A TEST OF AUTOMATIC ROAD EXTRACTION APPROACHES

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ABSTRACT:

Roads are important objects for many applications of topographic data. They are often acquired manually and as this entails significant effort, automation is highly desirable. Deficits in the automatic extraction hindering a wide-scale practical use have led to the idea of setting-up a EuroSDR test comparing different approaches for automatic road extraction. The goal is to show the potential of the state-of-the-art approaches as well as to identify promising directions for research and development. After describing the data and the evaluation criteria used, we present the approaches of a number of groups which have submitted results and give a detailed discussion of the outcome of the evaluation of the submitted results. We finally present a summary and conclusions.

1. MOTIVATION AND BACKGROUND

The need for accurate, up-to-date, and detailed information for roads is rapidly increasing. They are used in a variety of applications ranging from the provision of basic topographic infrastructure, over transportation planning, traffic and fleet management, car navigation systems, location based services (LBS), and tourism, to web-based applications. While road extraction has been performed by digitizing maps, the update and refinement of the road geometry is often based on aerial imagery or high resolution satellite imagery such as Ikonos or Quickbird. Additionally, terrestrial methods, particularly mobile mapping are of significant importance for determining attributes for navigational purposes.

Because road extraction from imagery, on which we focus for the remainder of this paper, entails 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 agencies (NMAs) and large private photogrammetric firms, have been left with many wishes to be fulfilled.

NMAs 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.

These considerations led to the idea of setting-up a road extraction test under the umbrella of EuroSDR (European Spatial Data Research – www.eurosdr.net). An important inspiration for it was the highly successful 3D reconstruction test of (Scharstein and Szeliski, 2002) which has become a standard in the field. The emphasis of our test is put on the thorough evaluation of the current status of research (including models, strategies, methods and data used). Through testing and comparing existing semi- or fully automated methods based on various datasets and high quality reference data extracted manually by an experienced operator from the image data used for the test, weak points as well as promising directions should be identified and, strategies and methods that lead to a fast implementation of operational procedures for road extraction, update, and refinement should be proposed. However, since most of the participating groups focus on road extraction rather than on refinement or update, the scope of this test has been limited purely on road extraction for the time being.

2. DATA AND TEST SET-UP

Initially, eight test images were prepared from different aerial and satellite sensors. All images have a size of at least 4,000 × 4,000 pixels. Unfortunately, this was found to be insurmountable by nearly all approaches and, therefore, the limiting factor of the test. Reasons for an inability to process the larger 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 images 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. Hence we decided eventually to cut out three smaller parts with 1,600 × 1,600 pixels of Ikonos images where we found the largest interest.

In the following, only those images are listed, for which at least three extraction results were submitted:

- 3 scanned aerial images from the Federal Office of Topography, Bern, Switzerland (image scale 1 : 16 000, focal length 0.3 m, RGB, 0.5 m ground resolution, 4 000 × 4 000 pixels – see Fig. 1))
  - Aerial1: suburban area in hilly terrain
  - Aerial2: hilly rural scene with medium complexity
  - Aerial3: hilly rural scene with low complexity
- 3 IKONOS images (Geo) from Kosovo, provided by Bundeswehr Geoinformation Office (AGeoBw), Euskirchen, Germany, given as pan-sharpened images in red, green, blue, and infrared (1 600 × 1 600 pixels – see Fig. 1 and 2)
  - Ikonos1-Sub1: urban/suburban area in hilly terrain

– Ikonos3-Sub1 and -Sub2: rural hilly scenes with medium complexity

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, here 5 pixels on both sides, i.e., 10 m for the Ikonos data, 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 of the reference network which lies within the buffer around the extracted data. The optimum value for completeness is 1.

Correctness: It represents the percentage of correctly extracted road data, i.e., the part of the extracted data which lie within the buffer around the reference network. The optimum value for 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 w. If an equal distribution of the extracted road data within the buffer around the reference network is assumed, it can be shown that $RMS = w/\sqrt{3}$. The optimum value is $RMS = 0$. As RMS mainly depends on the resolution of the image, it is given in pixels in this paper.

