CHAPTER 6

RESULTS AND EVALUATION

In this chapter the results of experiments on multiple aerial images are presented and discussed for the case described in chapter 5. A comparison will be made between results obtained by using specialized knowledge from the standards for road construction [Rijkswaterstaat, 1975] and those obtained by using a generalized road network model. The contents of these knowledge bases was described in section 5.3 and 5.4. The specialized knowledge is applied at two different resolutions (0.40 m. and 1.60 m.) in order to investigate the influence of resolution. The performance of the map-guided interpretation strategy is evaluated qualitatively as well as quantitatively, discriminating detection and classification of road elements and junctions.

6.1 ORGANISATION OF EXPERIMENTS AND ANALYSIS

Before results of the map-guided interpretation for the case study are described, it will be outlined which experiments were done and how the results will be presented, analysed and evaluated.

6.1.1 EXPERIMENTAL SET-UP

As already stated in chapter 5 the aim of the experiments is to investigate the influence of the incorporation of standards for road construction and the influence of resolution on detection and classification. For this purpose two knowledge bases were defined in section 5.3:

a) a generalized road network model in which the choice of objects, their properties and parameter setting of image processing techniques is based on general properties of networks of linear elements
b) a specialized road network model in which knowledge from the standards for road construction is incorporated.

All photographs are available on two different resolutions: 0.40 and 1.60 m. In order to investigate both effects three tests were done:

1) generalized road network model on resolution 1.6 m.
2) specialized road network model on resolution 1.6 m.
3) specialized road network model on resolution 0.4 m.

The influence of incorporation of the standards is investigated by comparing the results of the test 1 and 2. A comparison of the results of test 2 and 3 is used to investigate the influence of resolution. The next section will describe how the results of these three tests on nine images are presented and analysed.

6.1.2 PRESENTATION OF RESULTS

Results of these tests are new junctions detected on the motorway from the database and new road elements starting at these junctions. Besides these results, the specialized model also provides classifications of the single carriageway from the database and the detected junctions and road elements. In the presentation of the results two parts can be recognized.
First, the results are visualized and described qualitatively (section 6.2) yielding an explanation for the performance based on the situation in the image. The organisation of this section is such that for each image of the learning and test set respectively, results of the three tests are given per image.
Next, these results are quantitatively analysed in order to evaluate the next objectives:

- Judge classification based on incorporation of standards (section 6.3)
- Compare detection of generalized versus specialized road network model (section 6.4)
- Investigate influence of different resolutions on detection and classification (section6.5)

Ground truth for evaluation of both classification and detection is obtained by visual interpretation.

6.2 VISUALISATION OF RESULTS

Cleynenbreugel et al. [1990] already concluded that results are affected by two factors:

1) road context, i.e. density, shape and configuration of the road network
2) road appearance, i.e. contrast with background, canopy by trees and shadows.

From the road context and appearance it can often be explained why the interpretation process fails or succeeds. The configuration can be classified using the types of intersections defined in 4.3.1.

In this section for each image the results will be described and visualized in relation to the characteristics of the road network in the image. The original images are presented in section 5.2.1. For each image the result of one of the three tests is chosen to be shown in colour. This is a result of one of the three tests in the stage in which the changed parts of the carriageway which are not part of a junction are not yet removed. The reason why this stage is shown is that the location and size of the changed parts often explains why a certain link road is not detected. A subdivision is made between results obtained on the learning and test set.

6.2.1 RESULTS ON LEARNING SET

The learning set contains five images. Three of them depict (a part of) a T-intersection (fig. 5.1, 5.2 and 5.3) and two contain an interchange, constructed by a Haarlemmermeer solution (fig. 5.5) or semi-cloverleaf (fig. 5.4).

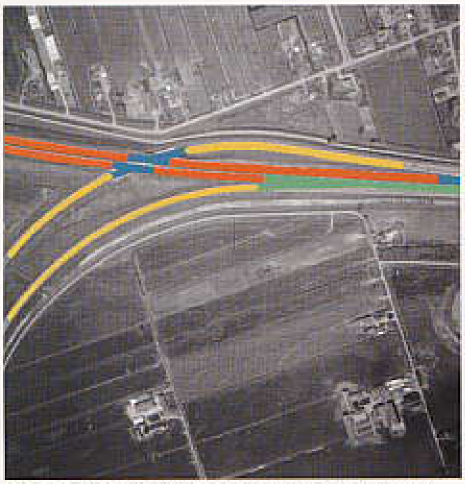

Fig. 6.1 Result of using the specialized road network model at a resolution of 1.6 m.

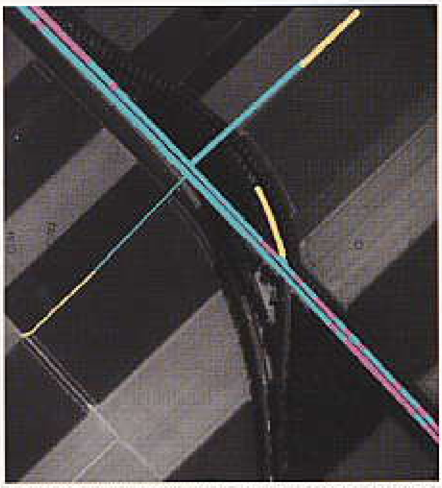

Fig. 6.2 Result of using the generalized road network model at a resolution of 1.6 m.

Fig. 6.3 Result of using the specialized road network model at a resolution of 0.4 m.

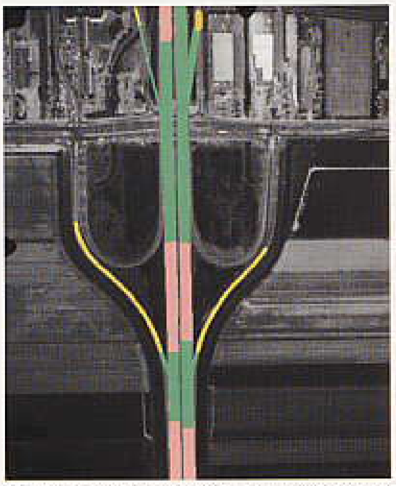

Fig. 6.4 Result of using the specialized road network model at a resolution of 1.6 m.

