AUTOMATED ROAD EXTRACTION AND UPDATING USING THE ATOMI SYSTEM - PERFORMANCE COMPARISON BETWEEN AERIAL FILM, ADS40, IKONOS AND QUICKBIRD ORTHOIMAGERY

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ABSTRACT:

In the recent years, the automated extraction of roads from digital images has drawn considerable attention due to the need for the efficient acquisition and updating of road data for geodatabases. The development of new digital aerial sensors and high-resolution satellite sensors signifies a revolutionary change in image acquisition and the possibility of fully digital processing from image acquisition to the generation of value-added products for various applications. At ETH Zurich in cooperation with and funded by the Swiss Federal Office of Topography (*swisstopo*), we have developed an operational system for the automated extraction of 3D road networks from imagery that integrates the processing of colour image data and existing digital spatial databases. The system focuses on rural areas, can use stereo or orthoimages and can determine 3D road axes, and possibly other attributes like width if the roads have a minimum width of ca. 3 pixels. Colour is of advantage but not a must, while a DTM or DSM is required. If no road database exists, it can be generated from scratch, using manual measurement of characteristic road seed points. The system has been extensively tested, mainly by *swisstopo*, on areas with diverse terrain relief and landcover types using different resolution stereo and orthoimages with good results. Recently, tests have been performed using ADS40, IKONOS and Quickbird data. This paper reports on the performance comparison of the ATOMI system using different sensor data in two varying test sites. The test results were qualitatively and quantitatively analysed using accurate reference data. Visual analysis and quantitative measures of accuracy, correctness and completeness are presented, with typical completeness and correctness values of over 90% and planimetric accuracy of 0.4 m to 1 m. The advantages and disadvantages using different sensor data for road network updating are also discussed.

1. INTRODUCTION

In modern map production, a shift has taken place from maps stored in analogue form on paper or film to a digital database containing topographic information. A digital topographic database is an essential part of a GIS. Recently, National Mapping Agencies (NMAs), especially in Europe, wish to generate digital landscape/topographic models that conform to reality and do not include map generation effects. In addition, various existing and emerging applications require up-to-date, accurate and sufficiently attributed digital data, especially of roads and buildings, including car navigation, tourism, traffic and fleet management and monitoring, intelligent transportation systems, internet-based map services, location-based services, etc. In 2002, two major European map providers and five car manufacturers started the project NextMAP to identify and evaluate the road database requirements for in-vehicle ITS (Intelligent Transportation Systems) and services applications, as well as the cost consequences involved for data capturing and data production techniques (http://www.ertico.com/activiti/projects/nextmap/home.htm). Also in 2002, twelve organisations from NMAs, road administrations and private sector key players of road data market submitted the HERDS (Harmonized European Road Data Solution) project proposal for EC funding. Furthermore, in the European Territorial Management Information Infrastructure project, roads are mentioned together with elevation and hydrography as the only objects, commonly agreed to be important enough to be defined as reference data, needed by most applications (see http://www.ec-gis.org/etemii/reports /chapter1.pdf).

To cope with higher product demands, increase the productivity and cut cost and time requirements, automation tools in the production should be employed. As aerial images are a major source of primary data, it is obvious that automated aerial image analysis can lead to significant benefits. In addition, the development of new digital aerial sensors and high-resolution satellite (HRS) sensors signifies a revolutionary change in image acquisition and the possibility of fully digital processing from image acquisition to the generation of value-added products for various applications. At ETH Zurich, in cooperation with the Swiss Federal Office of Topography (*swisstopo*), we have developed a practical system for the automatic extraction of 3D road networks from imagery that integrates processing of colour images and existing digital spatial databases, within the project ATOMI. Some reports on the system performance can be found in Baltsavias and Zhang (2003) and Zhang (2003b). This paper reports on the performance of the ATOMI system using extensive areas with varying relief and landcover and images from different sensors.