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.

3. ROAD EXTRACTION APPROACHES

We will shortly introduce the approaches of the participating groups (alphabetical ordering according to corresponding author):

Uwe Bacher and Helmut Mayer, Institute for Photogrammetry and Cartography, Bundeswehr University Munich, Germany: The approach is only suitable for the Ikonos images and is focusing on rural areas where roads are mostly homogeneous and are not disturbed by shadows or occlusions. It is based on earlier work from TU München of (Wiedemann and Hinz, 1999) and partially (Baumgartner et al., 1999). 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 at different scales, i.e., line widths, are then fused on a best first basis. From the resulting lines a graph is constructed, supplemented by hypotheses bridging gaps. After defining seed lines in the form of the best 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, 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., 1999) 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 novel feature of Bacher's approach.

Charles Beumier and Vinciane Lacroix, Signal and Image Center, Royal Military Academy, Brussels, Belgium: The approach for Ikonos images rests on the 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 with limited 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 based on 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 and Christian Heipke, Institute for Photogrammetry and Geoinformation (IPI), Hannover University, Germany: They use two approaches suitable for aerial images as well as for Ikonos data, both designed primarily for rural areas as Bacher above. 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., 1999). 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. Herewith it combines the high reliability of high resolution with the robustness against disturbances particularly for the topology of the lower resolution. Quadrangles are constructed from the parallel edges and, from them, in turn longer road objects taking also local context information into account. Gerke_WB in essence substitutes the Steger line extractor of the original Baumgartner approach by the full-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 and Jose Mena, Subdirección de Geodesia y Cartografía, Escuela Politécnica, Campus Universitario, Alcalá de Henares, Spain: This approach (Mena and Malpica, 2003; Mena and Malpica, 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 is done on three statistical levels. On the first level, only color information is employed using Mahalonobis distance. On the so-called "one and a half order" 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 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 usually 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, Institute for Photogrammetry and Cartography, Technische Universität München, Germany: Like Bacher's and Gerke's approaches it again rests on (Wiedemann and Hinz, 1999) and is particularly suitable for rural areas. It has only been used for the smaller pieces cut from the Ikonos images. As Hedman and Hinz found that 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 complementary, information particularly for rural areas. For Ikonos3-Sub1 they found that it was advantageous to use two different scales for line extraction in the blue channel. They also note that it is surprising and needs further investigations that the blue channel delivers the best results for line extraction, since this spectral range is supposed to be significantly affected by atmospheric attenuation.

Qiaoping Zhang and Isabelle Couloigner, Department of Geomatics Engineering, University of Calgary, Canada: The approach is used with minor modifications for all test images. The two Aerial images were re-scaled by a factor of two. At the core of the approach of Zhang and Couloigner is K-means clustering 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 sub-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. 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, 2006a; Zhang and Couloigner, 2006b). Road segments are found from the refined clusters via a localized and iterative Radon transform with window size 31×31 pixels with improved peak selection for thick lines. The segments are grouped bridging gaps smaller than five pixels and forming intersections. Finally, only segments longer than twenty pixels are retained.

4. RESULTS AND DISCUSSION

The results of the evaluation are summarized in Table 1 linking particularly good results to Figures 1 and 2. The table is ordered in the first instance according to the test areas (from aerial to satellite data) and in the second instance alphabetically according to the group and possibly its approaches. For each test area 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.

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 give important overall findings. 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 (Fig. 1a), which is the most difficult of the three images showing a suburban area.