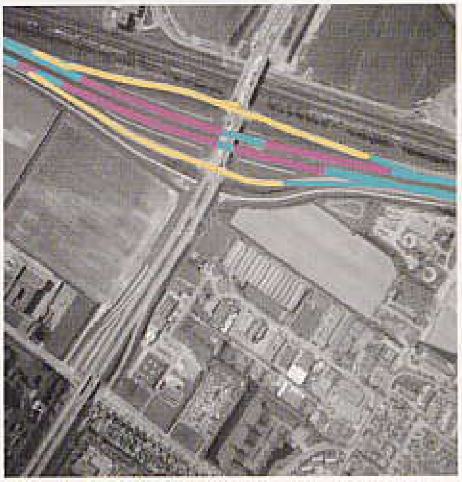

Fig. 6.5 Result of using the generalized road network model at a resolution of 1.6 m.

T-intersection:
This image (fig. 5.1) of a 2-lane motorway contains a T-intersection, which means that two link roads connect another motorway in one direction. One of these link roads crosses the road by a fly-over. This image at a resolution of 1.60 m. was intensively used for training during the development of the system. At low resolution all link roads were correctly detected and tracked till the image border using the generalized as well as the specialized road model (fig. 6.1). All junctions and link roads were correctly classified by the specialized model. At high resolution a light coloured strip was detected instead of one link road, because it matched better with the artificial road model than the real link road, in contrary to at low resolution. The reason is that more details, like road markings and cars, disturb the homogeneity of the road surface.

T-intersection with shadows
This image (fig. 5.2) contains a T-intersection with the same configuration as fig. 5.1, but trees and their shadows cover the road for a large part. Using the generalized road model (fig. 6.2) one link road in a fly-over was detected correctly, but tracked only for a small part. Two incorrect link roads perpendicular to the motorway were detected, corresponding to an unpaved road between two fields and linear structures in another field due to ploughing. They match better with the artificial profile model than the shaded link roads. Using the specialized road model these incorrect linear elements are not present within the search area of the Y-junction and else would have been rejected because their angle with the main carriageway is too large. In this case the link road at the Y-junction was detected and one of the link roads at the fly-over. The other link road at the fly-over was not found, because shadows cause that the changed parts on the carriageway at the Y-junction and fly-over were merged, resulting in maximally one link road. At low resolution the link road at the fly-over was tracked about halfway along, despite the shadows. At high resolution tracking stops earlier due to shadows. A large part of the link road in the Y-junction is shaded and cannot be measured manually either. At low resolution a part of the link road behind the shadow is detected when examining the Y-junction. The link road is tracked till the image border. At high resolution a part of the link road before the shadow is detected and the link road is tracked till the shadow.

Part of T-intersection:
This image (fig. 5.3) of a 3-lane motorway contains two Y-junctions, connecting a 1- and 2-lane link road. The 2-lane link road is located very close to the road. For this reason the Y-junction and 2-lane link road are not found using either the generalized or specialized road model, because the link road does not lie within the search area. Actually the 2-lane link road was detected in the larger area defined for searching a 1-lane link road at this point using the specialized road model, but was rejected because of its width.

A service road, which has a better contrast, partly touches and lies partly close to the 1-lane link road. When using the generalized road model this service road is found instead of the link road. When the specialized road model is used (fig. 6.3), the 1-lane link road is detected, because the width of the service road is not within the investigated range. However, the 1-lane link road is only tracked till the point where service road and link road come together, because this causes a severe disturbance of the profile model. At a resolution of 1.6 m. it is correctly classified as a 1-lane link road, but at a resolution of 0.40 m. as a 2-lane link road.

Interchange by semi-cloverleaf:
This image (fig. 5.4) of a 4-lane motorway contains a semi-cloverleaf of 1-lane link roads. The semi-cloverleaf contains as usually four Y-junctions connecting two lightly and two highly curved link roads, all leading to the same road, which crosses the motorway by means of a fly-over. When using the generalized road model only one lightly curved link road and its Y-junction are detected, while they are both detected using the specialized road model (fig. 6.4). The main reason is that the detected changed part of the motorway, which is part of the Y-junction, is split into two parts in the generalized road model, which results in a non-optimal position and small distance for searching. Both link roads are tracked until the points where they come together with the highly curved link roads. The highly curved link roads are not detected. This is more due to their weak contrast with the background then due to their curvature. Besides the positions of the changed parts of the motorway are not optimal. Because the slip-roads of the highly curved link roads already start at the fly-over, the Y-junction and fly-over are seen as one junction and the changed road elements are merged. When using the generalized model a light strip near the crossing road is detected. When using the specialized model two roads in the build-up area near the fly-over are detected (fig. 6.4). They are accepted because their orientation is such that the line from the changed part of the motorway to these roads has an angle with the motorway, which is allowed for Y-junctions. At high resolution only one of these roads was detected.

Interchange by Haarlemmermeer solution:
This image (fig. 5.5) of a 2-lane motorway contains an interchange for which a Haarlemmermeer solution is used. This means that it contains four link roads leading to two level crossings at a road, which passes the motorway perpendicular by means of a fly-over. At the Y-junction all link roads have 1 lane, but they widen to 2 lanes. All detected link road were classified as 2-lane link roads. In all tests three of the four link roads were detected. At low resolution the fourth link road is not detected in both tests because the detected changed road element is too short since it is split into two parts and in the specialized road network model it is consequently recognized as part of a fly-over. In the generalized road model (fig. 6.5) the link road are further tracked, even passing the level crossing. Using the specialized road model two link roads are tracked till the level crossing and the other till the cars waiting for the traffic light for the crossing. At high resolution the fourth link road was detected, but another one was not. The Y-junction of the link road actually lies outside the image border. Because at high resolution the position from which the link road is searched is less suitable than at low resolution, the angle with the link road is too large and consequently the cross-correlation is too low. The fly-over was not detected because there are level crossings near the motorway with a road, which crosses by a fly-over. Consequently the parts between the fly-over and level crossings are too short to be detected. The crossing road is still under construction at one side of the motorway and is difficult to see. The other side has separated carriageways.

