objects, e.g., the number of lanes for roads. The insufficient research output and the increasing user needs, necessitate appropriate actions. Practically oriented research, e.g., the ATOMI project at the ETH Zurich (Zhang 2004), has shown that an automation of road extraction and update is feasible to an extent that is practically very relevant. Companies that have developed semi-automated tools for building extraction and other firms too, could very well offer similar tools for roads. Thus, the central ideas of the proposed working group are:

- To survey the data specification needs of important data producers, mainly NMCAs, and their customers.

- To thoroughly evaluate the current status of research (including models, strategies, methods and used data), to test and compare existing semi- or fully automated methods using various data sets and high quality reference data, to identify weak points and, finally, to propose strategies and methods that lead to a fast implementation of operational procedures for road extraction, update, and refinement. Here, refinement means the improvement of planimetric accuracy, but also the addition of new information such as height and road attributes. (Originally, we intended to focus on update and refinement. However, we got almost no feedback on these issues and thus decided to limit the scope to road extraction.)

1.2 Implementation

A EuroSDR working group (WG) chaired by Helmut Mayer, Bundeswehr University (UniBw) München, and Emmanuel Baltsavias, ETH Zürich, was formed in 2002. It has now significantly exceeded its proposed life-time of one and a half to two years. Actions so far comprise:

- Establishment of a web-page. The WG was officially announced and presented (kick-off) at the workshop "Incremental Updating", October 2002, Frankfurt, Germany.

- The distribution of the two extensive questionnaires to Researchers and Manufacturers as well as Data Producers was done at the end of the year 2002

- In spite of considerable advertising efforts the response to the questionnaire for Data Producers was as low as one reply. For the Researchers and Manufacturers the feedback was better with ten replies, though none from industry. Because of the weak response from the side of the producers and because the reply from the researchers pointed mostly to an interest in a comparison of the results of the individual approaches on the same data sets, we decided to postpone the reporting of the outcome of the questionnaires to this report. Instead, we focused on generating data sets consisting of images together with ground truth and the preparation of software making it possible to evaluate the individual results based on quantitative evaluation criteria.

- Preparation and distribution of test data sets including documentation took much longer than expected, particularly as we wanted to include Leica ADS 40 digital aerial image data, which was only delivered in the middle of 2004. Data has kindly been provided by Swiss Federal Office of Topography, Bern, Switzerland, Leica Geosystems, Heerbrugg, Switzerland, and the Bundeswehr Geoinformation Office (AGeoBw), Euskirchen, Germany. The data was distributed following the ISPRS Istanbul congress in July 2004.

- Some first results were submitted and evaluated by the end of 2004. By mid 2005 the situation was very disappointing, however, more results were received by the end of 2005 and the beginning of 2006.

We are finally in a position to give a meaningful account of the results. Unfortunately, due to the long duration of the WG many things including the scientific focus of the WG chair and the availability of personnel working on road extraction has changed. Thus, we are not in a position to give a broad overview over the whole area. We rather limit the scope of this report to the analysis of the main outcome of the WG, namely the questionnaires received from the researchers and particularly the results and their evaluations for the test data.

2 Questionnaires

We developed two questionnaires, one for data producers and another for researchers and manufacturers. They were posted on the web and advertised on many occasions and with a larger number of personal Emails. Both questionnaires, including a summary of the answers received, can be found in full as Appendices 2 and 3.

2.1 Summary of responses to the Questionnaire for Producers of Road Data

The response to this questionnaire (cf. Appendix 2) consisted of one completed questionnaire even though we had advertised the questionnaire several times at EuroSDR meetings and via Email. We finally came to the conclusion that we requested too many answers, meaning too great an effort to complete the questionnaire, and also requested information which are seen as trade secrets. Additionally to the questionnaire we got some insights and opinions from insiders of the road data business. All this is summarized in the following, though the information was mainly obtained in 2003 and might be slightly out of date.

The one answer came from a state survey in Germany, which spent about fifty man years on road extraction over three years. Roads are obtained from GPS vans, digitizing from digital cadastral maps, as well as from governmental road construction agencies and municipalities. Roads are acquired from data which is a couple of months old and the average age of road data is just one year. Concerning accuracy, it was estimated to be in the 1 m range on average for the individual road segment, with the maximum error below 3 m. Yet, besides these good numbers one has to note that the data is cartographically generalized as the main application is topographic maps at a scale of 1:25000. Roads are acquired together with road class, number of lanes, and road width, all as defined in the (German) object class catalog ATKIS. For the latter, a detailed description of the topology for intersections is restricted to highways, but bridges, underpasses, and tunnels are modeled with some detail. As ATKIS defines a fully-fledged topographic information system, it also contains information about forest, water bodies, and settlements / buildings. The updating for roads takes approximately half an hour per square km and is done in an object oriented Intergraph environment. Right now they are switching to an update procedure based on information from governmental road construction agencies and local topographers. The group of customers comprises rescue services (fire brigades, police, ambulances – navigation systems), mapping (city plans), and engineering companies (urban planning, etc.). All location based services, e.g. insurance companies, parcel services, and geo-marketing are seen as potential customers.

Insiders of the road data business have told us that the requirements on road data are going to increase, to support assistance and control functions for cars. First, more detailed models can be used to control lighting or warn drivers if bends are too sharp. There is even the idea of obtaining 3D models for roads, e.g., from laser scanning, and use them to warn the driver or even brake the car if it is too fast. Information about individual lanes is also of interest for some applications. The requirements are under discussion and they are standardized in GDF (geographic data format) under the umbrella of official standardization bodies (CEN, ISO). Proposals range from cm accuracy (probably too high) up to the 5 m in use today.

GDF includes topology, road classes, crossings without lanes but with forbidden turns or one way streets, generalization levels, class codes for bridges and tunnels, and lots of other objects besides roads. The producers employ internal data bases and distribute via GDF. There is a quality code which is mostly not used. The geometry is modeled as polygons, i.e., as straight lines. There is a data field for height information, but it is not used. Whereas the width of the road, the number of lanes, the widths of the lanes, or the material of the road surface are usually not modeled, roundabouts and exits are.

For actual use in navigation systems the GDF data is usually generalized and stored in proprietary formats on four different levels, the lowest containing all roads and the highest only the highways. Generalization comprises geometry as well as attributes. There are often different data for visualization and for routing.

We were also informed that only about 20% of the effort goes into geometry. As, additionally, digitization of roads is nowadays done mostly in India and China, automation is not of first interest. Accuracy is in the range of 5 to 15 m which is enough in combination with map matching. Attributes mostly have to be acquired from ground level. It is done by regional bureaus supported by information from mail or parcel services. The acquisition of attributes, e.g., in the form of traffic signs, means lots of effort which has to pay off.

In summary, road data from governmental organizations could be of interest at least concerning its geometrical quality and information such as the road width and number of lanes for commercial data providers. As the geometry is only a part of the business, the question is whether the advantages are significant enough compared to the efforts needed for integration, let alone financial and legal issues.

2.2 Summary of responses to the Questionnaire for Researchers and Manufactures

Overall ten questionnaires were returned by May 2003. With the exception of one from the photogrammetry department of a mapping agency all answers came from researchers from universities. In the majority of the groups between two and four people are involved in road extraction. The average manpower available for road extraction over the last three years has been about three man years, with one group spending about eight man years. Thirty years / man years both came from the photogrammetry department of the mapping agency and it seems likely that these numbers actually describe production.

The completed questionnaires, a summary of which can be found in Appendix 3, show that many groups concentrate their work on the more simple kind of roads: Eight groups model narrow rural roads, six urban streets, and five dirt roads. Large roads or freeways with complex intersections or crossings are only dealt with by two groups each. With the exception of one, all groups can work with black and white images, though seven can also use color or multispectral images. Satellite images can be processed by half of the approaches, the answers at this time saying that there is a slight preference for panchromatic over multispectral. (Please note that for the actual test two years later – see Section 4 below – most approaches made heavy use of multispectral information.) Height information in the form of a Digital Surface Model (DSM) derived by Airborne Laser Scanning (ALS) is used by six groups and three also make use of Digital Terrain Models (DTM) derived from ALS. Comments point on pan-sharpened Ikonos data, that has actually been used in the test below, SAR images, as well as information about the date and time of image acquisition to allow for a prediction of shadows. A ground resolution of 0.6 m and 2 m is preferred by a majority of seven groups. Higher resolution images are used mainly in approaches originally developed for aerial imagery, with two groups focusing on urban streets going down to 10 cm and below. The coarse resolution from satellites of 10 m and above no longer plays an important role in road extraction, with newer, high resolution sensors available.

In terms of local road characteristics parallel roadsides / perceptual grouping and homogeneity in the direction of the road are both employed by a majority of seven groups. Scale-space behavior and the spectral characteristics of the road are used by three groups, whereas markings and cars on the road are only important for urban streets. (Again, the practical tests in Section 4 below showed that for Ikonos data most groups made use of the spectral information.) The comments show a vast variety of ideas for road extraction, comprising line extraction, texture analysis, homogeneous ribbons, machine learning, verification based on profiles, as well of grouping in DSM. The smoothness of road trajectories is modeled by eight of the groups by a variety of techniques consisting of splines, (zip-lock ribbon) snakes, Kalman-filters, piecewise parabolas, polynomial adjustment, Bezier curves, weighting by mean curvature, and weighting using fuzzy values for straightness. All groups except one employ the network characteristics of roads. Six do this by bridging local gaps and five by global optimization of the network. Techniques used comprise graph data structures, global path search, and local context. Gaps are closed according to length and collinearity, but also checking homogeneity, the existence of predicted shadows or by finding cars.

The width of the road is the attribute computed by almost all of the groups. Four groups determine the road class and three groups the number of lanes. Other attributes calculated by one or two groups are the width of lanes, road markings, surface material, height profiles, and internal quality measures. Eight groups model simple crossings while complex crossings and roundabouts are only dealt with by two groups. Highway exits are modeled by one group and highway intersections by none. Seven groups make use of contextual information, most of them by different modeling in urban, rural, and forest areas. Shadows and occlusions are also taken into account in four approaches. The comments show that for detailed contextual modeling information from DSM, possibly from LIDAR, is used to obtain hypotheses for buildings, i.e., high objects where there cannot be a road, or cars on the road as well as for predicting / explaining shadows and occlusions.

Geographic information system (GIS) data is not used at all by seven groups. However, two groups use it to refine the search space and one even to actively verify roads. For the latter, attributes and also the context of roads are employed to find evidence for roads, possibly adapting parameters or selecting specific algorithms - no evidence found meaning rejection. GIS data is also used for supervised learning and might be useful to guide an operator. On the other hand, three groups note that the extraction should be done independently of the GIS data to avoid bias. 3D information is employed by six groups, mostly in the form of a DSM generated by image matching or ALS. It is used mainly to verify that roads are smooth in 3D and have a limited steepness, but also to determine shadow regions, to segment urban and rural areas, as well as to fuse results from different aerial images. Three groups carry out precision estimation for the results and five label the results with a reliability flag, only three assuming that it is actually reliable. The evaluation is done by many groups according to Wiedemann et al. (1998) in comparison to ground truth data. Yet, there is also internal evaluation based on the network characteristics and one particular approach uses independent features evaluated by fuzzy values. For learning based approaches results are evaluated at each stage statistically. This information is then used to tune the algorithms.

Object oriented programming often with C++ is the basis of almost all groups. This is complemented for three groups by modeling uncertainty using the Theory of Evidence and fuzzy logic. Two groups use explicit reasoning and one automatic learning. Most approaches run under Windows, many under LINUX, and three groups use UNIX on different hardware architectures.

Most groups work on automatic solutions, only three groups focus additionally or exclusively on semiautomatic approaches. Therefore, the answers given for this issue have to be taken more cautiously than the rest. Two groups have developed an approach based on tracking, with one giving the points sequentially, guiding the tracking. Only two groups have yet devised an approach for editing automatically computed results, both restricting the automated processing by given regions and attributes defined by an operator or given by a GIS. One group labels the results with a (reliable) reliability flag.

The general characteristics of the approaches for which the corresponding questions have been answered are given in Appendix 3. They comprise key features, strong points, weaknesses or limitations, how the approach could be optimally exploited in a practical application, and most important features for an ideal system for practical, i.e., semi-automated, road extraction. For the latter, most groups propose a combination of reliable results of automatic road extraction with a user-friendly interface. If automation is used during the interactive phase, its speed has to be high enough.

Concerning data for the envisaged test, there was a slight preference for original image data over orthoimages. One comment said that mostly orthoimages show strong distortions in urban areas. Two thirds of the responding researchers prefer color or multispectral imagery, one commenting that infrared data would be helpful. GIS data is needed, e.g. for verification, or important for half of the groups. Seven of the groups wish that orthoimages be generated, two from DTM and four from DSM. Only two groups find ALS data important for the test. There are comments saying that DSM is important for urban areas, but could also come from a source other than ALS. The vector formats most groups can handle are ARC/INFO coverage or Microstation DGN files. Besides this there is a big variety of formats employed. Seven groups are interested in digital aerial line scanner data, e.g., from ADS40, but most of them comment that it is interesting for tests but of low priority. Finally, people commented that they find orthoimages in RGB, DSM, as well as lots of labeled images for evaluation purposes important.

All researches see road centerlines as the correct basic information for deriving statistics for road extraction. As parameters for an evaluation besides completeness, reliability and accuracy (RMS), correctness and the number of connected lanes for crossings as well as the number of lanes for roads are proposed. Half of the groups see an additional qualitative visual inspection as meaningful, yet commenting that this can just give a rough idea and that the eye tends to group together lines closing existing gaps. For semi automatic approaches the proposed idea was to define a quality level which is checked automatically and then to measure interaction time for comparison. This was accepted as a good idea by six groups, one noting that not only the time, but also the number of breaks for the operator is of importance. Finally, it is noted that for supervised methods it might be interesting to work with the same training data to obtain a better defined comparison.

In summary, the low number of groups having devised a semi automatic approach shows the focus on research and not on practice of the groups that sent in answers for the questionnaires. From our experience one of the key problems is that the interaction for a semi-automatic approach needs to be highly optimized for the current state of the approach at hand which implies considerable effort which is only meaningful if it is used in production. As there is still too much to be improved for the automatic approaches and production is shifted towards countries with low wages, there is a tendency to focus on the improvement of the automatic approaches where more is seen to be gained for the moment.

Therefore, we decided to focus the envisaged test on automatic approaches. To still get a practical flavor into the test, images of a size too small for practice, but challenging for the approaches, were used. According to the answer we got we devised a test data set with aerial and high resolution satellite data, all in full color, the digitally acquired data also including infrared. The data and the evaluation criteria used are detailed next.