No	Name **(best)**	Completeness ($\geq$ **0.6)**	Correctness ($\geq$ **0.75)**	RMS [pix]
		Aerial1		
1	Gerke_W	0.46	0.47	3.74
2	Gerke_WB	0.31	0.56	1.53
3	**Zhang** (Fig. 1a)	0.51	0.49	1.92
		Aerial2		
4	Gerke_W	**0.76**	0.66	2.87
5	**Gerke_WB** (Fig. 1b)	**0.65**	**0.82**	1.14
6	Zhang	**0.67**	0.49	1.72
		Aerial3		
7	Gerke_W	**0.81**	0.63	3.14
8	**Gerke_WB** (Fig. 1c)	**0.72**	**0.77**	1.3
9	Zhang	**0.72**	0.63	1.66
		Ikonos1_Sub1		
10	Bacher	0.34	0.66	1.29
11	**Beumier** (Fig. 1d)	0.48	0.69	1.3
12	Gerke_W	0.27	0.41	1.89
13	Gerke_WB	0.19	0.49	1.91
14	Hedman	0.31	0.51	1.25
15	Malpica	0.25	0.74	1.13
16	Zhang	0.56	0.41	1.52
		Ikonos3_Sub1		
17	**Bacher** (Fig. 2a)	**0.81**	**0.87**	0.97
18	Gerke_W	**0.8**	0.65	1.53
19	Gerke_WB	**0.68**	**0.75**	1.99
20	Hedman (Fig. 2b)	**0.77**	**0.78**	1.16
21	Malpica (Fig. 2c)	**0.6**	**0.79**	1.41
22	Zhang	**0.72**	0.35	1.22
		Ikonos3_Sub2		
23	Bacher (Fig. 2d)	**0.86**	**0.89**	1.
24	Gerke_W	**0.75**	0.52	1.35
25	Gerke_WB (Fig. 2e)	**0.71**	**0.84**	1.7
26	**Hedman** (Fig. 2f)	**0.85**	**0.91**	1.19
27	Malpica	**0.6**	**0.89**	1.59
28	Zhang	**0.7**	0.34	1.18

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

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 and 3 (Fig. 1b and c) showing rural areas for which it was designed. Particularly the result for Aerial3 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.

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. Beumier has only submitted this one result (Fig. 1d), but it is the best for this scene. 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. In terms of a trade-off between completeness and correctness Bacher, Malpica, and Zhang are similarly good. Looking at the individual results, however, one can very well see the different balance. Yet, for practical applications, the high correctness values for Bacher and Malpica would probably be preferred compared to Zhang.

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 (see also Fig. 2) 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, Hedman is slightly better on Sub2. 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. 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. Finally, a comparison of the results for Bacher and Malpica 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, also the ones not reported here.

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 available for the test are pan-sharpened with a physical resolution for the color of only about 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 -Sub2.

5. SUMMARY AND CONCLUSION

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 $\times$ 2,000 pixels. 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 to employ this information for road extraction and the results show its usefulness. However, particularly for the high resolution data, there is still much to be done.

As it took nearly two years to obtain the results presented here, we learned the hard way that it is extremely important to see as very long term the evaluation of the results for different approaches based on the same data. 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 this work.

Although there are only scarce resources both in academia and practice, we hope that this EuroSDR test will help to create a nucleus of interested researchers, who with the cooperation of NMAs, and if possible manufacturers, could form a well-coordinated and focused research network which can speed up the development of operational (or quasi-operational) systems for road extraction. Here, a focus should be on using a priori data. Though, we note that a fair test of these systems is a difficult issue due to the complexity of practical environments.

Promising directions for future research comprise statistical generative modeling. A particularly impressive instance is (Stoica et al., 2004) who have employed this kind of modeling 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.