2. BRIEF DESCRIPTION OF PROJECT ATOMI

2.1 Aims of ATOMI

The aim of ATOMI is to update roads digitised from 1:25,000 scale maps (part of the national VEC25 dataset) by fitting them to the real landscape, improve their planimetric accuracy to 1m and derive road centerline heights with an accuracy of 1 to 2 m. The topology and the attributes of the existing datasets should be maintained. This update should be achieved by using the image analysis techniques developed at the Institute of Geodesy and Photogrammetry, ETH Zurich (IGP). The whole procedure should be implemented as a standalone software package, should be operational, fast, and most importantly reliable. We do not aim at full automation (ca. 80% completeness is a plausible target), but the "correct" results should be really correct to avoid checking manually the whole dataset. After some initial work, the aims of ATOMI were restricted to improvement of the VEC25 (i.e. no extraction of new roads) with the first target being the open rural areas. More details of ATOMI can be found in Eidenbenz et al. (2000).

The standard input data used includes 1:16,000 scale colour imagery, with 30-cm focal length, and 60%/20% forward/side overlap, scanned with 14 microns at a Zeiss SCAI, a nationwide DTM (DHM25) with 25-m grid spacing and accuracy of 1-3/5-8 m in lowlands/Alps, the vectorised map data (VEC25) of 1:25,000 scale, and the raster map with its 6 different layers. The VEC25 data have a RMS error of ca. 5-7.5 m and a maximum error of ca. 12.5 m, including generalisation effects. They are topologically correct, but due to their partly automated extraction from maps, some errors exist. In some cases, DSM data in the working area was generated using matching (without subsequent editing) on commercial digital photogrammetric workstations with 2-m grid spacing. In the meantime, a much better DTM and DSM (with 2-m spacing and 0.5-m and 1.5-m accuracy in nonforest and forest areas) produced by airborne laser scanning exists for large areas and will be soon finished for all Swiss regions up to 2000 m height, but has not been used up to now.

2.2 The Road Reconstruction System

Our developed system makes full use of available information about the scene and contains a set of image analysis tools. The management of different information and the selection of image analysis tools are controlled by a knowledge-based system. In this section, a brief description of our strategy is given. We refer to Zhang (2003a) for more details. The initial knowledge base is established by the information extracted from the existing spatial data and road design rules. This information is formed in object-oriented multiple object layers, i.e. roads are divided into various subclasses according to road type, landcover and terrain relief. It provides a global description of road network topology, and the local geometry for a road subclass. Therefore, we avoid developing a general road model; instead a specific model can be assigned to each road subclass. This model provides the initial 2D location of a road in the scene, as well as road attributes, such as road class, presence of roadmarks, and possible geometry. A road is processed with an appropriate method corresponding to its model, certain features and cues are extracted from images, and roads are derived by a proper combination of cues. The knowledge base is then automatically updated and refined using information gained from previous extraction of roads. The processing proceeds from the easiest subclasses to the most difficult ones. Since neither 2D nor 3D procedures alone are sufficient to solve the problem of road extraction, we make the transition from 2D image space to 3D object space as early as possible, and extract the road network with the mutual interaction between features of these spaces.

The system can extract roads with a minimum width of ca. 3 pixels. It focuses on extraction of roads in open rural areas, by excluding roads in forest and urban areas using the existing information about the borders of these landcover classes. The existing road database information is used not only for giving an approximate position but also (a) to bridge and fill-in gaps in the extracted roads, and (b) to copy this information in nonprocessed areas (forest, urban) and connect it to the extracted road network in open rural areas. The aim of these two usages is to provide as final result a complete network (even if partially incorrect) avoiding results which consist of a set of broken and unconnected road segments. The system has been modified to work also with orthoimages, whereby the 3D information is extracted by overlaying the 2D information on the DSM or DTM. Although orthoimages have certain disadvantages compared to 2 or more images, the main being the inaccuracies introduced by the DTM/DSM during their generation, they are much easier to handle, are sensor independent and most importantly lead to reduced input data and much faster processing, a crucial factor for operational production.