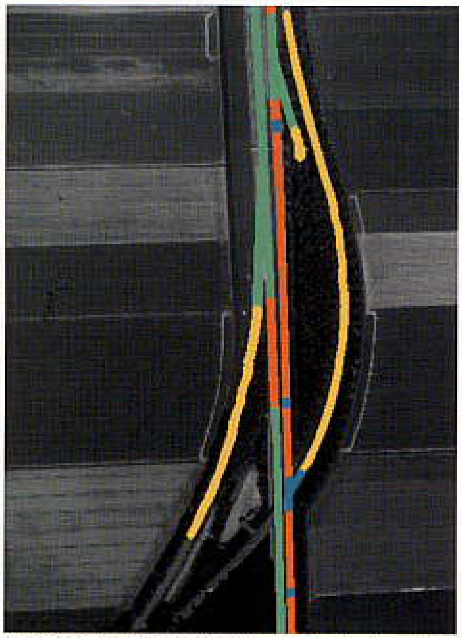

Fig. 6.6 Result of using the specialized road network model at a resolution of 0.4 m.

Fig. 6.7 Result of using the specialized road network model at a resolution of 1.6 m.

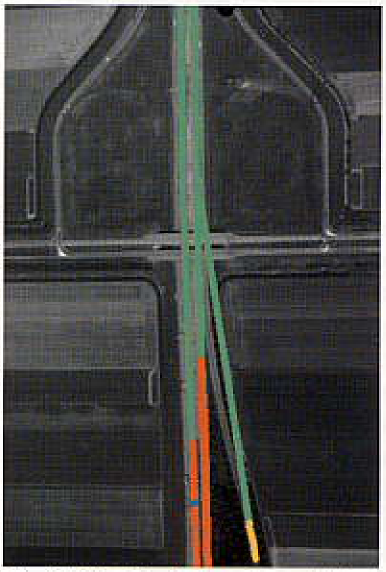

Fig. 6.8 Result of using the specialized road network model at a resolution of 1.6 m.

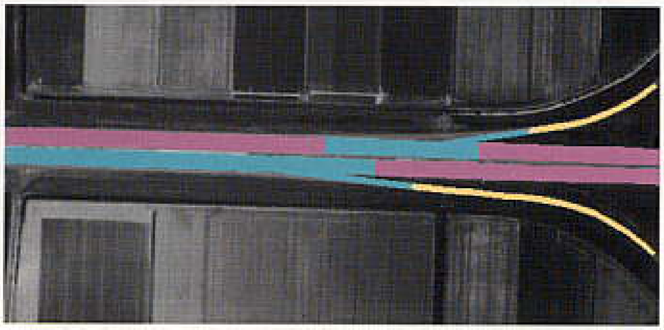

Fig. 6.9 Result of using the generalized road network model at a resolution of 1.6 m.

LEGEND

Generalized road network model
- 🟪 Road element
- 🟦 Junction
- 🟨 New road element

Specialized road network model
- 🟥 1-lane motorway
- 🟧 2-lane motorway
- 🟧 3-lane motorway
- 🟥 4-lane motorway
- 🟦 Fly-over
- 🟩 Y-junction
- 🟧 2-lane link road
- 🟨 1-lane link road

6.2.2 RESULTS ON TEST SET

The test set contains four images. The configuration of the intersection depicted in the image can be classified as a T-intersection for two of the images (fig. 5.6 and 5.8) and as an interchange for the other two (fig. 5.7 and 5.9).

T-intersection:
This is an image (fig. 5.6) of exactly the same T-intersection as fig. 5.2, but photographed at another date and from flying in another direction. There are fewer shadows, although trees still partly cover the road surface. When using the generalized road model, the link roads in the both fly-overs are correctly detected and tracked till the border of the image. The link road in the Y-junction is not detected because a narrow gravel strip near the motorway was found, which matches better with the artificial model than the link road. Using the specialized road network model this strip is not detected, because it is too narrow. In this case the link road and Y-junction are detected correctly. One link road in a fly-over is recognized, but the other is rejected. Not only because the changed part of the carriageway is classified to be part of a Y-junction, but also because the angle with the detected link road is too large. The result of using the specialized road model at high resolution is the same (fig. 6.6), except that a changed part of the motorway, detected because of a change in the median strip of the road, is recognized as Y-junction and a clearing between the trees is detected as link road.

Interchange by Haarlemmermeer solution:
In this image (fig. 5.7) main roads are connected to the motorway by a kind of Haarlemmermeer solution. At one side of the motorway there are three T-junctions instead of a crossing, connecting main roads in two directions. Also at the other side of the motorway the main road bifurcates in two directions. This image has a high degree of complexity. Three of the four link roads are partly covered by trees and shadows. There are also service roads present parallel to two of the link roads. The carriageways have no hard shoulder. Consequently they are not recognized as 2-lane motorway. Although the image is part of the test set, it was decided to change the knowledge base, because otherwise the whole interpretation process would not start for this image. In reality all motorways with separated carriageways have at least two lanes. If there would exist 1-lane motorways, the width of this unrecognized road would lie in the range for recognition. It was decided to introduce this unreal type in the knowledge base in order to express in this way the wrong classification of the motorway.
When using the generalized road model, one Y-junction and link road are correctly detected. The detected width of the link road is too small, because of the presence of shadows. At another Y-junction the service road was detected instead of the link road. In the third Y-junction an incorrect link road was detected corresponding to a linear structure due to ploughing. The fourth Y-junction was not found, but is hardly visible. Besides, due to shadows the changed part on the carriageway was split up in several parts. This junction is also not found using the specialized road model at low (fig. 6.7) and high resolution for the same reason. At low resolution also the same Y-junction and link road are detected correctly with the specialized road model and in the other two Y-junction the service roads are detected as link road. They have a better contrast than the link roads, the same direction and are not covered by trees. At high resolution these

service roads are also detected, but the correct Y-junction was not found.