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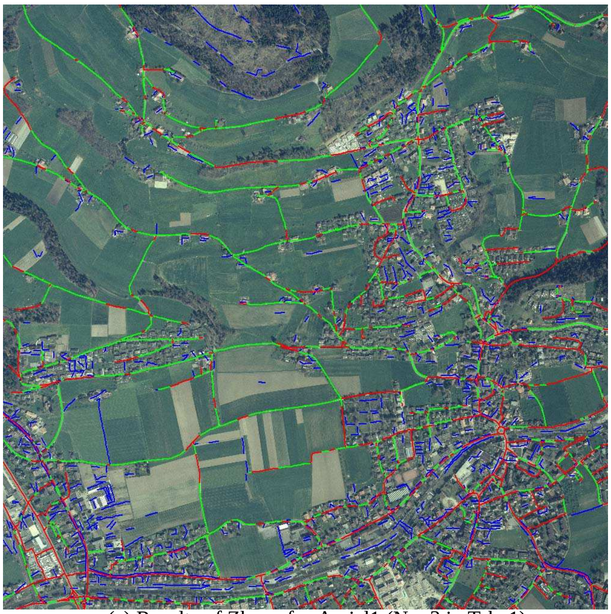
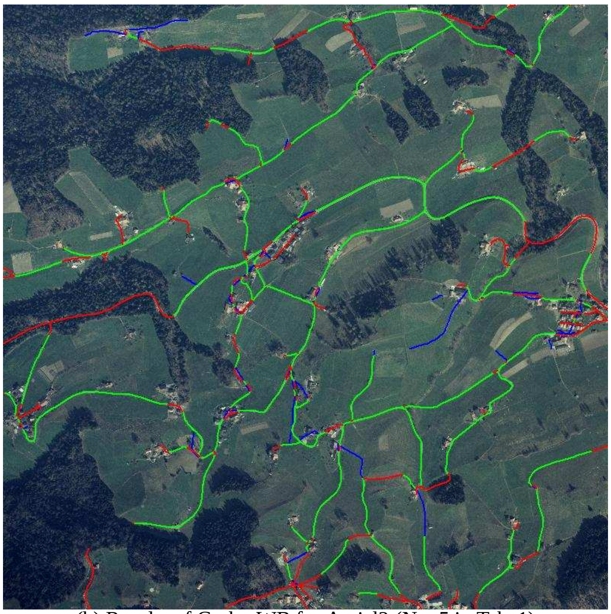
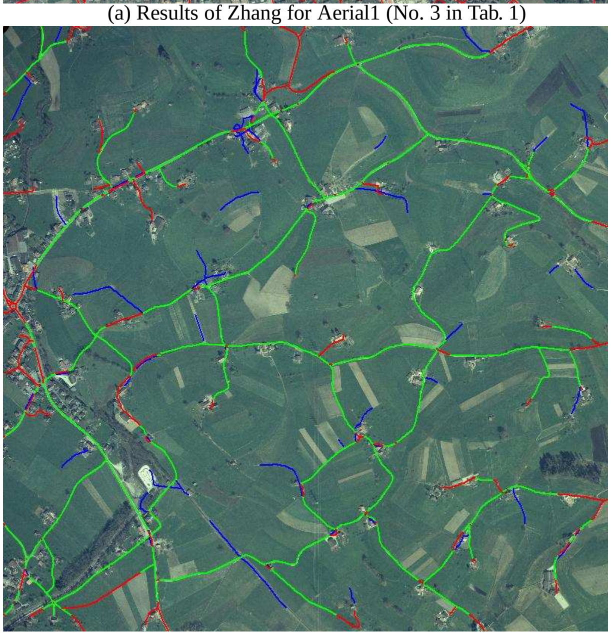


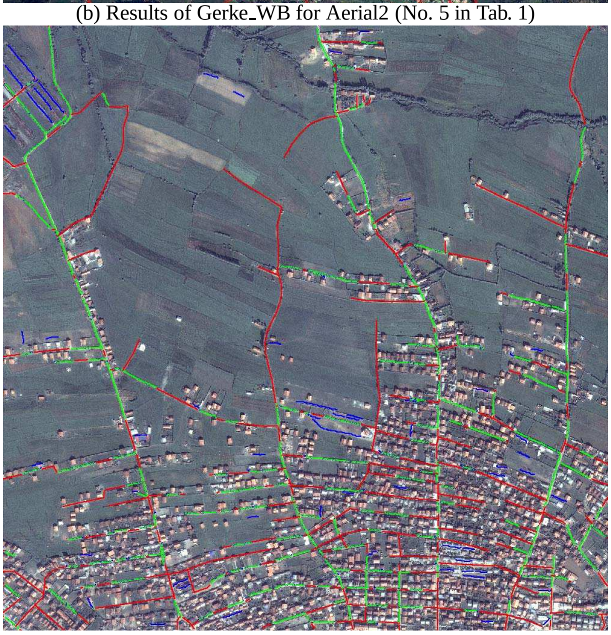
(a) Results of Zhang for Aerial1 (No. 3 in Tab. 1)