3 Test Data and Evaluation Criteria

Initially, eight test images were prepared from different sensors (for details see the README file in Appendix 5):

- 3 scanned aerial images from the Federal Office of Topography, Bern, Switzerland
  - Aerial1: suburban area in hilly terrain
  - Aerial2: rural scene with medium complexity in hilly terrain
  - Aerial3: rural scene with low complexity in hilly terrain
- 2 Leica ADS40 images from Leica Geosystems, Heerbrugg, Switzerland
  - ADS40_1 and _2: rural area with medium complexity in flat terrain.
- 3 IKONOS images from Kosovo, provided by Bundeswehr Geoinformation Office (AGeoBw), Euskirchen, Germany, given as pan sharpened images in red, green, blue, and infrared
  - Ikonos1: urban/suburban area in hilly terrain
  - Ikonos2: rural scene with medium complexity in hilly terrain
  - Ikonos3: rural scene with medium complexity in hilly terrain

All images have a size of at least 4,000 by 4,000 pixels. While we initially thought that this size should be a challenge that people should be able to overcome during the duration of the test, it was finally found to be insurmountable by nearly all approaches even two years after the envisaged end of the test and, therefore, the limiting factor of the test. We, therefore, decided eventually to cut out three smaller parts with 1,600 by 1,600 pixels of the Ikonos images, one from Ikonos1 and two from Ikonos3, as there seemed to be most interest in this area.

For evaluation we use criteria put forward by Wiedemann et al. (1998). The basic assumption is that reference data is available in the form of the center lines of the roads. Additionally, it is assumed that only roads within a buffer of a certain width, usually the average width of the roads, around the road are correct. The extracted roads which are inside the buffer of the given reference roads and *vice versa* are determined via matching of the respective vector data. The most important criteria defined by Wiedemann et al. (1998) based on these matching results to which we have restricted the analysis are:

Completeness: This is the percentage of the reference data which is explained by the extracted data, i.e., the part (percentage) of the reference network which lies within the buffer around the extracted data. The optimum value for the completeness is 1.

Correctness: It represents the percentage of correctly extracted road data, i.e., the percentage of the extracted data which lie within the buffer around the reference network. The optimum value for the correctness is 1.

RMS (root mean square): The RMS error expresses the geometrical accuracy of the extracted road data around the reference network. In the given evaluation framework its value depends on the buffer width. If an equal distribution of the extracted road data within the buffer around the reference network is assumed, it can be shown that RMS equals one divided by square root 3 of the buffer width. The optimum value for RMS is 0. As RMS mainly depends on the resolution of the image, it is given in pixels in this report.

The reference data has an estimated precision of half a pixel. It comprises major and secondary roads, but no paths or short driveways. The reference data has not been made available to the participants. The participants usually asked only once or twice for an evaluation, i.e., no optimization in terms of the reference data was pursued. Opposed to (Scharstein and Szeliski, 2002) we allowed people to optimize their parameters for each and every image, as constant parameters were seen as too challenging.

4 Approaches and Evaluation of Results

We have finally obtained for every data set at least one result. Results that could be evaluated have been sent in by six groups. We will shortly introduce the groups and their approaches (alphabetical ordering according to corresponding author given in bold). Details for some of the approaches can be found in Appendices 6 to 8. Selected results and their analysis are presented in (Mayer et al. 2006).

The approaches of Bacher, Gerke, and Hedman are all three based on the work of TU München of Wiedemann and Hinz (1999) and partially Baumgartner et al. (1999a, 1999b). Hedman mostly optimizes the line extraction of the former for the data at hand by employing the blue channel as well as the NDVI. Opposed to this, Bacher and Gerke also make use of the work of Baumgartner et al. (1999a, 1999b). While Bacher has devised an approach automatically generating training data for a multispectral classification and employs snakes on the classification result to bridge gaps, Gerke uses the original approach of Wiedemann and Hinz (1999) with customized parameter settings (Gerke_W) as well as the original approach of Baumgartner et al. (1999a, 1999b) with the improved basic line detection of Wiedemann and Hinz (1999 – Gerke_WB).

- Uwe **Bacher**, Institute for Photogrammetry and Cartography, Bundeswehr University Munich, Germany: The approach is only suitable for the Ikonos images. It is based on earlier work from TU München of Wiedemann and Hinz (1999) and partially Baumgartner et al. (1999a, 1999b). The approach of Wiedemann and Hinz (1999) starts with line extraction in all spectral bands using the sub-pixel precise Steger line extractor (Steger 1998) based on differential geometry and scale-space including a thorough analysis and linking of the topology at intersections. The lines are smoothed and split at high-curvature points. The resulting line segments are evaluated according to their width, length, curvature, etc. Lines from different channels or extracted with different scales, i.e., line widths, are then fused on a best first basis. From the remaining lines a graph is constructed, supplemented by hypotheses bridging gaps. After defining seed lines in the form of the most highly evaluated lines, optimal paths are computed in the graph and from it gaps to be closed are derived. Bacher has extended this by several means (Bacher and Mayer 2004, 2005). The central idea is to take into account the spectral information by means of a (fuzzy) classification approach based on fully automatically created training areas. For the latter parallel edges are extracted in the spirit of (Baumgartner et al. 1999a, 1999b) in a buffer around the lines and checked if the area in-between them is homogeneous. The information from the classification approach is used to evaluate the lines. Additionally, it is the image information when optimizing snakes to obtain a more geometrically precise, but also more reliable basis for bridging larger gaps in the network, which is another new feature of Bacher's approach.

- Charles **Beumier** and Vinciane Lacroix, Signal and Image Center, Royal Military Academy, Brussels, Belgium (also see Appendix 6): Their approach for Ikonos images rests on the gradient line detector of Lacroix and Acheroy (1998) which assumes that the gradient vectors on both sides of a line are pointing in opposite directions. Bright lines are extracted from the green channel with a slight Gaussian smoothing employing non-maximum suppression. Lines are tracked limiting the direction difference until a minimum strength is reached. Lines are only kept if they are at least 30 pixels long and are straight enough when checked via the square root of the inertial moment. For each of the line points the Normalized Difference Vegetation Index (NDVI) is computed from the red and the infrared channel and if it is below zero, the point is supposed to be vegetation and is rejected. Finally, the rest of the points are again tracked and checked to see if they are still long and straight enough.

- Markus **Gerke**, Institute for Photogrammetry and Geoinformation (IPI), Hannover University, Germany: Gerke uses two approaches, suitable for the aerial images as well as for the Ikonos data. Gerke_W is the approach of Wiedemann and Hinz (1999) – see Bacher above. Gerke_WB consists of a combination of Gerke_W with the approach of Baumgartner et al. (1999a, 1999b). The latter is based on extracting parallel edges with an area homogeneous in the direction of the road in between in the original high resolution image and fusing this information with lines extracted at a lower resolution, thereby combining the high reliability of high resolution with the robustness against disturbances, particularly for the topology, of the lower resolution. Baumgartner et al. (1999a, 1999b) then construct quadrangles and from them longer road objects also taking into account local context information. Gerke_WB in essence substitutes the Steger line extractor of the original Baumgartner et al. (1999a, 1999b) approach by the fully-fledged Wiedemann and Hinz (1999) approach and additionally puts less weight on the homogeneity in the direction of the road. Gerke notes that there is still room for improvement as he has not at all optimized the snakes used to bridge gaps.

- Jose **Malpica**, Subdirección de Geodesia y Cartografía, Escuela Politécnica, Campus Universitario, Alcalá de Henares, Spain: The approach of Malpica and Mena (2003, 2005) makes heavy use of the spectral and color characteristics of roads learned from training data. The latter is usually generated based on (possibly outdated) GIS data from the given image data. The basic image analysis for road extraction is done on three statistical levels. In the first level, only color information is employed using Mahalonobis distance. On the so-called "one and a half order" statistical level, the color distribution is determined for a pixel and its 5 x 5 neighborhood and compared to the learned distribution via Bhattacharyya distance. Bhattacharyya distance is finally also used on the "second order" statistical level where, for six different cross-sections of a 3 x 3 neighborhood of a pixel, co-occurrence matrices and from them 24 Haralick features are computed. The three statistical levels are normalized and combined employing the Dempster-Shafer Theory of Evidence. After thresholding and cleaning, the derived plausibility image for roads is the basis for deriving the main axes of the roads. A standard skeleton showing all, including the usual unwanted details, is combined with a coarse skeleton to obtain a graph with precise road segments without too many wrong short road segments. The segments in the graph are finally subject to a geometrical as well as topological adjustment.

- Karin **Hedman** and Stefan Hinz, Chair for Photogrammetry and Remote Sensing, Technische Universität München, Germany (see also Appendix 7): Like Bacher's and Gerke's approaches this again rests on (Wiedemann and Hinz 1999). It has only been tested for the smaller pieces cut from the Ikonos images. As Hedman and Hinz found that the line extraction is the critical point, they have optimized it: First, they noted that the blue channel gives the best results, with the NDVI adding little, but complimentary, information particularly for the rural areas. For Ikonos3_sub1 they found that it was advantageous to use two different scales for line extraction in the blue channel.

- Qiaoping **Zhang** and Isabelle Couloigner, Department of Geomatics Engineering, University of Calgary, Canada (see also Appendix 8): The approach is used with minor modifications for all test images (they produced results for all images besides the larger Ikonos images). For the more high resolution test data the images were rescaled by a factor of two (Aerial) or four (ADS40). At the core of the approach of Zhang and Couloigner is the K-means clustering algorithm with the number of classes set to an empirically found value of six. For most of the images three channels were used. The infrared channel was only employed for Ikonos1_sub1; for the other two Ikonos images it was regarded as too noisy. From one or more clusters the road cluster is constructed by a fuzzy logic classifier with predefined membership functions (Zhang and Couloigner 2006a). The road cluster is refined by removing big open areas, i.e., buildings, parking lots, fields, etc., again by means of a fuzzy classification based on a shape descriptor using the Angular Texture Signature (Zhang and Couloigner 2005a, 2006b). Road segments are found from the refined clusters via a localized and iterative Radon transform with window size 31 by 31 pixels with improved peak selection for thick lines (Zhang and Couloigner 2005b, 2005c). The segments are grouped bridging gaps smaller than five pixels and forming intersections. Finally, only segments longer than twenty pixels are retained.

The results of the evaluation are summarized in Table 1. It is ordered in the first instance according to the test areas (from analog to digital aerial to satellite data) and in the second instance alphabetically according to the group and possibly its approaches. For each test area where more than one result is available, the best result in terms of the geometric mean of completeness and correctness is marked in bold. In addition, all values for completeness or correctness, which are beyond a value of 0.6 or 0.75 respectively, are marked in bold. These numbers can be seen as a lowest needed limit so that the results become practically useful. The value for correctness was set to a higher value as experience shows that it is much harder to manually improve given faulty results than to acquire roads from scratch. To be of real practical importance, in many cases both values probably need to be even higher, e.g., for correctness around 0.85 and for completeness around 0.7, but we have chosen the lower values, to distinguish 'the probably useful' for the obtained results from the rest.

In Figures 1 to 10 we give one result for every image, besides the details from Ikonos3. Only for the latter have we obtained a larger number of results in the range beyond 0.85 for correctness and 0.7 for completeness deemed suitable for practical applications. Also because of that, we show some of the results for Ikonos3 and its details in Figures 5, 7, and 10 using a larger size. As the result for Beumier for Ikonos1_Sub1 is very interesting and the result of Gerke_WB for Aerial3 is definitely above 0.6 and 0.75 for completeness and correctness, we also present them larger in size in Figures 6 and 2.

Figure 1: Aerial1 – Zhang (left), Aerial2 – Gerke_WB (right); correctly extracted roads are given in green, incorrectly extracted roads in blue, and red marks the part of the ground truth for roads which could not be extracted.

Name (**best**)	Test area	Completeness (≥ **0.6**)	Correctness (≥ **0.75**)	RMS [pixels]
Gerke_W	Aerial1	0.46	0.47	3.74
Gerke_WB		0.31	0.56	1.53
Zhang (Fig. 1)		0.51	0.49	1.92
Gerke_W	Aerial2	0.76	0.66	2.87
Gerke_WB (Fig. 1)		0.65	0.82	1.14
Zhang		0.67	0.49	1.72
Gerke_W	Aerial3	0.81	0.63	3.14
Gerke_WB (Fig. 2)		0.72	0.77	1.3
Zhang		0.72	0.63	1.66
Zhang (Fig. 3)	ADS40_1	0.56	0.48	2.80
Zhang (Fig. 3)	ADS40_2	0.45	0.3	2.58
Gerke_W (Fig. 4)	Ikonos1	0.49	0.36	1.83
Gerke_W (Fig. 4)	Ikonos2	0.59	0.10	1.95
Bacher (Fig. 5)	Ikonos3	0.55	0.35	1.56
Gerke_W		0.62	0.16	1.57
Bacher	Ikonos1_Sub1	0.34	0.66	1.29
Beumier (Fig. 6)		0.48	0.69	1.3
Gerke_W		0.27	0.41	1.89
Gerke_WB		0.19	0.49	1.91
Hedman		0,31	0,51	1,25
Malpica		0.25	0.74	1.13
Zhang		0.56	0.41	1.52
Bacher (Fig. 7)	Ikonos3_Sub1	0.81	0.87	0.97
Gerke_W		0.8	0.65	1.53
Gerke_WB		0.68	0.75	1.99
Hedman (Fig. 8)		0.77	0.78	1.16
Malpica (Fig. 8)		0.6	0.79	1.41
Zhang		0.72	0.35	1.22
Bacher (Fig. 9)	Ikonos3_Sub2	0.86	0.89	1.
Gerke_W		0.75	0.52	1.35
Gerke_WB (Fig. 9)		0.71	0.84	1.7
Hedman (Fig. 10)		0.85	0.91	1.19
Malpica		0.6	0.89	1.59
Zhang		0.7	0.34	1.18

Table 1: Results of the evaluation. Bold names represent the best result in terms of the geometric mean of completeness and correctness for a test area where more than one result is available. Bold numbers are beyond 0.6 or 0.75 for completeness or correctness, respectively.

5 Analysis of Results

We focus the analysis on the details from the Ikonos images, as it is only for these smaller images that we have received a larger number of results. We comment on the images, discuss the individual approaches, and after giving important overall findings we end up in a short summary.