Our system includes tools for external evaluation of the extracted results, by comparing the extracted results with precise reference data. The quality measures used in this work aim at assessing completeness and correctness as well as geometric accuracy. Completeness measures the percentage of the reference data that lies within the buffer of the extracted roads, while correctness is the percentage of the extracted roads within the buffer of the reference data (Heipke et al., 1998). The buffer distance is defined using the required accuracy of the project ATOMI, i.e. 1 m. The geometric accuracy is assessed by the mean and RMS of the distances between the extracted roads and the reference data. The detailed description for the computation of the external evaluation measures is presented in Zhang (2003a).

The developed system has been implemented as a stand-alone package initially on SGI platforms for stereo and orthoimages and has been ported to Windows XP only for orthoimage processing, with the same user interface. The system imports imagery, the existing road database and other input data (e.g. DSM/DTM). The extracted road network as well as the computed road attributes including length and width are saved in 3D Arc/Info Shapefile format that is readily imported into existing GIS software. For the technical details of the system, we refer to Zhang (2003a, 2003b). The Windows XP version for orthoimages is termed ATOMIRO (with R standing for roads and O for orthoimages). All current and further improvements of the system and the tests reported here refer to ATOMIRO, while the SGI versions have been frozen.

3. TEST SITES AND DATA DESCRIPTION

Results from two test sites in Switzerland will be presented here, one in Thun and the other one close to the city of Geneva. The selection is mainly based on the consideration that the test sites should cover as many types of typical landcover in Switzerland as possible. Another consideration is the availability of images from multiple sensors. Both sites are in open rural areas but with different landcover. All road types in Switzerland can be found in the areas. The description of the test sites and the available imagery are listed in Table 1. Fig. 1 shows aerial images of the two test sites. Much larger and different regions have been used for tests by *swisstopo* with a total road length of about 9,000 km.

In Thun, the colour orthoimages were produced by *swisstopo* from aerial images of scale 1:16,000 using the DHM25. The 50-cm orthoimage is part of the nationwide dataset Swissimage (produced from 1:30,000 imagery with 15 cm lens) with a planimetric accuracy of about 1 m. The images for 20 cm and 60 cm were taken in spring 2003, and for 50 cm in summer 1998. An orthoimage created from ADS40 summer images using the DHM25 is also available. Due to weaknesses in the control point distribution and the bundle adjustment of the ADS40 images, a discrepancy between the ADS40 orthoimage and the 20cm orthoimage has been observed. A non-exhaustive comparison with manually selected feature points shows that the discrepancy varies between 0 and 80 cm. However, smaller differences also exist between the 1998 and 2003 aerial film orthoimages, caused by errors in the sensor orientation. Thus, the real accuracy of road extraction in image space is higher than the accuracy values derived from comparison between datasets (incl. the reference data), which have varying orientation errors.

	Thun	**Geneva**
Area (sq. km)	2.66 * 2.68	4.38 * 3.0
Height range (m)	560 ~ 2200	375 ~ 1200
Landscape	Open rural, Villages, Many small settlements	Open rural, Several villages, Forest, Large fields with bare soil
Imagery type (orthoimage pixel size)	aerial film (20cm, 50cm, 60cm) ADS40 (30cm)	aerial film (50cm) IKONOS PSM (1m) Quickbird PSM (70cm)

Table 1. Test site description and image specifications.