Part of T-intersection:
This image (fig. 5.8) is taken a bit further along the same motorway as in fig. 5.6 at the position where the other end of the link road which crosses the motorway by means of a fly-over, has a Y-junction with the motorway. This Y-junction lies under a fly-over of a main road. Consequently the changed parts of the carriageway are merged and either the Y-junction or the fly-over can be detected. Because another motorway is connected to the motorway, after the Y-junction the width changes from 2 to 4 lanes. However, the outdated motorway in the database without intersections contains 2 lanes. As a result a large part of the carriageway is detected to be changed and the point from which the new link road is searched lies far from the real Y-junction. Nevertheless the Y-junction and link road are detected correctly by the generalized as well as by the specialized road model at low (fig. 6.8) and high resolution, but the Y-junction cuts off the curve in the first part of the link road. The fly-over is not found on either of the carriageways. Also on the other carriageway a large part is detected to be changed because due to the Y-junction in fig. 5.6 the carriageway widened to four lanes, but in the database it contains only two.

Part of interchange:
This image (fig. 5.9) taken a bit further along the same motorway as in fig. 5.8 and 5.6 at the position where the link roads start which end at the main road which crosses the motorway by a fly-over in fig. 5.8. In this case the outdated database correctly contains 4 lanes. This configuration is relatively simple and in all tests both Y-junctions and link roads were correctly detected. The result when using the generalized model is shown in fig. 6.9. At low resolution the link roads are correctly classified as 1-lane link roads, but at high resolution they are recognized as 2-lane link roads.

6.3 RECOGNITION OF SPECIALIZED OBJECT TYPES

Compared to the generalized road model, the use of specialized knowledge provides classifications for types of road elements and junctions. The road elements originating from the databases are classified as a 2-, 3- or 4-lane main carriageways. Junctions are subdivided into Y-junctions and fly-overs. Road elements detected in the junctions are classified as 1- or 2-lane link roads. The aim of this section is to judge if these classifications are correct. A kind of confusion matrices are used for quantitative representation of results, expressing the relation between the real type, obtained by visual interpretation, and the recognized type, obtained by knowledge-based interpretation. Relative numbers are not given because of the small number of detected and classified objects. Results obtained at a resolution of 1.6 m. are evaluated. The influence of a higher resolution on the classification will be subject of section 6.5.

6.3.1 CLASSIFICATION OF THE TYPE OF CARRIAGEWAY

As already pointed out in section 5.4.1, the measured widths of the carriageways in the learning set correspond very well to the standards for road construction [Rijkswaterstaat, 1975] and the range of widths attached to each type is established using these measured widths. Consequently all carriageways in the learning set were correctly classified. Table 6.1 shows the confusion matrix. Notice that each image contains two carriageways.

Real type of carriageway	Recognized as type		
	2-lane	3-lane	4-lane
2-lane	6	0	0
3-lane	0	2	0
4-lane	0	0	2

***Table 6.1** Results of classification of type of carriageway on learning set at a resolution of 1.60 m.*

The carriageways in the test set were correctly classified, except for one aerial image: fig. 5.7. The reason is that because of a narrow fly-over, there is no hard shoulder present along the visible part of the carriageway. This deviation is too large to be covered by the standard deviation of measurements. It was decided (see section 6.2.2) to add the type 1-lane carriageway, in this way expressing that this 2-lane carriageway is incorrectly classified as 1-lane carriageway. Table 6.2 shows the relation between the real type of carriageway, obtained by visual interpretation and the type as which the road is recognized.
The results on the test set prove that the average width of the road, adopted from the standards for road construction, and the range, determined by using the learning set, provide a correct classification under the condition that the motorway fulfils the standards.

Real type of carriageway	Recognized as type			
	1-lane	2-lane	3-lane	4-lane
2-lane	2	4	0	0
3-lane	0	0	0	0
4-lane	0	0	0	2

***Table 6.2** Results of classification of type of carriageway on test set at a resolution of 1.60 m.*

6.3.2 DISCRIMINATION OF Y-JUNCTIONS FROM FLY-OVERS

Junctions are build from two parts: a part of the carriageway originating from the database and the first part of the link road. Parts of the carriageway detected to be changed are classified as part of a Y-junction or fly-over. The L/W-ratio is used as criterion. The left parts of table 6.3 and 6.4 show the results of this classification for learning and test set respectively. It is counted how many changed parts of carriageways detected at the location of a real junction are classified correctly or incorrectly.

Real type of junction	**Part of junction recognized as type**		**Complete junction recognized as**	
	Y-junction	fly-over	Y-junction	fly-over
Y-junction	11	1	8	0
fly-over	3	5	0	3

Table 6.3 *Results of discrimination of type of the junction on the learning set at a resolution of 1.60 m.*

Real type of junction	**Part of junction recognized as type**		**Complete junction recognized as**	
	Y-junction	fly-over	Y-junction	fly-over
Y-junction	7	1	5	0
fly-over	3	1	0	1

Table 6.4 *Results of discrimination of the type of junction on the test set at a resolution of 1.60 m.*

Only if the first part of a link road is detected, the junction is accepted. Otherwise it will be removed. The angle between both parts is used as criterion. The right parts of table 6.3 and 6.4 show the results of the classification of the complete junctions that were finally detected. Only junctions detected at the location of real junctions are considered, because results on detection of junctions are quantified in section 6.4.1 and 6.4.2.

Although there are some misclassification for the first part of the junction, the complete junction is always correctly classified. However, one should notice that due to an incorrect classification of the first part, the complete junction is not found and consequently not included in the right part of table 6.3 and 6.4. The main reason for an incorrect classification of the first part of a fly-over is that it is merged with the changed part of a nearby Y-junction. The misclassification of a Y-junction is less frequent. In both cases at the location of these Y-junction two or more small changed parts were detected, classified as fly-over. There is no significant difference between results obtained from the learning set and those from the test set.

6.3.3 CLASSIFICATION OF THE TYPE OF LINK ROAD

The average width of the tracked road elements is used to classify them into 1- or 2-lane link road. The confusion matrices in table 6.5 and 6.6 show that this classification was always correct for the learning as well as for the test set. The real type of the link roads in fig. 5.5 was difficult to fix, because they start as 1-lane link roads, but widen to two lanes. These were all classified as 2-lane link roads. In conclusion, the classification of the link roads is very reliable.