For the different images, we observed the following:

- **Aerial1-3**: All three images have only been processed by Gerke and Zhang. The latter performs best for Aerial1 (Figure 1), which is the most difficult of the three images showing a suburban area. It seems that for it the loss of information by down sampling by a factor of two by Zhang is more than made up by employing color information via classification, a feature Gerke is lacking. Gerke_WB gives the best results in terms of completeness and correctness for images 2 (Figure 1) and 3 (Figure 2) showing rural areas for which it was designed. Particularly the result for Aerial3 shown in Figure 3 is on a level which could be a viable basis for a practical application. Finally, comparing the results for Gerke_W and Gerke_WB one can see nicely how for Gerke_WB completeness is still sacrificed for correctness even when introducing additional information in the form of the homogeneity in the road direction for the original high resolution imagery.

Figure 2: Aerial3 – Gerke_WB; colors cf. Fig. 1

- **ADS40_1 and 2**: Results for both images (Figure 3) have only been produced by Zhang after down sampling them by a factor of four, thus not making full use of the available information. The results for both are not practically relevant, but one can observe that the performance for the easier rural image 1 is better than for the suburban image 2 where less than one third of the roads are correct and less than half of the roads have been found.

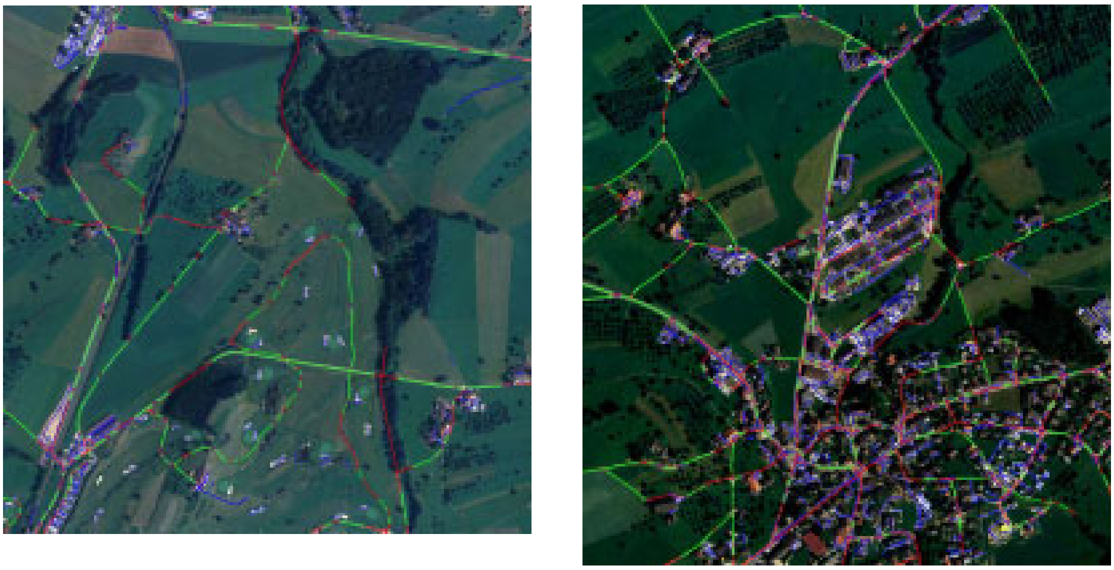

Figure 3: ADS40_1 – Zhang (left), ADS40_2 – Zhang (right); colors cf. Fig. 1

- **Ikonos1, 2, and 3**: Gerke_W was the only approach for which we received results for all three Ikonos images. Bacher who, in this case, basically uses the same approach as Gerke_W, but with different parameter settings, only processed Ikonos3. The results for Ikonos 1 (Figure 4) and 3 have been approximately as expected. Completeness and correctness for the suburban, i.e., more difficult Ikonos1 are lower than for the rural Ikonos3, with Bacher (Figure 5) achieving a more complete, but also more incorrect result. Ikonos 2 has proved more difficult than expected as demonstrated by the results (Figure 4). It is a rural scene with medium complexity, but a combination of different complications such as trees alongside the roads and small and elongated fields together with the low quality of the image possibly due to haze in the atmosphere resulted in a very high number of false hypotheses for roads, bringing down the correctness to a mere 10%.

Reasons for an inability to process the larger Ikonos scenes were apparently twofold. First, because of missing functionality for processing the whole image in patches which are then combined into one solution, intermediate results just exceeded the available memory. Second, even if this had not been the case, the time it takes to process the image together with the need to adapt the parameters to all variations in the larger scenes, meant these images required too much effort for most people. One gets a hint for the latter when comparing the results for the whole scenes Ikonos1 and 3 with the much better results for the relatively representative sub-areas, described below.

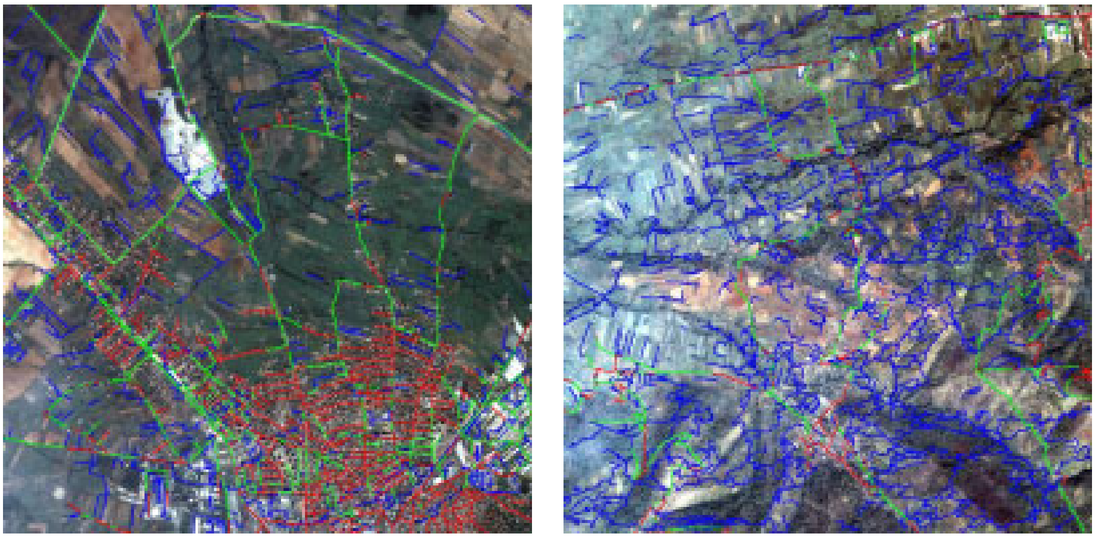

Figure 4: Ikonos1 – Gerke_W (left), Ikonos2 – Gerke_W (right); colors cf. Fig. 1

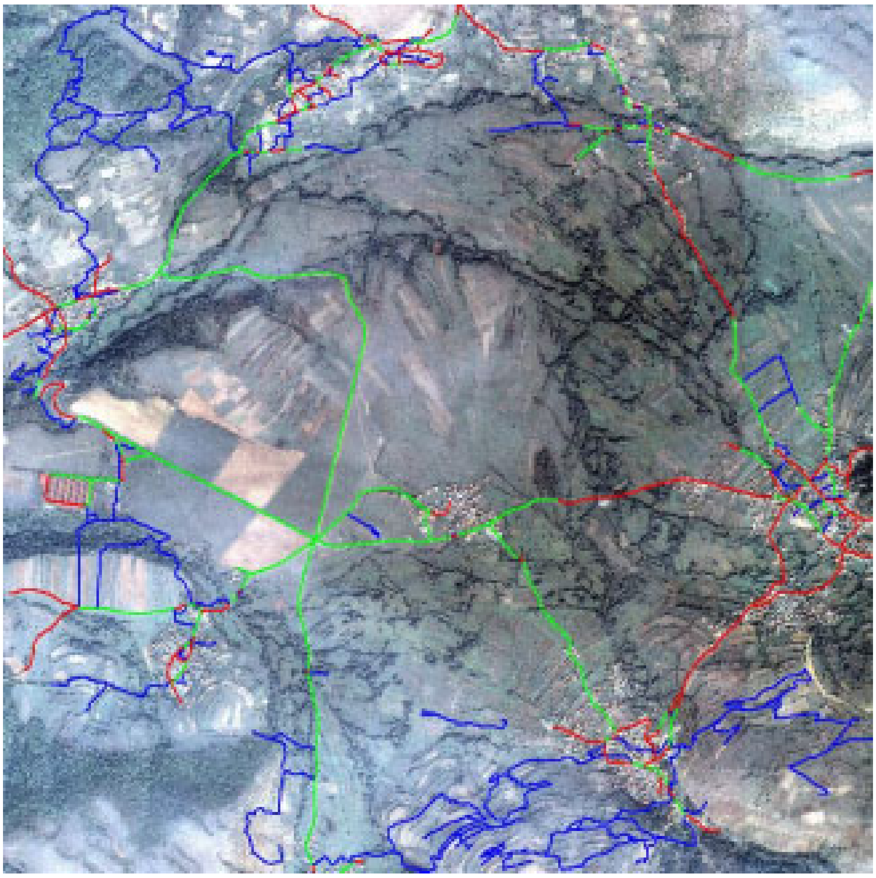

Figure 5: Ikonos3 – Bacher; colors cf. Fig. 1

- **Ikonos1_Sub1**: This image shows an urban/suburban scene and has been processed by six approaches, none giving a practically useful result. It seems to be too hard a challenge for the current approaches, although one has to notice that the results are notably better than for the whole scene, i.e., Ikonos1, from which it is a representative part. Beumier has only submitted this one result, but it is the best for this scene (Figure 6). It shows that a good line extractor combined with spectral information (NDVI) and well chosen constraints on the geometry can produce a pretty good result. Multiplying completeness with correctness gives a similarly high value for the approaches of Bacher, Malpica, and Zhang. Looking at the individual results, however, one can very well see the different trade-offs one can make particularly for difficult images between completeness and correctness. Yet for practical applications, the high correctness values for Bacher and Malpica would probably be preferred.

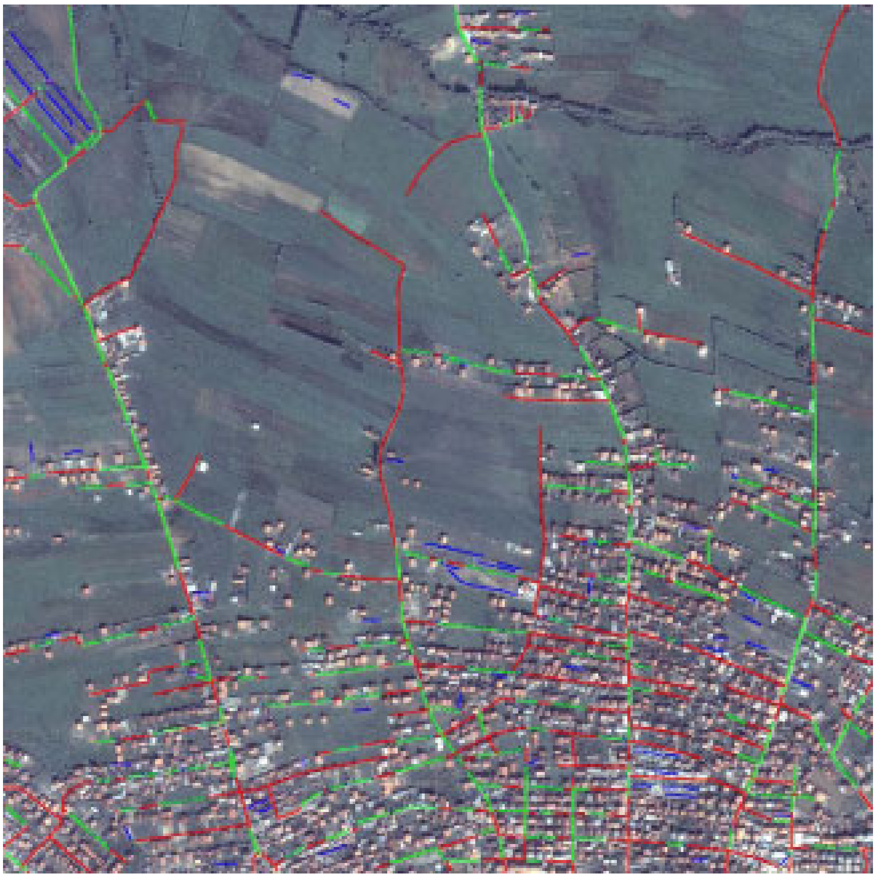

Figure 6: Ikonos1_Sub1 – Beumier; colors cf. Fig. 1

- **Ikonos3_Sub1 and Sub2**: These two images depicting rural scenes of medium complexity are the only ones for which a larger number of approaches, namely six, was applied and for which at least some of the results are in a range, which could be suitable for a practical application. This is particularly true for the approaches of Hedman and Bacher. Both rest on the approach of Wiedemann and Hinz (1999) and both make use of color information, Bacher in a more sophisticated way than Hedman. While Bacher has a clear edge for Sub1 (Figure 7), Hedman is slightly better on Sub2 (Figure 10 – please find the other images in Figures 8 and 9). Gerke's approaches also rest on (Wiedemann and Hinz 1999), but are less sophisticated in the way they make use of the color information, which seems to be a clear disadvantage here. While for Sub1 Gerke_W and WB perform very similarly, Gerke_WB taking into account the homogeneity of the road in the original resolution is markedly better on Sub2 (Figure 9). For the approaches based on color and texture Malpica achieves a higher quality particularly in terms of correctness than Zhang. This is especially true for Sub1 (Figure 8). Finally, a comparison of the results for Bacher and Malpica in Figures 7 and 8 shows the benefits of global network optimization inherent in all approaches based on (Wiedemann and Hinz 1999) together with snakes for bridging gaps. It is clearly visible that in Bacher's result many smaller gaps are bridged meaningfully.

We next comment on distinct characteristics of the individual approaches, if they have not been discussed already with the images.

- **Bacher, Gerke_W and _WB, and Hedman**: All three follow Wiedemann and Hinz (1999), the difference being which additional information is used. Bacher, with classification based on automatically generated training data is the most sophisticated and achieves the best results, but also Hedman's suitable selection of channels and scales as well as the use of the NDVI is sufficient to outperform Gerke_W and _WB, which do not make explicit use of color.

- **Gerke_W versus WB**: Gerke_WB can be seen as an extension of Gerke_W, taking into account higher resolution information in the form of parallel edges enclosing a region homogeneous in the direction of the road. Gerke_WB enforces more detailed constraints and, thus, as expected, the results for it show a lower completeness, but a higher correctness. This is true in all cases, but Gerke_WB seems to be particularly well suited for open rural scenes, where the roads mostly match its model of homogeneous areas.