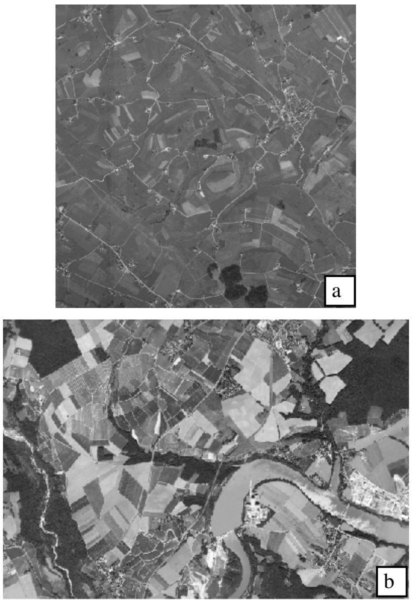

Figure 1. Overview of test sites: (a) Thun, (b) Geneva.

The Geneva test site (Fig. 1b) is near the city of Geneva, containing several larger villages, forest and a river. Another difference to the Thun site is that the scene contains grasslands and large fields of bare soil. In addition, many road-like lines are observed in the fields. The aerial orthoimage came from the Swissimage dataset. IKONOS and Quickbird images were also acquired in May 2001 and July 2003 respectively. The pansharpened (PSM) orthoimages of IKONOS and Quickbird were produced by a software system developed at IGP using a 2-m grid laser DTM with 0.5-m accuracy and had a planimetric accuracy of 0.5-0.8 m, estimated using 20-50 check points measured in 25-cm orthoimages of the Canton Geneva, produced using the same laser DTM (however with 1m grid spacing) and with ca. 0.5-m planimetric accuracy).

The reference data for the Thun and Geneva test sites were measured manually, by *swisstopo* in 20-cm pixel size aerial orthoimages and by ETH Zurich in the Swissimage orthoimages, respectively. The tests were performed on a DELL PC with Pentium 4, 1.8GHz CPU and 1GB RAM running Windows XP.

4. RESULTS AND DISCUSSION

4.1 Thun Site

Completeness and correctness is sufficient for all images in the Thun site, with slightly inferior results for the 50-cm and 60-cm pixel size orthoimages. Although the pixel size of the ADS40 image is slightly more than the 20 cm of the aerial film orthoimage, the results achieved are almost identical. Typical results of road reconstruction and junction generation are presented in Figs. 2-5, where the VEC25 and the extracted roads are shown as white and black lines. In each figure, (a), (c), (d) are the orthoimages with pixel size 20 cm, 50 cm and 60 cm respectively, while the 30-cm pixel size ADS40 orthoimage is shown in (b).

Fig. 2 is a scene with a four-road junction. Road surface and road sides are clear except at the left side of the figures, where a tree occludes the road. The scenes in Fig. 3 and Fig. 4 are slightly complex compared with that in Fig. 2. More shadows and occlusions are observed. In the settlement areas, some road sides are not defined. In Fig. 5, a first-class road is connected with two third-class roads at two junctions. The roadmarks on the first-class road are visible in all images, but are weak in the lower resolution images. The examples show that roads are generally correctly extracted from all images. Road junctions are also well formed. This observation is confirmed by the external evaluation of the extraction results using the reference data (see Table 2). To account for the discrepancy between the ADS40 and aerial film orthoimages, the buffer distance was set to 2 m, when assessing the results from the ADS40 orthoimage.

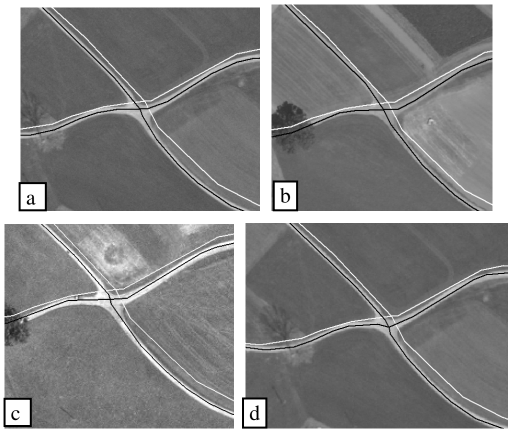

Figure 2. Examples of road extraction and junction generation in scenes with well defined roads.