Real type of link road	Recognized as type	
	1-lane	2-lane
1-lane	3	0
2-lane	0	5
1→2 lane	0	3

Table 6.5 *Results of classification of type of link road on learning set at a resolution of 1.60 m.*

Real type of link road	Recognized as type	
	1-lane	2-lane
1-lane	3	0
2-lane	0	3

Table 6.6 *Results of classification of type of link road on test set at a resolution of 1.60 m.*

6.4 DETECTION BY A GENERALIZED VERSUS A SPECIALIZED ROAD NETWORK MODEL

In this section the results on detection of junctions and link roads by using the generalized and specialized knowledge will be compared in order to investigate if addition of knowledge from the standards for road construction contributes to the interpretation. The results are compared for the successive stages of the interpretation process:

- detection of parts of the carriageway that possibly changed into a junction;
- detection of the first part of link roads;
- tracking of link roads.

6.4.1 DETECTION OF CHANGED PARTS OF CARRIAGEWAYS

The difference between the image processing technique for detection of changed parts activated by the generalized and that activated by the specialized road model is the value for the parameter which defines the threshold for the cross-correlation. In the specialized road model it has a different value for 2-, 3- and 4-lane carriageways. The threshold for 2-lane motorways is equal to the threshold value in the generalized road model. Consequently results in this stage can only be compared for 3- and 4-lane carriageways.

Type of carriage-way	Changed parts of carriageway detected by generalized road network model (resolution 1.60 m.)					
	present & detected	not present	not detected	present & detected		
				correct	split	merged
2-lane	12	12	0	9	1	2
3-lane	2	1	0	1	1	0
4-lane	6	0	0	3	1	2

Table 6.7 *Detection of changed road elements in the learning set with the generalized road network model*

Type of carriage-way	Changed parts of carriageway detected by specialized road network model (resolution 1.60 m.)					
	present & detected	not present	not detected	present & detected		
				correct	split	merged
2-lane	12	12	0	9	1	2
3-lane	2	1	0	1	1	0
4-lane	6	0	0	2	0	4

Table 6.8 *Detection of changed road elements in the learning set with the specialized road network model*

The most important criterium for evaluation is if a part of the carriageway at locations of junctions is detected to be changed. If not, the link road will never be found, thus the chance this happens should be very low. If a changed part of a carriageway is detected while there is no junction, it is no real problem as long as no incorrect link road is detected from this point, except that it costs more computer time. This will be evaluated in the next section. In table 6.7 and 6.8 the results on the learning set will be evaluated quantitatively by counting the number of changed parts of road elements that are:

- present and detected;
- not present;
- not detected.

A distinction is made between 2-, 3- and 4-lane carriageways. If a changed road element is detected at the location of a real junction, the chance to detect successfully the first part of a link road reduces if the changed part is split or merged. If it is merged with the changed part of another junction, only one of them will be found. If it is split, the distance used for searching the link road will usually be too short. In the right parts of table 6.7 and 6.8 a subdivision is made for the junctions counted as present and detected between those which are:

- correctly detected;
- split;
- merged.

For both road models at all real locations of junctions a part of the carriageway was detected to be changed at the cost of about the same number of changed part detected at locations without junctions. It is hard to compare results of the generalized and specialized road model because differences are only based on two images. For the 3-lane carriageways the figures in table 6.7 and 6.8 show no differences. For the 4-lane carriageway the number of merged present and detected changed parts increases when the specialized road network model is used. However, the location and size of the changed parts in fig 6.4 appears to be distributed more symmetrically for the left and right carriageway, than for the generalized model, of which the results are not visualized.

Table 6.9 and 6.10 show the same quantitative evaluation for the test set. In this case at the location of the fly-over in fig. 6.7 the carriageway was not detected to be changed, so the result is a little bit worse than for the learning set. There is hardly any difference between the generalized and specialized road model, except that a changed part is detected once while there is no junction, but this does not necessarily yield worse results.

Type of carriage-way	**Changed parts of carriageway detected by generalized road network model (resolution 1.60 m.)**					
	present & detected	not present	not detected	present & detected		
				correct	split	merged
2-lane	10	6	2	7	1	2
4-lane	2	0	0	2	0	0

Table 6.9 *Detection of changed road elements in the test set with the generalized road network model*

Type of carriage-way	**Changed parts of carriageway detected by specialized road network model (resolution 1.60 m.)**					
	present & detected	not present	not detected	present & detected		
				correct	split	merged
2-lane	10	6	2	7	1	2
4-lane	2	1	0	2	0	0

Table 6.10 *Detection of changed road elements in the test set with the specialized road network model at a resolution of 1.60 m.*

6.4.2 DETECTION OF THE FIRST PART OF A LINK ROAD

Three parameters of the image processing technique activated by the specialized road network model differ from the generalized model:

1) The width of the road in the artificial model corresponds to the expected width of the link roads according to the standards for road construction [Rijkswaterstaat, 1975];
2) The length of the search area corresponds to the maximal curvature of the road;
3) In a Y-junction the link road is searched in a circle segment based on the angle between link road and carriageway in the standards.

In order to evaluate and compare the ability to detect the first part of link roads, in table 6.11 and 6.12 the number of link roads are counted that are:

- present and detected;
- not present, but wrongly detected;
- present, but not detected.

A junction, which is not detected is only assigned to the last category if the changed part on the carriageway was detected.

Type of carriageway	Specialized road network model (resolution = 1.6 m.)			Generalized road network model		
	present & detected	not present	not detected	present & detected	not present	not detected
2-lane	8	0	4	7	2	5
3-lane	1	0	1	0	1	2
4-lane	2	2	4	1	1	5

Table 6.11 *Detection of the first part of link roads in learning set*

Type of carriageway	Specialized road network model (resolution = 1.60 m.)			Generalized road network model		
	present & detected	not present	not detected	present & detected	not present	not detected
1-lane	1	2	3	1	2	3
2-lane	3	0	3	3	0	3
4-lane	2	0	0	2	0	0

Table 6.12 *Detection of the first part of link roads in test set*

More link roads were detected in the learning set when using the specialized instead of the generalized road model. As a consequence the number of not detected first parts of link roads is lower, but also the number of not present link roads is lower. For the test set there is no difference. In the cases the generalized road model detects link roads while there are no junctions (e.g. fig. 6.2), these are not present within the circle segment searched by the specialized road model. In case another road is found at the location of a link road, these roads usually have a better correspondence with the artificial model than the real link road. If these other roads do not fulfil the criterion for the width of a link road and its angle with the main carriageway, they will not be found using specialized knowledge. Instead, the real link road is detected. This happened in fig. 6.3 of the learning set, where the service road with a better contrast was not detected when using the specialized road network model. The service roads detected in fig. 6.7, however, fulfil these criteria, so there is no improvement for the test set. The reason why another link road is not detected when using the generalized model, is that in this case the changed part of the carriageway is split.