- **Malpica and Zhang**: Both employ a classification approach using color or multispectral information, though in a different way. While Malpica also includes textures and learns the characteristics from given GIS data, Zhang uses an unsupervised classification. Malpica outperforms Zhang for the Ikonos data, but Zhang is more flexible with the unsupervised classification producing results for most images.

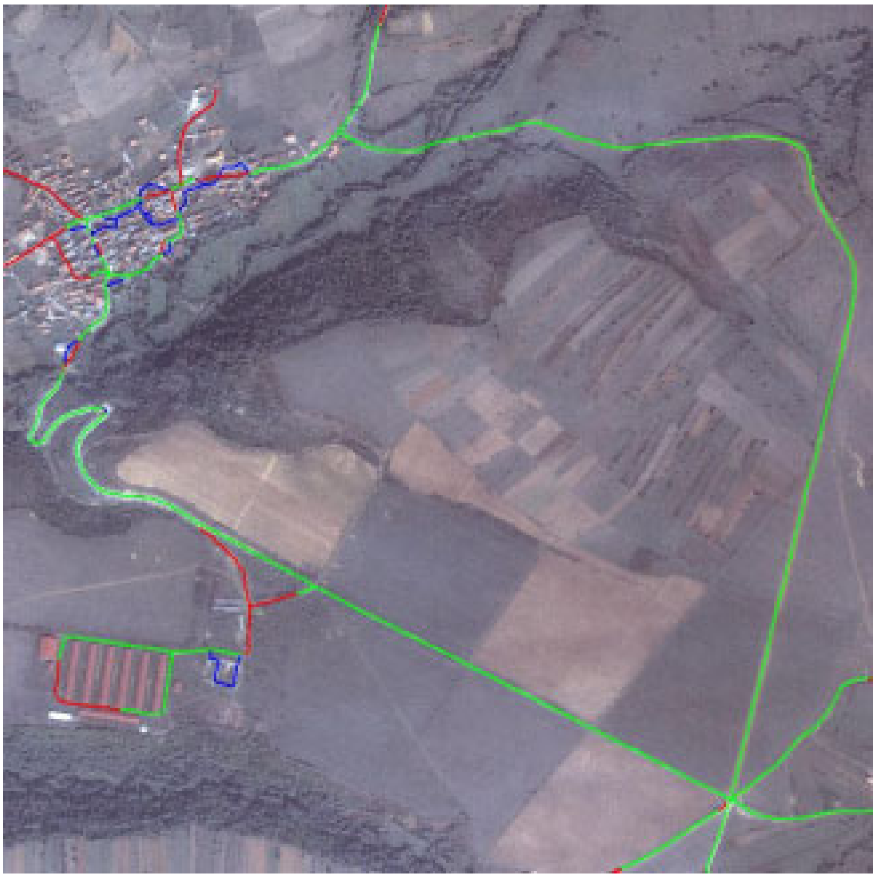

Figure 7: Ikonos3_Sub1 – Bacher; colors cf. Fig. 1

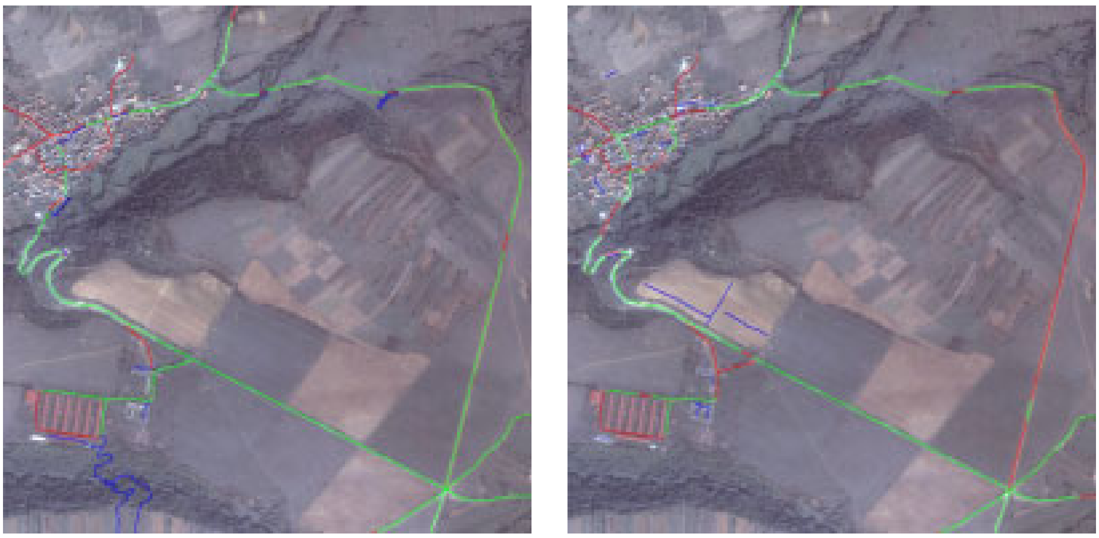

Figure 8: Ikonos3_Sub1 – Hedman (left), Ikonos3_Sub1 – Malpica (right); colors cf. Fig. 1

Figure 9: Ikonos3_Sub2 – Bacher (left), Ikonos3_Sub2 – Gerke_WB (right); colors cf. Fig. 1

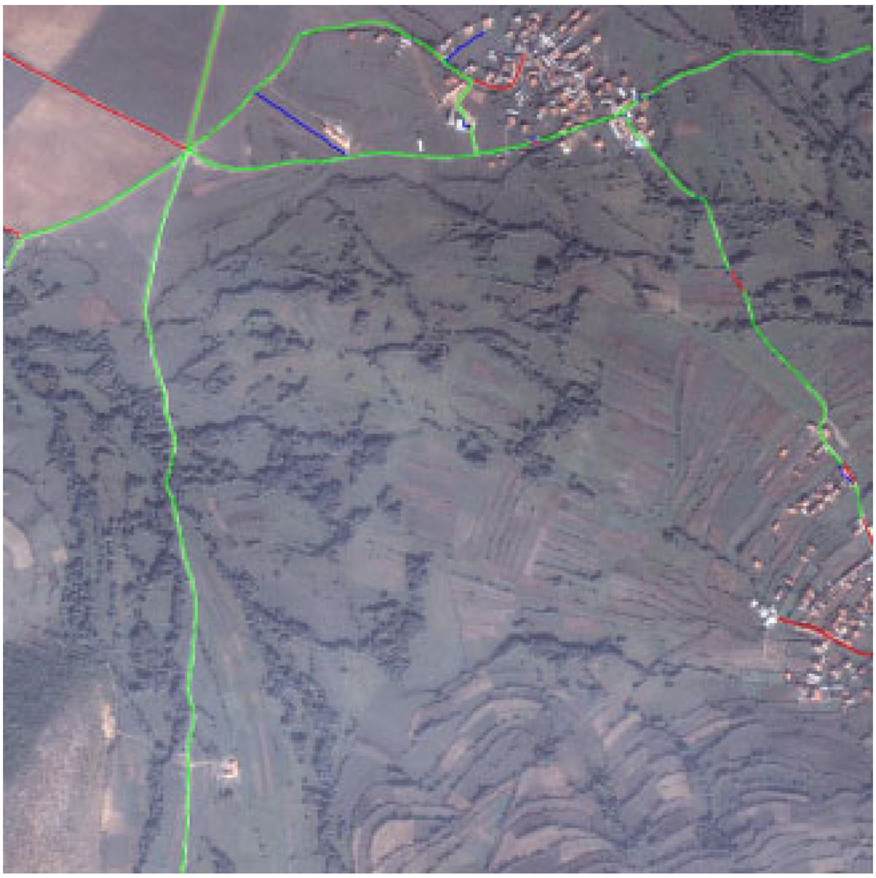

Figure 10: Ikonos3_Sub2 – Hedman; colors cf. Fig. 1

Finally, we want to note some important overall findings:

- The approaches based on line extraction, i.e., Bacher, Gerke_W, Gerke_WB and Hedman based on the Steger extractor as well as Beumier built on top of Lacroix's work give better results for the more line-like high resolution Ikonos data than approaches based on pixel-wise or local classification, i.e., Zhang and Malpica. It would be interesting to see how the latter perform on higher resolution aerial images where the line structure of the image is less marked and the spectral information should be of higher quality. Please note that the Ikonos data are pan-sharpened with a physical resolution for the color of only 4 m. One issue still to be investigated is the use of the original low resolution images.

- There is a trend to use color / multispectral information particularly for high resolution satellite data. This is done either as simple as the NDVI (Beumier and Hedman) or based on a more or less sophisticated classification (Bacher, Malpica, and Zhang). For the latter, training is done using given GIS data (Malpica), training areas are automatically generated from characteristic homogeneous road parts with parallel road sides (Bacher), or the classification is done unsupervised (Zhang).

- Network optimization and bridging gaps, e.g., by means of snakes, only seems to become important when a certain level of quality has been reached as, for example, by Bacher for Ikonos_Sub1 and 2.

In summary, the results show that it is possible to extract roads with a quality in terms of completeness and correctness which should be useful for practical applications, although only for scenes with limited complexity, namely up to medium complex rural scenes. This is true for aerial as well as high resolution satellite data. The test has also demonstrated that most approaches cannot deal with images larger than about 2,000 by 2,000 pixels at the moment. This is probably due to missing functionality to process images in patches and shows that the approaches focus on furthering the understanding of the basic problems rather than on practical development, where robustness to all possible situations would be the central issue.

With the advent of digital aerial cameras and high resolution satellite data making high quality color and spectral information available, there is a recent focus in research on road extraction to employ this information and the results show its usefulness. However, particularly for the high resolution data such as from the ADS40, there is still much to be done, e.g., by making use of the link to the typical materials used to construct roads or by employing line-finders that make full use of color information.

Additional remarks: One of the reviewers of this report suggested a cross-analysis of the data, i.e., results of the extraction. The idea would be to analyze in detail where the approaches produce the same or similar results and where and how they differ, to find complementary strengths. We had this in mind when starting the test, but finally decided not to analyze the data on this level. The main reason for this is that from what we know the different groups put very different effort into generating the data. Thus, while the data can be used for an overview, we think that analyzing it in depth would lead to an over-interpretation. To still give the possibility for a more in-depth analysis, we have published all data visually on our web-page.

6 Conclusions and Recommendations

The original proposal of the working group was much more focused on practical aspects. We not only wanted to make available a priori data to be used in the test, but also wanted to test semi-automated approaches. Unfortunately just obtaining the data actually used in the test proved a major issue taking more than two years, tens of Emails and phone calls, as well as lots of efforts by people at ETH Zurich, University of the Bundeswehr, and Leica Geosystems. Concerning a priori data we found already in the questionnaire that it is not of major interest for the mostly research oriented approaches. Additionally, opposed to image data which anybody can handle, a priori data is mostly vector data which comes in many formats with none being easily readable by everybody. Because of these two reasons we decided not to make available a priori data, although it exists for some of the datasets.

Similar concerns are valid for semi-automated approaches or automated approaches including pre- and post-processing. First, the interest from the participants was not high. Then, it is not clear what to test. From a practical perspective one wants to achieve a certain quality – which one might be able to define in terms of completeness, correctness, and RMS – and then the main issue is to acquire road data as fast and particularly cheap as possible. For this case one would need to do the test in production environments with experienced operators to obtain a reliable estimate of the ultimate performance. These environments do not exist from what we know. Additionally, they would be often specialized to certain types of landscapes existing in the respective country and thus it might be difficult to transfer results and conclusions. Because all of this we did not test semi-automated approaches.

Both, the use of a priori data as well as for practical semi-automated or automated approaches with pre- and post-processing, will become important (possibly even in the near future), but to define tests for them which give results that are mostly unbiased and give a clear message to the user we still see a couple of issues on the research side.

We planned to publish the findings in conferences or in a theme issue of an international journal. Due to the changed situation of the authors focusing much more on close range and computer vision (Helmut Mayer) or even leaving the University (Uwe Bacher), we are glad having at least managed to write a paper summarizing the main results of the test (Mayer et al. 2006).

The test has shown once again that the focus of the research is mostly on theoretic issues, often neglecting practical issues. We, therefore, had originally envisaged that the above activities and international cooperation would help to create a nucleus of interested researchers who, with the cooperation of NMCAs and, if possible, manufacturers, could form a well-coordinated and focused research network with milestones, commitments, and – most important – the necessary resources which can speed up the development of operational (or quasi-operational) systems for road extraction. We at Bundeswehr University Munich hope that other people will take up this idea and make it finally work. We do not have the resources to do so at the moment.

We finally learned the very hard way that it is extremely important to see as very long term what emerged as the core of our work, namely the evaluation of the results for different approaches based on the same data. The initial setup of the working group was very naive in this respect. Experience for similar tests, such as the highly successful 3D reconstruction test of Scharstein and Szeliski (2002) only gained momentum after some time. The goal has to be that, after a while, papers proposing a new approach only get accepted for higher level conferences when they show comparable or improved results on the test data compared to the state of the art.

It is, thus, very important to continue the test, even though we do not have the resources any more. We, therefore, hope that we can transfer our test. We have started discussing this issue with ISPRS working group III/5 “Road Extraction and Traffic Monitoring” chaired by Uwe Stilla, TU München, and Chunsun Zhang, South Dakota State University, USA. As the recent situation where Uwe Bacher runs the scripts manually and sends out the results via Email by hand is neither good in terms of work load nor response time for anybody interested in the evaluation results, the idea is to set up a web service to which one sends the results and gets back the evaluation.

Finally, we see promising directions for future research such as appearance based approaches, e.g, (Leibe and Schiele 2004), which might not be so easily adapted for roads themselves, but which have shown good results for cars, defining roads particularly in urban areas. Even more interesting might be statistical generative modeling. A particularly impressive example is (Dick et al. 2004) for buildings, but Stoica et al. (2004) have employed it for roads. To our knowledge this is the first time that the natural variability of the road network has been modeled in a realistic way. This is of big importance as the modeling of the network topology including the detailed characteristics of crossings is an area where not much research has been conducted.

Additional remarks: One of the reviewers of the report sees a trend for the NMCAs in the acquisition of very high resolution aerial imagery in the decimeter range. From it, highly detailed information including separate lanes and road marks could be acquired with very short update cycles. For this, a high degree of automation would be the only way to proceed. We agree with this, but note that we are not aware of any research on road extraction focused on this type of imagery at the moment.