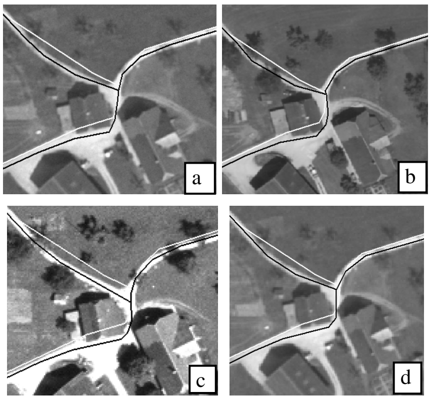

Figure 3. Examples of road extraction and junction generation in scenes with small settlements.

Figure 4. Examples of road extraction and junction generation in scenes with small settlements.

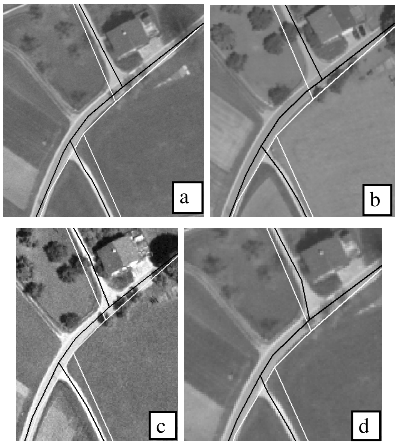

Figure 5. Results in a scene with a first-class road.

Our system delivers the best results with the 20-cm orthoimage. About 95% of the roads are correctly extracted with an accuracy of about 50 cm. The non-extracted or falsely extracted roads are mainly in small villages. Taking into account the discrepancy between the ADS40 and the 20-cm film orthoimage (as indicated by the large mean values), our system performed equally well on ADS40 data. Indeed, visual check over the whole test site shows that the results from ADS40 data are actually at the road centers. Furthermore, images from ADS40 are sharper and have a better radiometric quality compared to scanned film. Image quality is important in general and for object extraction, and depends on such image properties as well, and not only on the ground pixel size (which is often used wrongly as synonymous to image resolution and image quality).

Table 2 also shows that all quality measures are gradually deteriorating with decreasing pixel size. One cause for less completeness is that paths in fields are only partially extracted because the path surface is blurred and road edges are very weak (Fig. 6), while in small villages performance was also worse (Fig. 7). However, the quality deterioration is much less than the pixel size reduction. E.g. for 60-cm vs. 20-cm pixel size, in the first case we have 9 times less data, but completeness, correctness and accuracy deteriorate only by 7.5%, 4.5% and 40%. On the other hand, this slight quality decrease may still mean expensive additional manual editing, so the question of pixel size choice should be carefully considered.

Quality measures		**Aerial 20cm**	**Aerial 50cm**	**Aerial 60cm**	**ADS40 30cm**
Completeness (%)		95.44	90.49	88.28	95.27
Correctness (%)		94.65	92.53	90.68	94.24
Length of reference (km)		42.08	42.08	42.08	42.08
Length of extraction (km)		42.43	41.15	40.97	42.54
RMS error (m)	x	0.45	0.60	0.72	1.00
	y	0.43	0.61	0.75	0.97
Mean error (m)	x	0.04	0.17	0.29	0.57
	y	0.08	0.22	0.19	0.44
Processing time (s)		1872	774	620	1184

Table 2. Quality evaluation of the results in Thun site.

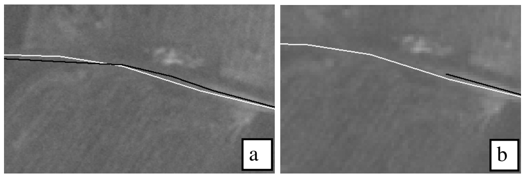

Figure 6. A path extracted in 20-cm pixel size image (a), but only partially extracted in 60-cm pixel size image (b). The black lines are the extracted results and the white lines are the reference data.