Because the emphasis during development of the image processing technique was more on detection of Y-junctions than on fly-overs, the performance for both is compared in table 6.13 and 6.14. The number of detected Y-junctions or fly-overs is shown in relation to the total number present.

Type of carriageway	**Specialized road network model (resolution = 1.60 m.)**		**Generalized road network model**	
	detected / total Y-junctions	detected / total fly-overs	detected / total Y-junctions	detected / total fly-overs
2-lane	5/6	3/6	4/6	2/6
3-lane	1/2	0/0	0/2	0/0
4-lane	2/4	0/2	1/4	0/2
all	8/12	3/8	5/12	2/8

Table 6.13 Detected in relation to total number of link roads in Y-junctions and fly-overs of learning set

Type of carriageway	**Specialized road network model (resolution = 1.60 m.)**		**Generalized road network model**	
	detected / total Y-junctions	detected / total fly-overs	detected / total Y-junctions	detected / total fly-overs
1-lane	1/4	0/2	1/4	0/2
2-lane	2/2	1/4	1/2	2/4
4-lane	2/2	0/0	2/2	0/0
all	5/8	1/6	4/8	2/6

Table 6.14 Detected in relation to total number of link roads in Y-junctions and fly-overs of test set

Results for detection of the first part of link roads in Y-junctions are obviously better than for fly-overs. There is not much difference between the results on the learning and test set for Y-junctions. Also the improvement when using the specialized model is larger for Y-junctions. In total 65% of all link roads in Y-junctions was found against 45% if the generalized model is used. Total results of detection of the first part of link roads in fly-overs are the same for the specialized as for the generalized road model. About 30% was detected.

6.4.3 TRACKING LINK ROADS

In the specialized knowledge two parameters are calculated using the standard for the maximum curvature of the road. The first is the step size and the second is the possible deviation from the predicted position. The length of the detected link road is used as a measure to evaluate whether the addition of knowledge contributes to the performance. These are shown in the first two columns of table 6.15 and 6.16. The results in the third column will be discussed in section 6.5.3.

type of link road	length (in m.) from generalized model, resolution 1.6 m.	length (in m.) from specialized model, resolution 1.6 m.	length (in m.) from specialized model, resolution 0.4 m.	manually measured length (in m.)
1-lane	-	355	337	559
	320	336	339	237
	-	251	255	314
2-lane	583	582	-	706
	463	422	443	499
	250	253	272	285
	-	566	98	452
	160	277	121	204
1->2 lane	319	298	295	290
	-	-	290	331
	681	200	-	376
	655	166	241	188

***Table 6.15** Length of link roads in the learning set*

It is not possible to find an overall trend by comparing the lengths of the link roads detected when using the generalized and specialized model. In two cases use of the generalized model yields a much longer link road. The reason is that road tracking proceeds after the level crossing by following another link road (fig. 6.5). However, if the visibility becomes worse, e.g. due to shadows, the specialized model starts to perform better and produces longer link roads.

The lengths of the detected link roads are also compared with the length of the link roads obtained by manual measurements. The road is measured manually from the point where the inner side of the link road branches off the outer side of the dual carriageway. The lengths of the manually measured link roads are shown in the last column of table 6.15 and 6.16. In order to be able to compare this length with the length of the detected link road, the intersection point of the first part of the detected link road with the carriageway is determined and the length of the remaining part is added to the length of the tracked road. In most cases the measured length in the learning set is larger than the detected length, but differences are small, except for two cases. One of them is comparable with fig. 6.3, in which tracking stops because a service road lies very close to main carriageway. In the other case tracking stops before the level crossing of fig. 5.5 due to cars waiting for a traffic light. In fig. 5.3 the length of the road detected with the specialized model is even larger than the measured length, because small parts of the roads between the trees were found, while the manual measurement stopped when the number of trees increased. Results on the test set are comparable to those on the learning set. In most cases the measured length is larger than the detected length. The reason why in one case the detected length is considerably larger is that the point where the detected link road starts lies rather far from the real intersection point.

type of link road	length (in m.) from generalized model, resolution 1.6 m.	length (in m.) from specialized model, resolution 1.6 m.	length (in m.) from specialized model, resolution 0.4 m.	manually measured length (in m.)
1-lane	433	434	411	465
	256	266	355	375
	247	178	-	262
2-lane	-	408	400	526
	632	634	636	622
	199	-	-	219
	548	522	518	410

Table 6.16 *Length of link roads in test set*

6.5 DETECTION AND CLASSIFICATION ON LOW VERSUS HIGH RESOLUTION

During development of the system, images of a reduced resolution were used. This is often done, because it reduces the computation time considerably. The average computation time on a Sun4 Sparc Workstation at a resolution of 0.40 m. was about 12 hours for the complete interpretation. One should notice that the complex segmentation routine for detection of junctions takes about 98% of the time. Computation times of interpretation strategies at high resolution in which the routine is not included are more acceptable for practical application.

In this section it is investigated how sensitive the specialized knowledge and image processing techniques are to changes in the resolution. The influence on detection as well as on classification will respectively be determined. Results on the learning and test set are taken together. Section 6.5.1 - 6.5.3 discusses results on detection and section 6.5.4 - 6.5.6 on classification.

6.5.1 DETECTION OF CHANGED PARTS OF CARRIAGEWAYS

Table 6.17 shows the same quantitative evaluation as for the learning and test set at low resolution (table 6.8 and 6.10). At high resolution only one fly-over in fig. 5.7 of the test set was not detected instead of both. The number of not present changed parts reduced slightly, but results are about the same.