A reviewer of (Mayer et al. 2006) pointed on several issues not discussed so far which should be taken into account for a follow up of the test. One issue is certainly how much parameters are allowed to be tuned. Particularly for smaller image sizes optimal sets of parameters might be more important than the approach applied. On the other hand, the images are fairly different and a single set of parameters might lead to very unfavorable results. An issues closely linked to this is if the ground truth is given out to the participants, possibly together with the code used for evaluation. This can on the one hand be used by the participants to find out about good parameter settings but also strategies by running multiple trials. On the other hand it can lead to approaches that just perform well for the given couple of images. Depending on the state of the field both issues have their pros and cons. Concerning the ranking it was proposed to have one official criterion (the geometric mean of completeness and correctness is one, although it needs to be discussed further) for overall ranking, but to also give the user the possibility to see the ranking according to individual criteria, such as completeness.

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Appendices

Appendix 1: Project Proposal

Proposed OEEPE Project

Automated extraction, refinement, and update of road databases from imagery and other data

Proposal for an OEEPE test of Commission II "Image analysis and information extraction"

Background and motivation

Extraction of topographic objects from aerial and satellite imagery has been the topic of intense research over the last decade. The main objects to be extracted include: digital surface models (DSM) and digital terrain models (DTM), buildings, roads, and other thematic objects, such as agricultural fields. The data used are mainly aerial imagery. Mostly film is utilized, but more and more also digital cameras are employed, with increasing use of color and color infrared (CIR). Additionally, new sensors such as airborne laser scanning (ALS), airborne SAR, and to a lesser degree hyperspectral and thermal sensors, as well as high-resolution satellite imagery play an important role. This is in contrast to classical spaceborne sensors, which are used more on the extraction of broader classes and landcover/landuse. Additional data, such as a priori information from maps, GIS and cadaster, have been used to support the extraction process, albeit in a limited fashion, by restricting the search space. Regarding methodology, most research efforts are aimed at automating the extraction of the above objects.

Major research tendencies for automated object extraction include: use of more than two images, early transition to 3D, use and combination of multiple cues and multiple algorithms for the detection and extraction of objects, object models at various levels of detail and generality, use of *a priori* information in the form of existing data, utilization of extended context and constraints, use of multi (-sensor, -temporal, -spectral, -scale) approaches. The various research groups involved can be divided into three classes: (a) those coming from geomatics, geodesy, and photogrammetry, (b) computer vision groups, often working for military projects, but without much practical experience, (c) Remote Sensing (RS) oriented groups, employing mainly spaceborne data for various applications. In spite of intense research efforts, very few results have reached an operational stage and have been employed in practice, with the exception of advances in DSM/DTM extraction as well as landcover/landuse classification, and the development of useful tools for semi-automated building extraction. Full automation is currently practically impossible for almost all applications. However, very few researchers realized this and focused on performance improvement via genuine semi-automated methods. Another important factor hindering the practical use of automated procedures is the lack of reliable measures indicating the quality and accuracy of the results, thus necessitating lengthy and cumbersome manual editing.

For roads, although they are much better structured and more homogeneous in their appearance than buildings, no practically useful semi-automated tools for their extraction have yet been developed. Lack of focused international cooperation has led to wide repetition of efforts, development of theoretical frameworks that do not work, and small advances in practice. Manufacturers of commercial systems have developed very few tools for the semi-automated extraction of the above objects, and their cooperation with academia has been minimal. Thus, users and producers of such data, including national mapping agencies (NMCAs) and large private photogrammetric firms, have been left with many wishes to be fulfilled.

On the other hand, the need for accurate, up-to-date, and increasingly detailed information (including various attributes) for many topographic objects, primarily buildings and roads, has rapidly increased. Roads in particular are needed for a variety of applications ranging from provision of basic topographic infrastructure, over transportation planning, traffic and fleet management and optimization, car navigation systems, location based services (LBS), tourism, to web-based applications and virtual environments, etc. Roads also constitute an important component of the increasingly requested and used 3D City Models. NMCAs in Europe increasingly plan to update their maps in shorter cycles. Many aim at the development of a landscape/topographical database from which cartographic data will be derived, and plan to add 3D information for important objects such as roads and buildings. Their customers have increasing demands regarding the level of accuracy and object modeling completeness, and often request additional attributes for the objects, e.g., the number of lanes for roads. That the interest of NMCAs and large firms in automated tools is high has been exemplified by the Swiss Federal Office of Topography (L+T), the Belgian national geodetic institute (NGI), and the Japanese firm PASCO regarding the system developed within the ATOMI project of ETH Zürich and L+T. Other projects are performed by the University of Hannover for the German Bundesamt für Kartographie und Geodäsie (BKG), or Technische Universität München (TUM) and the University of the Bundeswehr (UniBw) Munich for the German military survey. While road extraction has sometimes been performed by digitizing maps, road update and refinement usually can only be performed from aerial imagery, while some ground-based methods including mobile GPS are also important.

The insufficient and inefficient research output and increasing user needs, necessitate appropriate actions. Practically oriented research, e.g., ATOMI, has shown that an automation of road extraction and update is feasible to an extent that is practically very relevant. Companies that have developed semi-automated tools for building extraction and other firms too could very well offer similar tools for roads, even more as semi-automated road extraction is much easier and faster than building extraction. Thus, the central ideas of the proposed project are:

- To survey the data specification needs of important data producers, mainly NMCAs, and their customers.

- To thoroughly evaluate the current status of research (including models, strategies, methods and used data), to test and compare existing semi- or fully automated methods using various data sets and high quality reference data, to identify weak points and to propose strategies and methods that lead to a fast implementation of operational procedures for road extraction, update, and refinement. Although these latter three tasks are strongly interrelated and have many commonalities in used methods and data, the focus will be on update and refinement. Here, refinement means the improvement of planimetric accuracy, but also the addition of new information such as height and road attributes.

It is envisaged that the above activities and international cooperation will help create a nucleus of interested researchers who, with the cooperation of NMCAs and, if possible, manufacturers, can form a well-coordinated and focused research network which can speed up the development of operational (or quasi-operational) systems for road extraction. These systems could be integrated in commercial photogrammetric, RS, or GIS systems. Funding of such a research network could be from the 6th EU FP or other sources such as, for example, EuroGeographics.

Implementation

The project should be implemented by the formation of a working group (WG), with a proposed life-time of one and a half to two years from its constitution. It is proposed that the Chair/Co-Chair of the WG are respectively: Helmut Mayer, UniBW München and Emmanuel Baltsavias, ETH Zürich. The WG will recruit members among researchers active in the field, data producers and users, as well as commercial vendors. A list of potential interested groups has already being compiled. These groups will be informed of the aims and plans of the WG and will be asked for input to refine the aims and finalize activities. Concrete plans and activities include:

1. Establishment of a web-page with full and up-to-date information. The WG aims could be officially announced and presented (kick-off) at a planned workshop "Incremental Updating" before Intergeo, 14-15 October 2002, Frankfurt.

2. Distribution of a questionnaire to data producers and users mainly including NMCAs and firms producing digital road maps, especially for car navigation.

3. Distribution of a questionnaire to researchers in the field, including groups outside Europe.

4. Preparation of a report summarizing the outcome of points 2 and 3 and giving an overview and classification of existing methods and the state-of-the-art in the field, including an extensive literature review, for which much material has been already collected. Road modeling aspects as well as data structures, e.g., hierarchical, object-oriented, play a significant role for successful extraction and will be treated accordingly. Attribute information, although currently mainly neglected, may be of importance for generation of a rich and useful road database. Attributes could include width, number of lanes, road class, (coarse) surface material, road markings, etc. Attention will also be paid to related tasks such as automatic generalization and data mining. Knowledge about automated generalization may lead to a refined search space when starting from given generalized map data, while data mining or machine learning can discover and formulate properties hidden in existing road databases, which can be favorably exploited in the update and refinement. The results of this point will be preferably presented within a larger, already planned event such as the Joint ISPRS Conference "Photogrammetric Image Analysis", 17-19 September 2003, Munich.

5. Preparation and distribution of test data sets, including extensive documentation. At this stage, evaluation procedures for the results and quantitative quality measures should be elaborated and finalized before point 6 below.

The test and related data will be designed in a way that it will allow the participation of groups using various methods and data: single/stereo/multiple images, black and white (B/W)/color/CIR imagery, DSMs/DTMs stemming from photogrammetry or ALS, 2D/3D extraction, semi-/fully automated methods, etc. However, the test will clearly focus towards (3D) approaches that aim at operational procedures and the extraction of a large part of the road network and not just a few (isolated) road sides/edges. The input and output data requirements will basically comply with the needs of European NMCAs. For example, aerial color stereo film imagery of scale 1:15,000-1:30,000 will mainly be used together with existing DTMs and vector GIS/map data. To reduce the amount of data and simplify their processing and analysis, as well as for better focus, uncommon data, such as CIR, may be made available at a limited extent. The data will focus on low to medium difficulty cases, i.e., flat to hilly terrain, rural and suburban areas. A limited amount of urban data may be made available to demonstrate the limitations of some recent approaches. Accurate reference data, possibly with some attributes, like width, will be provided for the major part of the data set. If data from the new digital photogrammetric cameras is available sufficiently early, it will be integrated. For the provision of test and reference data, the support of NMCAs is a must. Such data already exist in Switzerland and

Belgium, provided by their NMCAs. High-resolution satellite data from Ikonos or Quickbird is considered at a considerably lower priority, as these data are not extensively available, their cost is high, their resolution often insufficient, and research on road extraction from these data limited.

6. Analysis of the submitted results investigating different aspects including: completeness, reliability, accuracy, main advantages/disadvantages of each approach, input data requirements and other conditions, especially the sensitivity of the results to the selection of the parameters, delivery of attribute information, again including completeness, reliability, and accuracy. In addition, qualitative analysis of the results, including stereo superimposition of derived vectors, will be performed. The contribution of NMCAs in this process is necessary. The coordinating center for the analysis will be UniBw München.

7. Presentation of the main WG work with a workshop towards the end of its life in a practically oriented event maybe at Institut Géographique National (IGN), Paris, or Institut Cartographic de Catalunya (ICC), Barcelona. The WG work can also be presented and combined with other similar work at other appropriate events, such as by dedicated technical sessions. Cooperation with ISPRS, especially WGs IC II/IV, III/3,4,6,7,8, IV/7 is absolutely necessary, while ties with IEEE GRSS Data Fusion Committee, and Earsel SIG Data Fusion will be exploited with lower priority.

8. Publication of a final report within the OEEPE official publications.

9. Possible coordinated publication of several papers or a theme issue in an international journal.

Time Plan

If the project and WG is approved at the OEEPE June meeting, the first five action points above should be finalized by the end of 2002. The performance and analysis of test results should be concluded by August 2003. The project work and WG could be concluded by the end of 2003.

Support and financing

The support of NMCAs for provision of data and evaluation of test results, especially manual control, are an important prerequisite. To cover expenses related mainly to organization of events and use of part-time personnel (especially students) for data preparation and analysis, an amount of 3,000 Euro is proposed.

Helmut Mayer and Emmanuel Baltsavias, June 4, 2002

Appendix 1.A. Possible interested groups

(incomplete, to be refined after project and WG establishment)

1. Academia/Research

Active or previously active in road extraction: University College London (Dowman, Muller), École National Supérior de Télécommunications (Maître, Roux), Univ. of Alcalá (Malpica), ETH Zürich (Baltsavias, van Gool), Univ. of Karlsruhe (Bähr), Research Inst. for Optronics and Pattern Recognition (FOM) (Stilla), Univ. Stuttgart (Fritsch, Haala, Walter), Univ. Hannover (Heipke, Liedtke, Sester), TUM (Ebner, Baumgartner, Wiedemann, Hinz), UniBw München (Mayer), Univ. Bonn (Förstner), TU Dresden (Fuchs), Univ. Haifa (Peled, Barzohar), TU Delft (Vosselman), Université des Sciences et Technologies de Lille (Jedynak), Royal Institute of Technology, Stockholm (Klang), Carnegie Mellon University (McKeown), University of Southern California (Nevatia, Price), Brown University (Cooper), Univ. of Main (Agouris), Univ. of New South Wales (Trinder, Sowmya), Sao Paulo State University, Brazil (Aluir Porfirio Dal Poz)

Other: Finish Geodetic Institute (HyppÄ, Sarjakoski), TU Helsinki (Haggren), TU Wien (Kraus), TU Dresden (Maas), Joanneum Research Center (Paar, Schardt), Univ. Massachusetts (Hanson, Riseman), DLR (Lehmann), Purdue Univ. (Bethel), OSU (Schenk), Austrian Research Centers, Seibersdorf (Steinnocher)

2. NMCAs

Switzerland (Käser), Belgium, IGN (Jung, Airault, Vignilo), ICC (Colomer, Torre), Ordnance Survey (Murray, Holland), Ireland, Sweden (Talts), Rikjswaterstaat, BKG (Grünreich), State Surveying Offices in Germany (Baden-Württemberg, Bayern, Niedersachsen, Nordrhein-Westfalen), Austria, Finland

3. System manufacturers and data producers

LHS (Miller, Stegmeier), Z/I Imaging (Dörstel), Inpho (Gülch), ESG (Ohlhof), Supresoft (Zhang), Racurs, Matra Systems, CyberCity AG (Steidler), ESPA (Lammi), Erdas, PCI, eCognition, ESRI, Intergraph, Space Imaging (Dial, Gibson), Earth Watch, ImageSat Int'l, Spot Image

4. Private companies and other

Car navigation data: TeleAtlas, Robert Bosch, Navtech

Large photogrammetric and engineering companies (focus mainly in Europe): EuroSense, Aerodata (Belgium), ISTAR (France), TerraImaging, KLM Karto, Fugro-Inpark (NL), Kampsax (Denmark), Hansa Luftbild (Germany), Swissphoto (Switzerland), Simmons Mapping, Aerofilms (UK), Finnmap (Finland), Lantmaeteriet/Metria (Sweden), Fotonor (Norway), Pasco, Kokusai, Asia Air Survey, Aero Asahi, Kimoto (Japan), ASI, Earth Data Int'l, Woolpert, Merrick, 3001 (USA), North West, Intera, Nortech (Canada), AAM Geoscan (Australia)

Appendix 1.B. Test and reference data

(incomplete, to be refined after project and WG establishment)

- Aerial film imagery
- Scale: 1:15,000, maybe also 1:30,000
- Focal length: 30 cm, maybe also 15 cm
- Color; B/W can be derived from color images; maybe CIR in suburban areas
- Terrain covered: flat to hilly, rural, forest borders, small villages, suburban, maybe
- denser city areas although with not very high buildings. Land cover should include water bodies.
- Scanning: high quality geometry, scan pixel size 10-15 microns, good radiometry and color rendition
- Camera calibration protocol or interior orientation parameters.
- Exterior orientation, preferably from bundle adjustment, however without use of additional parameters.