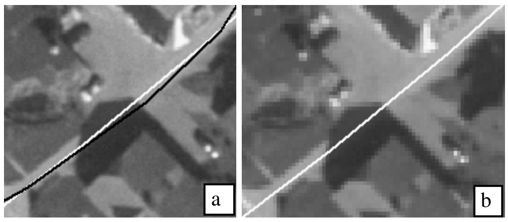

Figure 7. A village road extracted in 20-cm pixel size image (a), but not in 60-cm pixel size image (b). The black lines are the extracted results and the white lines are the reference data.

Table 2 shows that the processing speed of our system is high (e.g. ca. 30 minutes for more than 40-km roads in 20-cm pixel size images), and that processing time decreases almost 1:1 with orthoimage pixel size. The processing time also depends on the road density and to a lesser extent complexity of the scene, increasing with them. Extensive tests at *swisstopo* with 50-cm orthoimages show that roads in an average road density 1:25,000 map sheet covering 210 km^2 can be extracted in 3-4 hours on a Dell PC with Pentium 4, 2GHz CPU and 2GB RAM running Windows XP. Thus, using this not up-to-date computer configuration, all 1:25,000 map sheets of Switzerland could be processed in 36 days. Note that typical map sheets, excluding large urban centers, large lakes and the Alps, have about 2,500 km of roads, with about 45%-50% of them in rural areas.

4.2 Geneva Site

Our system achieves good results with the 50-cm orthoimage (Swissimage), similar to the ones in Thun (see Table 3). However, the performance (mainly the completeness) with the HRS data is poor, especially the 1-m IKONOS image. In this image, higher-class roads are usually extracted, while most narrow roads such as 4th, 5th and 6th class roads are not, because the system prerequisite of 3 pixel wide roads is not fulfilled. The increased ground resolution in Quickbird makes more roads visible than in IKONOS, and also the road surface and road edges are clearer, resulting in a better performance. However, compared with the 60-cm aerial film orthoimage in Thun, the completeness is still rather low.

Quality measures		**Aerial 50cm**	**IKONOS-PSM 100cm**	**Quickbird-PSM 70cm**
Completeness		90.89%	54.22%	72.68%
Correctness		95.36%	81.22%	89.58%
Length of reference (km)		50.72	50.72	50.72
Length of extraction (km)		48.35	33.87	42.16
RMS error (m)	x	0.62	0.93	0.81
	y	0.56	0.82	0.75
Mean error (m)	x	0.07	-0.73	-0.44
	y	-0.05	0.34	0.50
Process time (s)		1510	992	924

Table 3. Quality evaluation of the results in Geneva site.

It is apparent that the definition quality of an object does not depend only on the pixel size but other image quality factors too, and that each object type can be favourably extracted within an object-specific image scale range. Critical factors influencing image quality, like atmospheric and illumination conditions, sensor and sun elevation and image sharpness are much less or not controllable with spaceborne sensors compared to airborne ones, resulting thus in inferior image quality and object definition with the former, even if the ground pixel size is similar. Both HRS images lead to accuracy (RMS) of less than 1m. The mean values are high, due to a systematic bias caused by probable errors in the transformation from the coordinate system of Canton Geneva to the Swiss coordinate system. Thus, in reality the road accuracy from the HRS images is similar or slightly better than that from Swissimage, if the HRS orthoimages are produced with a submeter accuracy DSM/DTM (as in this case) or the sensor elevation is high. Fig. 8 shows several examples of extracted roads and road junctions from the Swissimage, IKONOS and Quickbird orthoimages.

In the Geneva test site, no extraction is applied to the roads inside the villages since the sizes of the villages are large and are classified as urban area. The non-extracted roads are usually those in fields with very weak edges. An example is given in Fig. 9. False extraction in Swissimage occurs when a road in fields is neighbouring with road-like lines (Fig. 10a). Several false extractions are also because the actual road width differs from the width expected for the given road class. This was noticed with several 5th and 6th class roads. An example is shown in Fig. 10b, where a ca. 6.6-m wide 5th class road is incorrectly extracted.