(b) Results of Gerke_WB for Aerial2 (No. 5 in Tab. 1)



(c) Results of Gerke_WB for Aerial3 (No. 8 in Tab. 1)



(d) Results of Beumier for Ikonos1-Sub1 (No. 11 in Tab. 1)

Figure 1. Results of EuroSDR Road Extraction Test: Correctly extracted roads are given in green, incorrectly extracted roads in blue, and missing roads in red.

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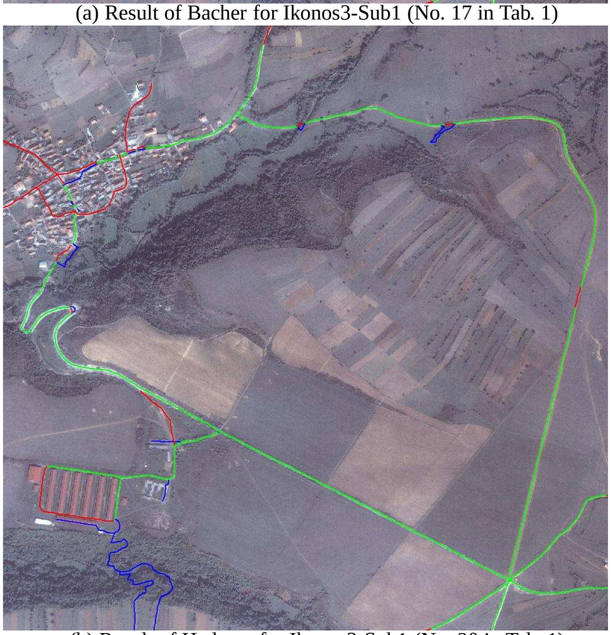
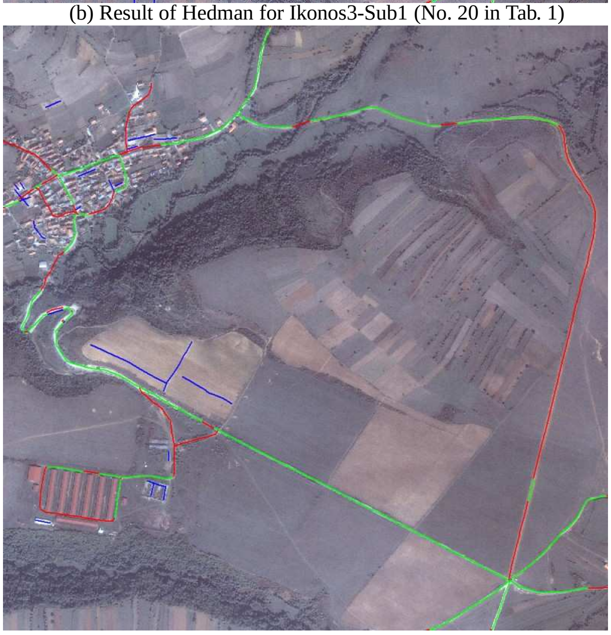
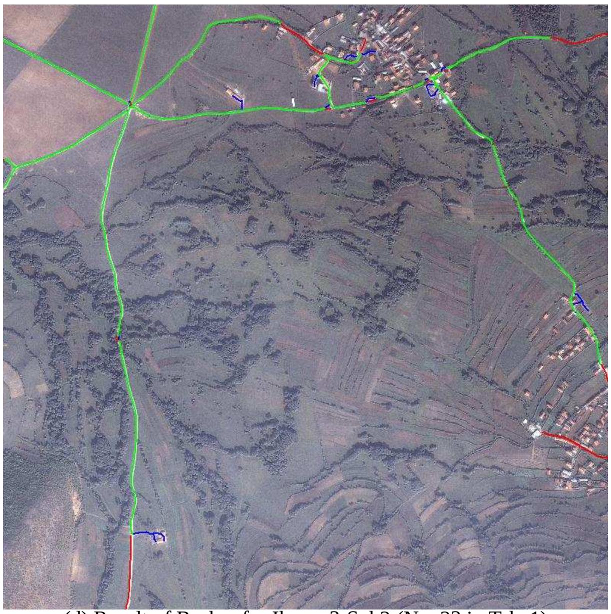
(a) Result of Bacher for Ikonos3-Sub1 (No. 17 in Tab. 1)