- Possibly only parts of images will be distributed to reduce data size.
- Some areas should include fourfold image overlap.
- Date and time of image acquisition for shadow analysis.
- DTM: As typically existing in Europe. Possibly also higher quality derived by ALS.
- DSM: Derived from matching and/or ALS.
- Orthoimages: It is an open question whether orthoimages should be generated using DTM or DSM.
- Optionally associated topographic maps in digital raster form for overview and other purposes, if possible divided in separate color layers, and at scale ca. 1:25,000
- Vector GIS or map information comparable to a scale of 1:25,000 including roads, forest boundaries, water body boundaries, (possibly administrative) built-up area boundaries. Data for roads should be topologically structured and include additional information, e.g., road classes and attributes such as width, existence, and type/color of road marks, etc. For road vector data, error statistics should be given, e.g., mean, RMS, maximum absolute error. For geometric attributes, such as width, mean, RMS, and range might be useful. Road data should preferably include medial axes and not the road sides/edges. If possible height information should be made available for the road points, e.g., by means of interpolation using a DTM or DSM. Railway lines, and small features like paths, small bridges, etc., should be excluded.

Formats for distribution of data should be common. For raster, simple and tiled TIFF, for vector, ASCII, DXF, DGN, Arc/Shape, etc., will be used. Details will be specified at a later stage. Multiple (2-3) formats for each data set may be used.

Appendix 2: Questionnaire for Producers of Road Data

This appendix gives the original questionnaire together with the single submitted answer (comments in Times font and selections as ■ - for affiliation we give the respondent's institution at the time of the completion of the questionnaire):

- Wolfgang Stößel, Bayerisches Landesvermessungsamt, Munich, Germany

This questionnaire is intended for producers of road data in large quantities, such as National Mapping and Cadastral Agencies (NMCAs), National Road Administrations (NRAs), large private firms generating road databases for navigation, etc. Some of these institutions not only produce data, but also use them for own products, e.g., maps, or they get the data from other sources, e.g., outsourcing. Though, they all specify the requirements that this data have to fulfill. Often they also sell the data to external customers, or receive data requests from them.

The response of the questionnaire will support the work of the WG as defined under "Motivation/Objectives" in the above WEB page, and in particular will help to determine (a) how road data are produced today and how they are planned to be produced in the near future; (b) what the specifications are for the road data incl. attribution; (c) what the road data requirements of various users and for various applications are. The results of the questionnaire will be analyzed, synthesized and made publicly available through various means, including an EuroSDR Official Report.

We plan to make the answers publicly available on our website. If you cannot accept this policy, please tick the field below.

General information

Corresponding Person
(First name, Surname):

Email:

Name of your institution:

Full address:

Country:

Phone number:

Fax number:

WWW address:

How many people are employed in your organization? 650

How many people of your organization are currently involved in road extraction? Give these in full persons, e.g., if two persons are involved 50%, give 1. 50

How much manpower was available over the last three years for road extraction (in man years)? 50

How many public organizations in your country are involved in acquisition of road data incl. their attributes?

Is there a cooperation and data exchange between these organizations and to what extent? yes

Please tick, if you do not want your answers to be published on the web ☐

A. How are road data produced by your organization today?

1. From aerial imagery (tick all that apply)

☐ Digitized aerial film ☐ Digital cameras

☐ Orthoimages ☐ Stereo images ☐ More than 2 images
Scale of aerial imagery
Focal length of the camera mm

Pixel ground resolution (pixel footprint) for digitized film, digital images, or orthoimage m

☐ Black/white ☐ RGB ☐ False color infrared ☐ More than 3 spectral channels (specify how many channels)

Data used for first acquisition of the data: ☐ yes ☐ no

Data used for data update: ☐ yes ☐ no
Which system is used (give product name, e.g., Zeiss Planicomp analytical plotter, LH Systems DPW770 digital photogrammetric station, etc.)?
List all systems used:

Is the processing:

Manual: ☐ yes ☐ no

Semiautomatic (specify which system is used): ☐ yes ☐ no

Automatic with possible subsequent editing (specify which system is used): ☐ yes ☐ no

2. From satellite imagery
List all sensors used:

☐ Orthoimages ☐ Stereo images
Pixel ground resolution (pixel footprint) m

All spectral channels used: ☐ yes ☐ no

Data used for first acquisition of the data: ☐ yes ☐ no

Data used for data update: ☐ yes ☐ no

Which system is used (give product name, e.g., Erdas Imagine, LH Systems DPW770 digital photogrammetric station, etc.)?
List all systems used:

Is the processing:

Manual: ☐ yes ☐ no

Semiautomatic (specify which system is used): ☐ yes ☐ no

Automatic with possible subsequent editing (specify which system is used): ☐ yes ☐ no

3. By terrestrial means
Specify here the system and methodology used, e.g., by using GPS van in open areas.

Kinematic GPS in a van

4. By digitizing maps or other plans:

Are ☐paper maps/plans used and/or ■digital ones

Specify the type of maps/plans used, e.g., topographic map, cadastral plan, etc.

DFK (digitale Flurkarte – cadastral map with some topographical contents)

Map/plan is ■B/W and/or ☐Color

Give the scale of the maps/plans

Is the digitizing:

Manual: ☐ yes ☐ no

Semiautomatic (specify which system is used): ☐ yes ☐ no

Automatic with possible subsequent editing (specify which system is used): ☐ yes ☐ no

5. By making use of existing road data from other databases
Please specify the type of road data used, and if known how they were produced.

(Governmental) Road construction agencies, municipalities

6. Please specify any other data not listed above, that are used for road extraction, e.g., airborne laser scanner with intensity, airborne radar, digital terrain model (DTM), digital surface model (DSM) including trees and buildings, etc. Give important specifications of the data and how road extraction is performed (e.g., from airborne radar data using the Star-3i system of Intermap, manual extraction using orthoimages with pixel footprint 0.5 m, etc.).

7. What is the average time difference of the time of the acquisition of the primary data from which the road data is generated to the time of road data acquisition? E.g., road data acquired in 2001 from aerial imagery flown in 1998 would have a time difference of 3 years.

3 to 6 months

8. What is the average age of the road data compared to now?
E.g., for 2002 and the above example, it would be 4 years.

about 1 year

9. Roads are extracted as:

☐ road edges or ■ directly as road centerlines including width?

10. Is height information included? ☐ yes ☐ no
If yes, how is height determined?

☐ Directly measured, e.g., in stereo images

☐ Derived from DTM

☐ Derived from DSM

11. Estimated geometric accuracy
Planimetry:

Mean error 1 m RMS error 1 m Maximum absolute error < 3 m
Height (if applicable):
Mean error – RMS error – Maximum absolute error
How are the above accuracy measures derived? E.g., from sample statistics using reference data, based on experience, etc.

estimated, based on experience

12. List below all additional information (attributes) derived, e.g., road class, number of lanes, road width, surface material, etc. For geometric attributes, e.g., road width, give the geometric accuracy with which this attributes are extracted and specify what the accuracy measures represent, e.g., RMS. For each attribute give its importance from a user/application point of view as low, medium, high.

road class (high), number of lanes (high), road width (high)

13. Is the road data topologically connected? ☐ yes ☐ no
If yes, how is the topology established?

☐ Automatically

■ Manually through post-editing

14. How are road classes defined?

☐ Based on a map object legend, e.g., highways, 1st class, 2nd class, etc.

☐ Indirectly, by using road width or other attributes. Please specify which.
List all road classes used, including dirt agricultural roads, paths, bridges, etc., but excluding railway lines and waterways.

according to ATKIS object catalog

15. What information is stored for road intersections? E.g., number of road segments meeting at intersection, detailed topology for instance of individual lanes.

Intersections only for highways

16. Is the road data cartographically generalized?

☐ yes ☐ no

17. Are bridges a separate class with start/end points? ☐ yes ☐ no

Are underpasses a separate class with start/end points? ☐ yes ☐ no

Are tunnels a separate class with start/end points? ☐ yes ☐ no

18. Is time information stored for the road data? ☐ yes ☐ no (approximately)

Is this the ☐time of primary data acquisition, e.g., of the aerial imagery and/or ☐time of road extraction

19. In some cases of automatic and semi-automatic road extraction it is useful to extract roads with different approaches depending on the land cover. Is the following data available at your organization to determine the land cover?

- forest boundaries ☐ yes ☐ no

- boundaries of water surfaces ☐ yes ☐ no

- coastlines ☐ yes ☐ no

- boundaries of settlements (villages, towns) ☐ yes ☐ no

- outlines of buildings (possibly generalized) ☐ yes ☐ no

20. If you use semi-automated or automated methods for road extraction:

- do these methods provide accuracy measures? ☐ yes ☐ no
- do these methods provide reliability measures (e.g., road definitely correct, definitely wrong, uncertain needing manual control)? ☐ yes ☐ no
If yes, how is the reliability derived?

How reliable are these reliability measures?

- what is the degree of completeness of road extraction (incl. possible errors) and for what land cover, e.g., 0% in forests, 90% in open rural areas, 50% in suburban areas with detached houses, 20% in dense urban areas

- what is the percentage of manual pre- and post-editing required, e.g., 70% automatic computer processing, 30% manual editing

21. Independently of whether road extraction is manual, or (semi)automated:

- Are the accuracy measures valid ☐global or ■for individual road segments?

- What is the acquisition time incl. both automated and manual processes per square km on a state-of-the-art computer for a region of average road density (e.g., mixed rural and urban)?

updating road data: approximately 0.5 hours per square km

- What computer operating system is used in the processes involved in road extraction?

■UNIX ☐Linux ☐Windows

22. What data formats are used for the road data incl. their attributes?

Internally: Intergraph; for exchange: NFF, shape, EDBS, DXF

23. What system is used for the storage and management of the road data?

Intergraph MG Dynamo

Is the system?

☐ Relational

☐ Object-relational

■Object-oriented

B. How does your organization plan to extract road data in the near/middle future?

If you plan any changes for the points listed under A, please explain them here.

Information provided by (governmental) road construction agencies; local topographers

When do you plan to implement the above changes? E.g., in 1-2 years.

at the moment (2002)

C. Customers and applications

List below all applications for which your organization is using the road data internally, i.e., excluding selling them to third parties.

Production of DTK 25 (digital topographic map 1 : 25 000)

List below all your current groups of customers and for each list the application and briefly describe the required road data. E.g., list geometric accuracy and attributes needed, how up-to-date the data should be, etc. For each required road attribute give its importance from a user/application point of view as low, medium, high. If, e.g., a group of customers are large transportation companies, the application is fleet management and optimization, and the requirements for the road data are: not older than 1 year, planimetric geometric accuracy 5 m RMS, no height information necessary. Attributes needed are road width (high), number of lanes (high), and surface material (medium).

Rescue services (fire brigades, police, ambulances) – navigation systems; mapping (city plans); engineering companies (urban planning, etc.)

List below all your potential groups of customers (only those that are safely potential customers, avoiding speculations) and for each customer, list the application and briefly describe the required road data. E.g., list geometric accuracy and attributes needed, how up-to-date the data should be, etc. For each needed road attribute give its importance from a user/application point of view as low, medium, high.

location based services (insurance companies, parcel service) geo marketing

D. Requirements of your organization on the data

Here, the desired requirements of your organizations should be listed if they differ from the current status listed under A. For each required road attribute give its importance from a user/application point of view as low, medium, high.

Please, add in the field below any additional remarks

Thank you for your collaboration

Appendix 3: Questionnaire for Researchers and Manufacturers

This appendix gives the original questionnaire together with a summary of the answers given (numbers on the right hand side, comments in Times font). The detailed answers on the general characteristics of the approaches can be found in Appendix 4.

The questionnaire was completed by the following people whom we want to thank very much (for affiliation we give the respondent's institution at the time of completion of the questionnaire):

- Chunsun Zhang, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland
- Jason Hu, Department of Earth and Atmospheric Science, York University, Toronto, Canada
- Oktay Eker, Photogrammetry Department, GCM. Ankara, Turkey
- Markus Gerke, Institute for Photogrammetry and Geoinformation (IPI), Hannover University, Germany
- Jose Malpica, Subdirección de Geodesia y Cartografía. Escuela Politécnica, Campus Universitario, Alcalá de Henares, Spain
- Christian Wiedemann, Chair for Photogrammetry and Remote Sensing, Technische Universität München, Germany
- Albert Baumgartner, cf. Wiedemann
- Stefan Hinz, cf. Wiedemann
- Arcot Sowmya, School of Computer Science and Engineering, University of New South Wales, Sydney, Australia
- Michel Roux, Ecole Nationale Superieure Des Telecommunications; Departement Traitement du Signal et des Images, Paris, France

Objectives and publication policy

The information gathered by means of this questionnaire will first of all be used to make available test data which optimally fits the interests of the participants. Yet, the result of the test is not only meant to show the strengths of the individual approaches. Together with the information collected from this questionnaire it will help to analyze the benefits of different models and strategies especially for different scene contents such as urban, suburban, as well as rural with concrete roads and rural with dirt roads.

We do not only intend to summarize our findings in an EuroSDR report, but we will also make available all results and answers to the questionnaires on the web page of the working group, if not stated otherwise by the participant.

Instructions for filling out the questionnaire
Please tick or answer as appropriate.

General information

Corresponding Person:

Email:

Your institution:

Full address:

Country:

Phone number:

Fax number:

WWW address:

How many people of your group are involved in road extraction?

1, 1, (30), 4, 2, 4, 4, 4, 2, 3

How much manpower was available over the last three years for road extraction (in man years)?