Type of carriage-way	Specialized road network model (resolution 0.40 m.)					
	present & detected	not present	not detected	present & detected		
				correct	split	merged
2-lane	23	16	1	17	2	4
3-lane	2	0	0	1	1	0
4-lane	8	1	0	4	0	4

Table 6.17 *Detection of changed road elements in learning and test set at a resolution of 0.40 m.*

6.5.2 DETECTION OF THE FIRST PART OF A LINK ROAD

Compared to the results at low resolution with the specialized road model (table 6.11 - 6.14) the number of detected first parts of link roads, which were not present, increased (table 6.18). One of them does not correspond to a road, but to an elongated clearing between the trees. The reason why it is found, is that a lower threshold of the cross-correlation (0.70 instead of 0.75) is used to accept detected parts and this clearing has a cross-correlation equal to the threshold. This shows that it is actually too low. The number of detected first parts decreased and consequently the number of not detected increased.

Type of carriageway	Specialized road network model (resolution = 0.40 m.)				
	present & detected	not present	not detected	detected / total Y-junctions	detected / total fly-overs
1-lane	0	3	6	0/4	0/2
2-lane	10	2	8	6/8	4/10
3-lane	1	0	1	1/2	0/0
4-lane	4	1	4	4/6	0/2
all	16	6	19	11/20	4/14

Table 6.18 *Detection of the first part of link roads in the learning and test set at a resolution of 0.40 m.*

Totally 55% of the first parts of link roads in Y-junctions was detected using the specialized road model at high resolution. This means a small reduction of the performance compared to a resolution of 1.60 m. In about 20% of the fly-overs the first part of a link road was found.

6.5.3 TRACKING LINK ROADS

The length of the tracked link roads at both resolutions was already given in table 6.15 and 6.16. Also in this case it is not possible to detect a general trend in the differences in length detected by the specialized model at a resolution of 1.6 against 0.4 m. Differences are not too large, except for fig. 5.3 in which the detected length is considerable shorter at a resolution of 0.4 than at 1.6 m. Another exception is fig. 5.9, in which on the contrary the detected length at high resolution is larger, because in this case the location of the changed part is better, which yields that the first part of the link road is not cut off like at low resolution.

6.5.4 CLASSIFICATION OF THE TYPE OF CARRIAGEWAY

The results of classifying the type of carriageway are exactly the same on a resolution of 0.40 m. as for 1.60 m. The same confusion matrices as in table 6.1 and 6.2 can be made.

6.5.5 DISCRIMINATION OF Y-JUNCTIONS FROM FLY-OVERS

The results for recognition of the type of junction at high resolution are worse (table 6.19) compared to the low resolution (table 6.3 and 6.4), especially for fly-overs. Even more fly-overs were recognized incorrect than correct and two complete fly-overs are recognized as Y-junction. In one of them a service road was detected, but in the other one the real link road. Although it starts from a fly-over, it actually has an angle with the main carriageway within the range defined in the knowledge base for a Y-junction. As a conclusion, values for the angle should be adapted based on the learning set for another resolution.

Real type of junction	**Part of junction recognized as type**		**Complete junction recognized as**	
	Y-junction	fly-over	Y-junction	fly-over
Y-junction	19	0	10	0
fly-over	7	4	2	3

Table 6.19 *Results of discrimination of the type of junction on the learning and test set at a resolution of 0.40 m.*

6.5.6 CLASSIFICATION OF THE TYPE OF LINK ROAD

The classifications of 2-lane links road all are correct (table 6.20 and 6.21), just like at the low resolution (table 6.5 and 6.6), but three of the two 1-lane link roads are recognized as 2-lane link roads. It arises that at low resolution these 1-lane link roads were detected when 2-lane link roads are searched, because 2-lane link roads are searched first. Due to rounding off errors at low resolution, the range with widths for searching 2-lane link roads also includes a value within the domain classified as 1-lane link roads. As a consequence the link road is correctly classified. At high resolution the range of widths for searching 2-lane link roads does not overlap with the domain for recognition of 1-lane link roads. However, during detection the 1-lane road yields an acceptable match with the model for a 2-lane link road and as a result a link road is detected which is too wide and misclassified. Consequently 1-lane link roads are not searched any more. One should also note that one of the misclassified 1-lane link roads is rather wide and the manual measurements also would give a classification as 2-lane link road.

Real type of link road	**Recognized as type**	
	1-lane	2-lane
1-lane	2	1
2-lane	0	4
1→2 lane	0	3

Table 6.20 *Results of classification of the type of link road on the learning set at a resolution of 0.40 m.*

Real type of link road	**Recognized as type**	
	1-lane	2-lane
1-lane	0	2
2-lane	0	3

Table 6.21 *Results of classification of the type of link road on the test set at a resolution of 0.40 m.*

6.6 DISCUSSION AND EVALUATION

The previous sections aimed to describe the qualitative and quantitative results as objectively as possible. In this section results are discussed and analysed in order to evaluate the objectives. After the performance is discussed in general (section 6.6.1), the results with incorporation of the standards in the specialized road network model is compared with the results when using the generalized model (section 6.6.2). The other objective, investigation of the influence of different resolutions is discussed in section 6.6.3. Next, in section 6.6.4 performance on detection and classification is compared for the specialized model at both resolutions. Finally, in section 6.6.5, some remarks about practical problems, which occurred during execution of the tests will be made.

6.6.1 GENERAL PERFORMANCE

In images with a rather simple configuration and good road appearance like fig. 5.9 and 5.1, all new junctions and road elements are detected and correctly classified. Use of the generalized road network model gives about the same result as the specialized road model. However, if the road appearance deteriorates, like due to shadows as in fig. 5.2, the specialized model performs better. Also if the configuration is more complex, like a semi-cloverleaf in fig. 5.4, the specialized model gives better results.

The performance of the specialized road model on the test set is comparable to the performance on the learning set for both detection and classification. Because the learning and test set are rather small, 5 and 4 images respectively, it is not possible to compare results quantitatively, but the trends are the same.