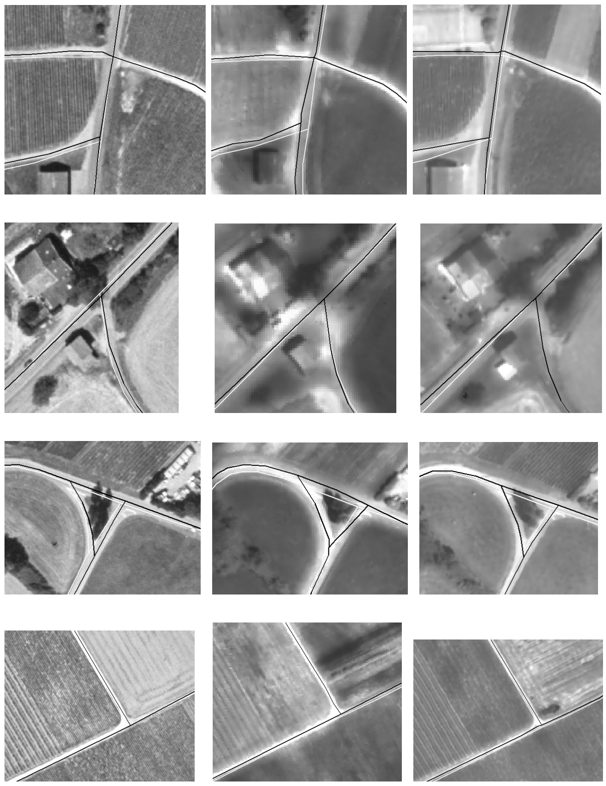

Figure 8. Examples of extracted roads and road junctions in the Geneva site orthoimages. The black lines are the results and the white lines are the VEC25 roads. Left: Swissimage, middle: IKONOS, right: Quickbird.

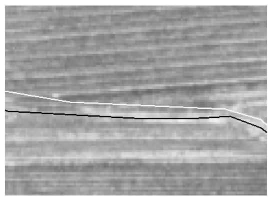

Figure 9. Road in field with weak edges can not be extracted from Swissimage. Black line: reference data. White line: VEC25 roads.

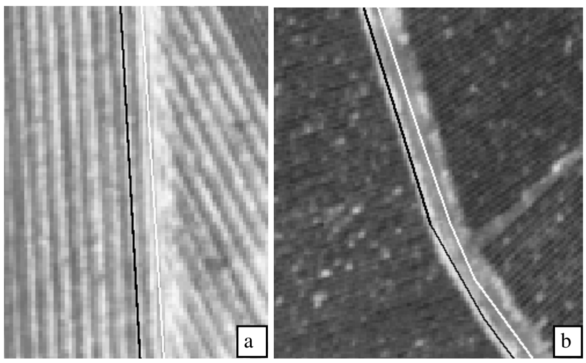

Figure 10. Examples of false extraction from Swissimage. Black line: extraction results. White lines: reference data. (a) a road is incorrectly extracted due to the interference of many road-like features. (b) false extraction caused by assuming wrong road width for the given road class.

Fig. 11 presents two examples (3 images in one row for each) to show the limitation when our system is applied to HRS data. In the figure, the VEC25 roads and extracted results are presented as white and black lines respectively, while the Swissimage, IKONOS and Quickbird orthoimages are shown from left to right. In both examples, the roads are extracted from Swissimage. The road shown in the first scene (first row) is not extracted in the IKONOS image, while the road in the second scene (second row) can not be extracted in the HRS data due to haze. Clouds prohibit road extraction in the example of Fig. 12.