3, 1, (30), 3, 3, 8, 8, 8, 2, 2

Please tick, if you do not want your answers to be published on the web ☐

Road modeling

1. What kind of roads are modeled?

☐ Dirt roads [5]

☐ Rural narrow roads [8]

☐ Urban streets [6]

☐ Large Roads with complex crossings [2]

☐ Freeways including highly complex intersections [2]

☐ Others [0]

If others please specify:

2. What data is used?

☐ Black and white images [9]

☐ Color imagery [7]

☐ Color infrared (CIR) imagery [1]

☐ Multispectral aerial imagery [3]

☐ Panchromatic satellite imagery [5]

☐ Multispectral satellite imagery [4]

☐ Digital terrain models (DTM) from image matching or airborne laser scanning (ALS) [3]

☐ Digital surface models (DSM) from image matching or airborne laser scanning (ALS) [6]

☐ Other [2]

If others please specify:
Pan-sharpened Ikonos; date and daytime of image acquisition; SAR images

3. What ground resolution is basically employed?

☐ Less than 10 cm [2]

☐ 10 cm to 60 cm [3]

☐ 60 cm to 2 m [7]

☐ 2 m to 10 m [2]

☐ More than 10 m [2]

4. What local road characteristics are used?

☐ Roadsides are parallel edges; (perceptual) grouping [7]

☐ Homogeneity in the direction of the road; tracking [7]

☐ Scale-space behavior or roads; combination of lines in coarse scales and roadsides in fine scale [3]

☐ Markings and cars on the road [2]

☐ Cars on the road [1]

☐ Spectral characteristics of the road surface material [3]

☐ Other [1]

Please describe road modeling in more detail:

roads modeled as Steger lines; texture analysis; homogeneous ribbons with constraints on length, curvature and width; machine learning; verification based on profiles; grouping of hypotheses in DSM based on graph representation.

5. How is the smoothness of road trajectories modeled?

☐ Not at all [2]

☐ Splines (a) [2]

☐ Snakes (b) [2]

☐ Kalman-filter (c) [1]

☐ otherwise (d) [7]

If a) - d), please specify:

piecewise parabola; evaluation by fuzzy values based on length, straightness, constancy width, constancy gray value; robust polynomial adjustment; weighting of lines according to smoothness and collinearity during grouping; zip-lock ribbon snake, Bezier curve; smoothness via weighting by mean curvature; piecewise linear

6. How is the network character of roads modeled?

☐ Not at all [1]

☐ Local gaps are bridged. (a) [6]

☐ Global optimization of the network (b) [5]

☐ otherwise (c) [4]

If a) - c), please describe your modeling in more detail:

decision for grouping based on gap length and direction difference; graph data structure; global path search incl. analysis of path lengths; based on grouping criteria and local context – network enforced by simple crossing extraction; generation and weighting of connection hypotheses is based on local criteria (length, collinearity) – graph constructed from road segments and connection hypotheses – promising hypotheses from globally optimum paths – verification by checking homogeneity, shadow, or cars; network broken down in components on different levels, e.g. pairs of edges, junctions – compositional: add up to full network

7. What attributes are determined?

☐ Road class [4]

☐ Road width [9]

☐ Number of lanes [3]

☐ Width of lanes [2]

☐ Road markings [2]

☐ Surface material [2]

☐ Other (please list) [1]

height profile and intern quality measure

8. What types of crossings are modeled (in which way)?

☐ Simple crossings (3-4 road segments meeting at the intersection) [8]

☐ Complex crossings (more than 4 road segments meeting at the intersection) [2]

☐ Roundabouts [2]

☐ Highway exits [1]

☐ Highway intersections including over- and underpasses [0]

Please characterize type and modeling more in detail:

crossing = junction point and parts of neighboring road axes; modeled similarly as connection hypotheses – derived from graph representation

9. Is context made use of?

☐ Not at all [3]

☐ Different modeling of roads in urban, rural, and forest areas [6]

☐ Modeling of shadows and occlusions [4]

☐ Modeling of other objects or the whole scene (global or holistic modeling) [1]

Please explain in more detail:

mainly from buildings obtained by LIDAR data; adapt parameters to these three context classes; detailed model for rural areas only; potential occlusions and shadows from DSM via ray-tracing based on date / daytime information – shadows refined by extracting dark, homogeneous regions – DSM is also used to exclude locally high blobs and to limit search space for car detection (cars in DSM valleys)

10. How is GIS data employed?

☐ Not at all [7]

☐ To refine the search space [2]

☐ To actively verify roads. The reliance on the outdated road data is high. [1]

Please characterize the chosen policy in more detail:

road extraction in area of road objects using attributes and contextual information from the database – goal is to find evidence (if none is found, it is rejected); vectorial data from GIS used in supervised recognition on segmentation level; verification and update of GIS-data should be based on extraction independent of prior GIS data (noted three times) – GIS data mainly as context for adapting parameters and selecting specialized algorithms – could also be used to guide operator through result

11. How is 3D information used?

☐ Not at all [4]

☐ Road has smooth 3D surface and limited steepness. [4]

☐ Information from DSM generated by image matching or ALS is used. [5]

☐ Road features are actually matched in two or more images. [0]

Please explain in more detail:

DSM from LIDAR for segmentation of open and building areas; only for determination of height for objects; weighting of extracted lines; detection of approximate shadow regions; to derive context information and to fuse lane segments extracted in multiple overlapping images (accuracy requirements low)

12. Precision and Reliability

☐ Is the precision of the result estimated? [3]

☐ Are the results labeled with a reliability flag and what criteria are used to derive this flag? [5]

☐ Is the reliability flag reliable and to what extent? [3]

Please explain in more detail:

no internal evaluation – comparison with objects from database; evaluation according to Wiedemann 1998; analysis of larger network parts according to smoothness etc.;each object attached with fuzzy quality value computed from features not used before, i.e., it is independent – experience: makes system less sensitive against improper parameter settings; standard statistical measures used to evaluate results at every stage and to tune the learning algorithms

13. Basic modeling and software tools used

☐ Object oriented programing (e.g., C++) [8]

☐ Explicit reasoning (e.g., semantic network or rule based system) [2]

☐ Automatic learning [1]

☐ Modeling of uncertainty (e.g., Bayes network) [3]

Please explain in more detail:

C++, delphi, etc.; modeling of uncertainty by Theory of Evidence; uncertainty: fuzzy logic; Semantic network is used to make knowledge explicit – concepts and relations are mapped to C++ class hierarchy – specialized extraction strategy including where to look for – uncertainty by fuzzy sets

14. Computer environment

☐ Windows NT, 2000, XP [6]

☐ LINUX [4]

☐ UNIX (please specify) [3]

SGI (IRIX), Solaris

Semi-automatic road extraction (only if applicable)

1. How could the basic strategy be categorized?

☐ Road tracking / following starting from a given point in a given direction (a) [2]

☐ Automatic determination of the road trajectory from manually given end points and possibly iteratively refined intermediate points (b) [0]

☐ Editing of the results of automatic extraction (c) [1]

☐ Combination of a) or b) with c) [0]

Please explain in more detail:

Seed points are sequentially given and extraction results emerge

2. If results of automatic road extraction are used:

☐ Is the automated processing restricted by given regions and attributes defined by the operator or derived from GIS data? [2]

☐ Are the results labeled with a reliability flag? [1]

☐ Is the reliability flag reliable? [1]

Please describe in more detail:

General characteristics of the approach (answers cf. Appendix 4)

1. Please summarize the key features of the approach:

2. What are the strong points of the approach?

3. What are the weaknesses or limitations of the approach?

4. How could the approach be optimally exploited in a practical application? How would the envisaged practical application look like?

5. What features do you see most important for an ideal system for practical (semi-automated) road extraction?

Test and reference data

Basic test data will consist of

-Aerial film imagery; scale: 1:15,000, maybe also 1:30,000; focal length: 30 cm, maybe also 15 cm; color - B/W can be derived from color images; maybe CIR in suburban areas; high quality scanning geometry; scan pixel size 10-15 microns; good radiometry and color rendition.

- High resolution satellite imagery: Pan-sharpened multispectral data from IKONOS and/or QuickBird.

- Terrain covered: flat to hilly, rural, forest borders, small villages, suburban, maybe denser city areas although not with very high buildings. Land cover should include water bodies. For less developed areas also dirt roads should be covered.

- Camera calibration protocol or interior orientation parameters

- Exterior orientation, preferably from bundle adjustment, however without use of additional parameters

- Some areas should include fourfold image overlap.

- Date and time of image acquisition for shadow analysis.

- DTM as typically existing in Europe. Possibly also DSM derived from matching and/or higher quality from ALS.

- Optionally associated topographic maps in digital raster form for overview and other purposes, if possible divided in separate color layers, and at about scale 1:25,000.

- Vector GIS or map information comparable to a scale of 1:25,000 including roads, forest boundaries, water body boundaries, (possibly administrative) built-up area boundaries. Data for roads should be topologically structured and include additional information, e.g., road classes and attributes such as width, existence, and type/color of road marks, etc.

- For road vector data, error statistics should be given, e.g., mean, RMS, maximum absolute error. For geometric attributes, such as width, mean, RMS, and range might be useful. Road data should preferably include medial axes and not the road sides/edges. If possible height information should be made available for the road points, e.g., by means of interpolation using a DTM or DSM. Railway lines and small features such as paths and small bridges should be excluded.

- Formats for distribution of data should be common. For raster, simple and tiled TIFF, for vector, ASCII, DXF, DGN, Arc/Shape, etc., will be used. Multiple (2-3) formats for each data set may be used.

Questions:

1. Are orthoimages or the original aerial/satellite imagery with multiple overlap including calibration and orientation information preferred?

☐ Orthoimages [4]

☐ Original Data [6]

Remark: orthoimages show strong distortions in urban areas

2. Is color or multispectral imagery needed or at least preferred?

☐ yes [7]

☐ no [3]

Remark: infrared would be helpful

3. Are GIS data needed or of importance?

☐ yes [5]

☐ no [5]

Remark: needed to verify results

4. Should orthoimages be generated?

☐ yes [7]

☐ no [3]

If yes, using:

☐ DTM and / or [2]

☐ DSM [4]

Remark: both; no ortho but DSM needed; for experiments and extending feature set

5. Is ALS information considered important for the test?

☐ yes [2]

☐ no [7]

Remark: yes, for urban areas; or DSM from other source; only for DSM; not really needed but interesting

6. Which vector formats can you handle?

dxf, Arc/Info shape file and others; Arc Info; Microstation DGN (IDGS) or kdms vector formats; Arc/Info coverage or ungenerate files; DGN, ARC-INFO generate; ArcInfo and home-made ASCII; ArcInfo; standard ArcInfo

7. There is a possibility to provide data from the new digital photogrammetric cameras using linear CCDs (e.g., ADS40). Such data can be provided only as orthophotos (no stereo or multiple images) but in several channels (panchromatic, RGB, NIR). Would you be interested in processing such data and to what extent?

☐ yes [7]

☐ no [3]

Remark: interested (PAN, RGB); test would be interesting, but low priority; willing to experiment

8. What else is important?

Orthoimages in RGB; DSM; lots of labeled/marked images for evaluation purposes

Test statistics

1. Are the road centerlines possibly augmented by the width the right basic information for deriving statistics for road extraction?

☐ yes [9]

☐ no [0]

Remark: we use centerlines from extraction algorithm for comparison with roads from database

2. What else besides completeness, reliability, accuracy, and parameters describing the global network topology could/should be quantitatively evaluated automatically?

crossings – completeness, correctness, RMS, # of connected roads); # of lanes

3. Is a qualitative visual inspection meaningful besides the automatic quantitative evaluation?

☐ yes [4]

☐ no [4]

Remark: could be useful to get rough idea of individual strengths and weaknesses, but not useful to derive meaningful ranking of different results; not enough detail to discriminate – e.g., eye joins broken lines

4. For semi-automatic approaches we propose to define the expected quality, i.e., level of detail, precision, and completeness, and then compare the timings for operator interaction and computing time. The achieved results would be evaluated automatically to make sure that the demanded quality is actually reached. Does this make sense?

☐ yes [6]

☐ no [0]

Remark: not only total interaction time is relevant, but also number and duration of breaks between operator's activities; in addition the time duration of interactions and automatic processing should be recorded in a table

Please, add in the field below any additional remarks

In order to compare different supervised methods, the same images should be used with the same training areas; when will the data be ready

Thank you for your collaboration

Appendix 4: General Characteristics of the Approaches

Chunsun Zhang

Key features: the approach extracts 3-D road network from stereo aerial images by integrating knowledge processing of color image data and existing digital geo-database. It uses existing knowledge, image context, rules and models to restrict search space, treat each road subclass differently, check the plausibility of multiple possible hypotheses, and derive reliable criteria, therefore provides reliable results

Strong points: 1. fusion of information from different cues 2. works directly in object space 3. different classes of roads are treated using different features 4. multiple cues are used to create redundancy to reduce the complexity of image processing, to account for errors, and to increase success rate and the reliability of the results 5. junctions are generated and modeled 6. almost all the roads in rural areas are correctly and reliably extracted

Weaknesses or limitations: the performance is poor in urban areas

Optimal exploitations in practical applications: the developed system will soon be used for 3-D road production in rural areas.

Most important features for practical road extraction: completeness and reliability

Jason Hu

Key features: 1. multi resolution method is used 2. a fast and template matching based algorithm is used - 3. hierarchical perceptual grouping approach

Strong points: before the grouping for segment linking, evaluating the saliency of the primitives and using a sequential grouping method make it more reliable

Weaknesses or limitations: need to integrating more informations on complicated texture and contextual for road extraction from dense urban area

Optimal exploitations in practical applications: it should be fused into a practical system seamlessly. easy-to-use and flexible.

Most important features for practical road extraction: to meet the demands in accuracy, robustness and interactivity so the efficiency. it should be integrated into a practical system (for digitizing etc.)

Markus Gerke

Key features: Verification/Falsification of roads in a database (no generalized data) - Making use of additional knowledge (context classes, attributes of roads)

Strong points: reliable results for rural areas -supports an operator: he/she has to focus attention just on objects where the automated process did not find a road

Weaknesses or limitations: success of extraction algorithm in dense urban areas or in forest areas depends on degree of occlusions -extraction of "new" roads reliable only in open landscape

Optimal exploitations in practical applications: It is a practical application (prototype running at the BKG (Federal Agency for Cartography and Geodesy, Germany)): It supports an operator in the verification process: he/she has to focus attention just on objects where the automated process did not find a road

Most important features for practical road extraction: Depending on the resolution of the target database:-reliable extraction of primitives -sophisticated grouping algorithms, but with an easy possibility of user interaction/post editing

Additional remarks: We are using the road extraction software from Christian Wiedemann, TU Munich, extended for our purposes. This software uses the so called "Steger algorithm" for line extraction. Rather than extracting roads from a "blank" image our task is the update of an existing GIS database (ATKIS DLM Basis).

Jose Malpica

Key features: Binary segmentation through the Dempster Shafer Theory of Evidence, followed by the conversion raster to vector and the evaluation of the results

Strong points: Texture color analysis in the segmentation phase. Mathematics definition and determination of the topology of the graphics elements.