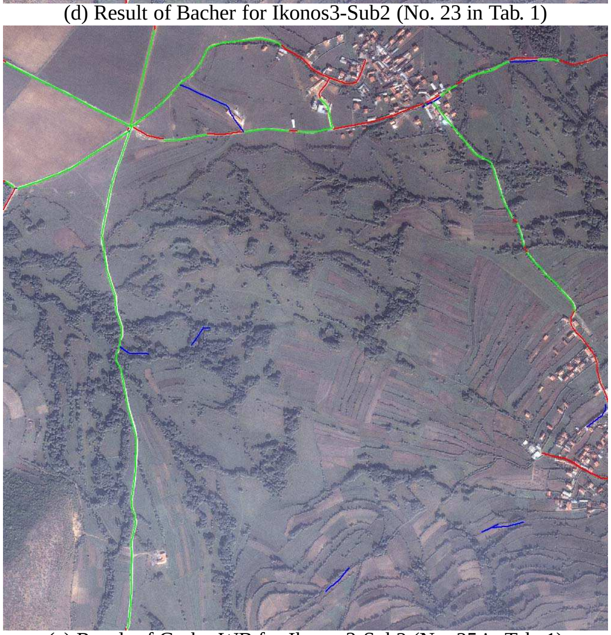
(b) Result of Hedman for Ikonos3-Sub1 (No. 20 in Tab. 1)



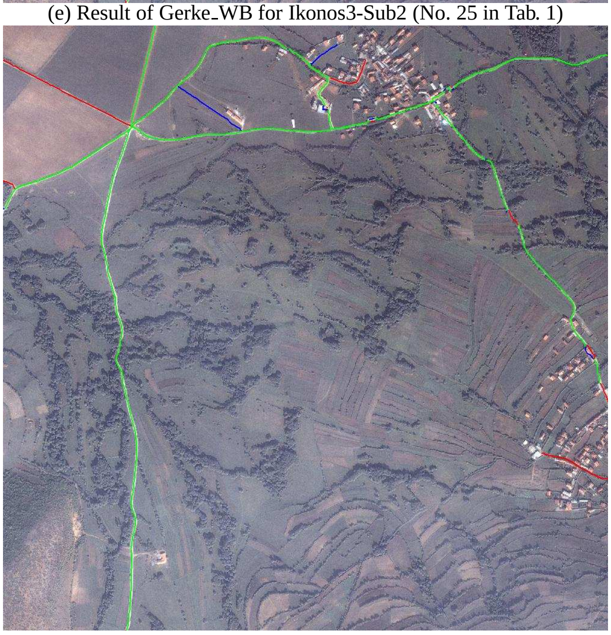
(c) Result of Malpica for Ikonos3-Sub1 (No. 21 in Tab. 1)



(d) Result of Bacher for Ikonos3-Sub2 (No. 23 in Tab. 1)



(e) Result of Gerke_WB for Ikonos3-Sub2 (No. 25 in Tab. 1)



(f) Result of Hedman for Ikonos3-Sub2 (No. 26 in Tab. 1)

Figure 2. More results of EuroSDR Road Extraction Test (colors see Fig. 1)