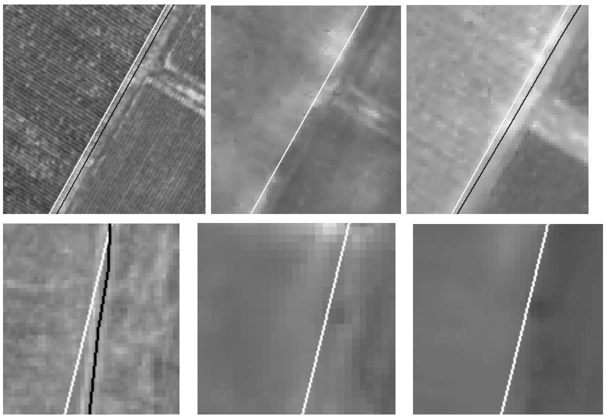

Figure 11. Examples showing limitations of our system applied to HRS data. See text for explanation.

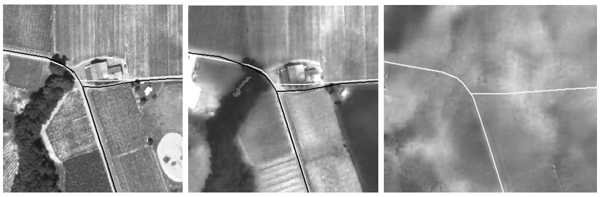

Figure 12. Example showing clouds in the Quickbird image preventing road extraction. Left: Swissimage, middle: IKONOS, right: Quickbird. The VEC25 road and extraction results are presented in white and black lines respectively.

5. CONCLUSIONS

In this paper, we have reported the performance comparison of the ATOMI road reconstruction system between aerial film orthoimages of varying pixel size, ADS40 and HRS orthoimages over two test sites in Switzerland, using accuracy, completeness and correctness quantitative measures and visual control. It is shown that about 95% of roads in rural areas are correctly extracted using aerial film and ADS40 orthoimages with 20-cm and 30-cm pixel size, respectively. With increasing pixel size, the system performance deteriorates but to a much less degree. However, even though the landcover of the two test sites is largely different, our system achieved in both ca. 90% completeness with 50cm aerial orthoimages. Thus, the general conclusion is that the ATOMI system can reconstruct road networks in rural areas using aerial orthoimages with maximum pixel size of ca. 50-60 cm with a completeness and correctness of 90%-95% and an accuracy of 0.4-0.7 m. The speed is sufficient for operational production, while the result includes both extracted and non-extracted (old) data resulting in a complete network with the topology and attributes of the input road database plus new derived attributes like road width. Using manual on-screen digitising of road seed points, the method can be extended to generation of a road database from scratch.

The test shows that the system performance is poor with the HRS data, especially for 1-m IKONOS PSM imagery. Both HRS can deliver submeter accuracy, however the problem lies with the poor object definition and image quality. Only half of the roads in the test sites are reconstructed, mainly higher-class roads with larger width. The surface of the narrow roads (lower-class roads) is usually blurred and the road edges are weak and not clear in the HRS images, thus most of the lower-class roads are not extracted. The test results show that the performance on the 70-cm Quickbird data is considerably better than that on the 1-m IKONOS data, but still of lower completeness than the 60-cm pixel size aerial orthoimage. Other extraction methods, not requiring road widths (ribbons) of 3 pixels or more, may be more appropriate for orthoimages with such pixel size. Generation of Quickbird orthoimages with 60 cm, or deployment of new HRS with 40 cm - 50 cm ground pixel size (license for which the US government has already provided) may pave the way for application of the current approach with good completeness even for such imagery, if the imaging conditions are favourable.

Our system can still be improved, for example, by better use of the existing road vectors to bridge gaps. Post-control on whether the solution conforms in shape and topology to road construction and intersection principles needs to be completed. The self-diagnosis and reliability measures derived for the extraction results are not robust enough. Use of denser and more accurate laser DSMs/DTMs and of the NIR channel of digital sensors can be used for better quality results. Extension of the method to areas with low buildings and forest borders may be feasible. These and other aspects will be topics of future research.

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