Weaknesses or limitations: It's convenient to edit bigs gaps (the small ones are bridged)

Optimal exploitations in practical applications: Run the application automatically to extract all the roads, followed by manual edition of the results.

Most important features for practical road extraction: Our system provides in detail the general road network structure using only the RGB imagery

Christian Wiedemann

Key features: local, regional and global modeling, global grouping, network analysis, modeling of simple crossings

Strong points: global grouping, network analysis

Weaknesses or limitations: selection of seeds for path search

Optimal exploitations in practical applications: unknown

Most important features for practical road extraction: fast during interactive phase, user interface

Albert Baumgartner

Key features: local grouping, use of scale-space behavior of roads, local context, rural areas, panchromatic images, ground resolution: 02.-0.5 m

Strong points: scale-space, context

Weaknesses or limitations: weak global grouping, acceptable results only for rural areas

Optimal exploitations in practical applications: no reliable statement possible; maybe intermediate results could be used to speed up interactive extraction; the operator could e.g., decide which road segments should be connected; alternative: post editing (efficient tools required to edit typical errors)

Most important features for practical road extraction: reliability of automatic parts; convenient user interface (to control/guide automatic tools and for post-editing of results); fast enough to avoid inactive time for operator ('user real time') or - if not fast enough - breaks can be used for other tasks

Stefan Hinz

Key features: designed for complex urban areas; needs high resolution overlapping images; extracts detailed road information (lanes, cars); is still basic research

Strong points: relies on detailed, scale-dependent, explicit road and context model ;makes heavy use of context to control and complete the extraction; incorporates self;diagnosis systematically.

Weaknesses or limitations: weak model for junctions; occluding dense vegetation; shadowed, very narrow (one-lane) roads; car detection is not reliable in case of traffic jams

Optimal exploitations in practical applications: Aside from gathering detailed road and updating GIS-road axes it would be interesting if this approach could be combined with close range or mobile mapping applications (e.g. for the creation of virtual cities). But, for this, there is still a long way to go

Most important features for practical road extraction: convenient user interface; strategy of necessary interactions / corrections fits into daily work flow

Arcot Sowmya

Key features: Our approach machine learning based, hierarchical, compositional and reuses learned concepts at every stage.

Strong points: Recent innovations include inductive clustering which is able to automatically select a good recognition algorithm, tune its parameters and also pick the best class out of the results. Exciting new classification techniques such as Support Vector Machines and Genetic Algorithms have been applied. A strong reference model and evaluation procedure have been developed.

Weaknesses or limitations: The approach requires labeled images, which are difficult to obtain.

Optimal exploitations in practical applications: The training and recognition phases are separate. Training on labeled images can be performed off-line in an automated setting. Actual recognition should be very fast on the trained system.

Most important features for practical road extraction: The ability to make on-line corrections, which should be automatically included into the system for future images. This is still in the future, though.

Appendix 5: README File

EuroSDR Test on "Automated Extraction, Refinement, and Update of Road Databases from Imagery and Other Data"

Objectives of the Test

To thoroughly evaluate the current status of research including models, strategies, methods and used data, to test and compare existing semi- or fully automated methods using various data sets and high quality reference data, to identify weak points, and to propose strategies and methods that lead to an implementation of operational procedures for road extraction, update, and refinement.

Test data

8 Test images from different sensors:

-Aerial Images (3)
-Leica ADS40 (2)
-IKONOS (3)

Aerial Images

The given ortho images have a ground resolution of 0.5 m and a size of 4000 by 4000 pixels. The original images have an image scale of 1:16000, the principal distance of the camera was 0.3 m (normal angle lens), and they were scanned with a Zeiss SCAI scanner with 14 micrometer pixel size. The ortho-images were generated using an enclosed (ASCII-format) digital surface model (DSM) with 2 m grid size generated by image matching (Leica Photogrammetric Suite including manual elimination of blunders). The images cover an area close to the city of Thun, Switzerland.

-aerial1 contains a suburban area in hilly terrain
-aerial2 contains a rural scene with medium complexity in hilly terrain
-aerial3 contains a rural scene with low complexity in hilly terrain

Leica ADS40

The Leica ADS40 is a digital photogrammetric camera with 3 panchromatic and 4 spectral linear CCDs, each with 12,000 pixels and 6.5 microns pixel size. The focal length was 62.5 mm. The images cover an area close to Waldkirch, Switzerland. The images are orthoimages (generated with an enclosed, ASCII-format, DTM), have a ground resolution of 0.2 m and the size of the images is:

-ads40_1: 5800 x 5765 pixels
-ads40_2: 4880 x 5290 pixels

They are an 8 bit version and the original 16 bit version available. ads40_1 and ads40_2 comprise both rural areas with medium complexity in flat terrain.

IKONOS

The images come from the SI product GEO and have a ground resolution of 1 m and an image size of 4000 by 4000 pixels. There are an 8 bit version and the original 11 bit data. The 4 spectral channels of IKONOS are made available as pan-sharpened images. The images cover areas located in the Kosovo.

-ikonos1 contains a urban/suburban area in hilly terrain
-ikonos2 contains a rural scene with with medium complexity in hilly terrain
-ikonos3 contains a rural scene with with medium complexity in hilly terrain

Evaluation

The evaluation is done against manually digitized ground truth using the same input images?. For this, the test participants should send the resulting data to a web-server which computes the results via a CGI script. In the first stage of the test only the road centerline will be evaluated. The data has to be sent in form of an ASCII file. The format is (col and row in sub-pixel image/pixel coordinates):

```
col1 row1
col2 row2
...        first line
coln rown
-99
col1 row1
col2 row2
...        second line
coln rown
-99
etc.
```

A line is defined as a poly-line between two intersections or between an intersection and a dead-end. The center of the upper left pixel is the origin of the coordinate system. The y-axis is pointing downwards and the x-axis is pointing to the right.

Test participants should also send via e-mail a text file (ASCII or Word format) with a description of the algorithms used, the parameter settings for the tests, a personal evaluation of the results (this can be verbal/qualitative mentioning particular difficulties etc.), and a bibliography with relevant own publications and other comments relevant for the test. The description of the algorithms should be kept short and when possible publications describing the details of the used methods should be send as PDF files. Please use for the file names as suffix .txt, .doc, .pdf and as suffix the name of the organization or the participant.

Evaluation Results

The results consist of:

- percentage completeness

- percentage correctness
- geometric accuracy in pixels
- topological correctness
- an image containing the correct parts of the network in green, the incorrect parts in red and the missing parts in blue.

The evaluation is always done for the whole image.

Restrictions of Use and Copyright

Acknowledgments

We would like to thank the Swiss Federal Office of Topography, Bern, Switzerland, Leica Geosystems, Heerbrugg, Switzerland, and the Bundeswehr Geoinformation Office (AGeoBw), Euskirchen, Germany, for making available the data for this test.

Appendix 6: Documentation by Beumier and Lacroix

Note: we have edited the documentation by changing the references to the literature according to our nomenclature.

Algorithm

a) Bright line detection (raster output)

A detection of bright lines is performed using the Gradient Line Detector described in (Lacroix and Acheroy 1998). The process is based on the fact that, at each side of a crest or valley line, the gradient vectors point in opposite directions. The filtering process, applied to the green channel, does not require any parameter setting unless the value of the smoothing Gaussian (1.2 in this experiment) and the type of object , i.e., crest or valley (crest in this case). The filtering process generates a crest/valley norm and a discretized direction (0-3) which is locally perpendicular to the local crest/valley direction. In order to obtain a one-pixel wide line detection, a non-maximum deletion is then performed, using the discretized direction. The output is an image with high values where bright lines are likely to be present.

b) Segment analysis (vector output)

b1) Linear Segments were extracted from the output image of a). For this, maximum line values are followed in predefined directions with a tolerance of + and – 45°. A segment search is stopped when no neighboring points has a minimal magnitude (here 4, non critical). The segment is rejected if it does not have enough pixels (here 30) or if the deviation from a straight line is too high. The deviation *lin_dev* is computed as the square root of the inertial moment (1.0 pixel in this case).

b2) For each segment point, NDVI is computed (red and infrared channels). Points with NDVI superior to 0 are rejected.

b3) Finally, linear segments are searched in the remaining points with the procedure explained in b1) and satisfying segments are saved to file.

Discussion

This simple procedure delivers bright roads (as appearing in this image). Typical false alarms are aligned bright roofs, with a width similar to roads. Missing segments are darker, hidden or shadowed parts of roads.

Parameter about contrast is not critical and can be set from histogram. The *lin_dev* value is not critical (especially if there were a linking procedure) but helps rejecting spurious lines. The minimum length parameter is a compromise between rejecting spurious lines and keeping short segments (linking in specific direction would help).

No “High-Level” processing has been applied (segment linking and completion) and would be the major improvement.

Appendix 7: Documentation by Hedman and Hinz

Note: we have edited the documentation by changing the references to the literature according to our nomenclature

Algorithm

The extraction of roads is performed with the TUM road extraction approach (Wiedemann and Hinz 1999). The first step consists of line extraction using Steger's differential geometry approach (Steger 1998), which is followed by a smoothing and splitting step. By applying explicit knowledge about roads, the line segments are evaluated according to their width, length, curvature, etc. Afterwards, overlapping lines are fused using a "best-first" strategy based on the previous evaluation. During this fusion step, there is a possibility to fuse the extracted segments from different channels and/or extraction with different line width. A weighted graph of evaluated road segments is constructed. For the extraction of the roads from the graph supplementary road segments are introduced and seed points are defined. Best-valued road segments serve as seed points. They are connected by an optimal path search through the graph.

Parameter Settings for each test area

Three smaller IKONOS images were analyzed.

Image	Channel	Line width	Higher contrast	Lower contrast	Bright/dark lines
IKONOS1_sub1	Blue	9	30	15	Bright
IKONOS3_sub1	Blue	14	30	10	Bright
	Blue	10	30	10	Bright
	NDVI	10	30	10	Dark
IKONOS3_sub2	Blue	10	30	10	Bright
	NDVI	12	30	10	Dark

Personal Evaluation

The result obtained from the automatic road extraction is highly dependent on the parameters. Especially the set up for the line extraction is a critical step. Therefore much effort has been put into the selection of these parameters. Since each scene shows different scenarios and landscapes (hilly, rural/urban), the careful choice of the parameters for each scene alone and not a common parameter choice for the total collection of the images is justified. Each channel (red, green, blue, NIR, NDVI) was analyzed separately. The best results were obtained for the blue channel. Even though the results from NDVI were poor, the extraction turned out to be complimentary compared to the other channels. A fusion of blue and NDVI turned out to be the best option for the rural scenes (IKONOS3_sub1 and IKONOS3_sub2). In one of the scenes (IKONOS3_sub1), the road width differs depending on whether the surrounding area is rural or urban. To get a satisfactory result, a second line extraction from the blue channel using wider line width was carried out.

The automatic road extraction procedure is originally developed for rural areas, which explains the poor result of the urban scene (IKONOS1_sub1).

Appendix 8: Documentation by Zhang and Couloigner

Note: we have edited the documentation by changing the references to the literature according to our nomenclature and by deleting copied parts.

Algorithm

The main steps of our methodology and their corresponding algorithms are briefly described below.

1) Image resampling (only for Aerial and ADS40)

The original images, are resized to half (Aerial) / one fourth (ADS40) of the original size using an image viewer free-ware.

2) Image segmentation

The *K*-means clustering algorithm is used for this purpose.

Aerial and ADS40: All the three bands are used. In all the cases, the number of clusters is set to six and two of them have been identified as possible roads. These two clusters are used to create a road cluster.

Ikonos: All the four bands are used for the *Ikonos1_sub1* image, while only the RGB bands are used for the *Ikonos3_sub1* and *Ikonos3_2* images. The NIR band is discarded for the latter two images because of its low quality. We used the 11-bits images. In all the cases, the number of clusters is set to six and two of them have been identified as possible roads. These two clusters are used to create a road cluster.

3) Road cluster refinement

The road cluster is refined by removing the big open areas, which are usually spectrally similar land covers such as buildings, parking lots, crop fields, and so on. The refinement is based on our shape descriptors of the Angular Texture Signature in combination of a fuzzy classifier. Details can be found in (Zhang and Couloigner, 2005a, 2005b).

4) Road centerline segment detection

The road centerline segments are detected from the refined road pixels by a localized and iterative Radon transform. A gliding window algorithm achieves the localization of the Radon transform. The window size used is 31 by 31 pixels. The iterative Radon transform is then performed locally on each window. We have improved the peak selection techniques so that we can accurately estimate the line parameters of thick lines in the Radon transform. Details can be found in (Zhang and Couloigner 2005c, 2005d).

5) Perceptual grouping

The road segments are further grouped to form the road network. A gap will be bridged if it is shorter than 5 pixels along the road direction. Possible road intersections are detected and used in the road polyline formation process. Only the road polylines that are longer than 20 pixels are written to the output file.

6) Coordinates rescaling (only for Aerial and ADS40 – cf. 1)

The final coordinates are rescaled by a factor of two (Aerial) / four (ADS40) to match the original image coordinate system.

Personal Evaluation

Personally we think that our results are very satisfactory. Most of the roads are correctly extracted with a good positional accuracy. This is impressive for a fully-automated approach without any post manual editing. Our main concerns are:

1) Problems with wide roads (Aerial and ADS40)

Although the proposed methodologies work quite well in finding small roads, wide roads have not been extracted successfully. The reason might be that the road width is still too larger for our methods to work well. Further reducing the spatial resolution might be necessary for this kind of wide roads;

2) Problems in perceptual grouping (Aerial and ADS40)

Our perceptual grouping algorithm is still incomplete and under development. It creates some topological problems especially in road intersections.

3) Problems with shadowed areas (Aerial and ADS40)

As common for a fully automated approach, we have problems in extracting roads in shadowed areas.

4) Omission errors (Aerial and Ikonos)

In our road cluster refinement step, we still have problems with some wide roads, major road intersections, and roads adjacent to a building, parking lot or crop field. Those roads are misclassified as non-roads and will harm the topology of the whole road network. We are still working on it.

5) Large commission errors (Ikonos only)

Due to the usage of the spectral clustering approach for image segmentation, many spectrally similar land covers are misclassified as roads. This mainly accounts for the large commission errors.

6) Problems with dense residential areas (Ikonos only)

In dense residential areas, we have problems in both the image segmentation and the road refinement steps due to the large volumes of noises, artifacts, and spectrally similar objects. It is difficult to automatically (even manually) extract a complete road network in this kind of areas.