A disadvantage of the developed interpretation strategy is the dependence between the successive search actions. If the part of a carriageway at the location of a junction is not detected as changed, the link road will never be found. Therefore, it is necessary to add search actions from detected link roads to find other link roads and junctions, which were not detected at the road which they branch off from. For example, detection of junctions on new link road, as well as at the end of a new link road, can help to detect missing crossing roads. A consequence is that if a link road is tracked and ends near the carriageway, it should be reconsidered if there is a junction at that location. In this way the fourth Y-junction in fig. 6.5 could have been found. Often successive aerial images taken during one flight will be needed, because at a scale of 1:4000 motorway intersections usually cover several photographs. Especially the performance on detection of fly-overs is low. A beneficial addition would be to check whether there is a continuing link road detected at the other carriageway. If it is not detected, it should be searched by re-segmentation. Also the detection of shadows near a fly-over could be helpful, but they are not always present.

6.6.2 GENERALIZED VERSUS SPECIALIZED ROAD MODEL

Addition of knowledge from the standards for road construction proved to be really useful. The effect of addition of knowledge becomes most clear for detection of the first part of a link road using the specialized knowledge. The number of linear structures and other roads nearby which are recognized as link roads is reduced, for example in fig. 6.2. Often these roads are wider or more narrow than a link road or have a larger angle with the main carriageway than a link road in a Y-junction. If these roads, however, fulfil the previous conditions, they are still found, like the roads in fig. 6.4. As a consequence, the first parts of link roads that were detected but incorrectly classified, will be rejected, like one of the link roads in the fly-over in fig. 5.2, which was classified as part of a Y-junction.

Results on the detection of the first part of a link road in a Y-junction are better than for a fly-over. Evaluation of the specialized knowledge learns that most included knowledge to limit the search space is tailored more for detection of link roads in Y-junctions:

- the range for the width of the link road assumes a one-way road, which is the case in most Y-junctions. However, in most fly-overs (for example fig. 5.5 and 5.4) there is a two-way road of which the width exceeds the defined range.
- the length of the search area is based on the maximum curvature of a link road in a Y-junction of a cloverleaf. The curvature of roads in fly-overs is usually less.
- the range of the direction of the link road is more precisely defined for Y-junctions than for fly-overs. The reason is that no distinction is made between main routes and link roads from a Y-junction crossing the motorway by means of a fly-over. The first type usually crosses perpendicular, while the angle of the second type can vary.

This means that more knowledge specific for fly-overs should be added to improve the results. Another motivation for this conclusion is that for Y-junctions the specialized model performed significantly better than the generalized model, while for fly-overs results are about the same.

6.6.3 LOW VERSUS HIGH RESOLUTION

The experiments also made clear that the performance is dependent on the resolution of the images. Geometric constraints in the knowledge base are specified as real-world values. They are based on standards or determined by experiments, i.e. the L/W-ratio and angle. These were determined for low and high resolution separately. Values based on radiometric properties, more particular the threshold for cross-correlation, showed to be rather sensitive to the resolution, even though the lower resolution was computed from the high resolution. A reason is that with the resolution also the amount of detail and therefore the homogeneity changes. For example, cars and road markings are better visible. The images of the high resolution seemed to be less suitable for detection of road elements as a whole than at medium resolution. In conclusion the chosen object scale should coincide with the chosen image resolution.

6.6.4 DETECTION COMPARED TO CLASSIFICATION

Only if the specialized road network model is used, this comparison can be made. In a first observation classification results seem to be much better than results on detection. Especially at low resolution results are very good: all segmented objects are classified correctly except those objects for which the real class is not defined. However, results of detection are worse: at 100% of the locations of a real Y-junction and at about 85% of the real fly-overs the motorway is detected to be changed, but totally only 65% of link roads in Y-junctions is detected against about 30% in fly-overs. As already mentioned in section 6.3.2 one should notice that an incorrect classification can result in omission errors in detection and rejection of the misclassified object. As a result, the bad classification reveals itself in the quantitative measures as a bad detection.

6.6.5 REMARKS ABOUT PRACTICAL PROBLEMS

Suitable digital databases of the outdated situation are in practice often not available. Especially because a database is needed in which the roads are defined as planes and not as lines, representing the road side. Conversion between both definitions is often not direct possible with the available means and consequently additional manual measurements are necessary. Knowledge based techniques have potentials to support this conversion, but this is a research subject on its own. Therefore, in this case study manually measured databases were used for the experiments.

A problem of the photographs from which an image set could be chosen, is that they were already used for manual measurements. As a consequence text and lines were drawn on most images. These caused worsening of the segmentation. During selection it was watched that the photographs contained as little writing as possible. For application in practice it is important that the quality of the photographs is as good as possible. In this case study the quality of the scanned photographs is not optimal, because a simple flatbed scanner was used.

A useful hint is to watch the histogram of grey values carefully during scanning. It should be as wide and smooth as possible, but avoid clipping. If necessary, processing for image improvement which affects the histogram can better be done after scanning, because it should be seen as part of the processing chain and alternative processing is possibly needed.

PART III

CONCLUSIONS AND RECOMMENDATIONS

In this part the conclusions are drawn about the suitability of the concepts for knowledge-based interpretation for the extraction of road networks from aerial images. Besides evaluation of the scientific contribution, also the potential for application in photogrammetric practice will be considered. Finally recommendations for further research are given.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This chapter starts with general conclusions, including an overview of the main contributions and shortcomings of the designed interpretation strategy (section 7.1). More detailed conclusions are given (section 7.2) on both subjects which are emphasized in this thesis:
- interpretation strategy;
- contents of the knowledge base.

The overall conclusion is that addition of knowledge from standards and definition of specialized object types contributes to interpretation. In section 7.3 we deal with the question if this improvement is good enough to make the concepts for knowledge-based interpretation potentially suitable for application in practice. Finally, recommendations for further research (section 7.4) are given.

7.1 GENERAL CONCLUSIONS

In this thesis it is shown that knowledge-based concepts are suitable for extraction of topographic objects, in particular roads, from aerial images. An interpretation strategy is designed which uses both information from an outdated or incomplete road map and a priori knowledge about road networks.

As already noted in the introduction of this thesis, interpretation of aerial images is a very difficult task to automate. Consequently, we are yet far from a fully automatic system for updating of road maps by interpretation of aerial images. The main cause still seems to be the complex contents of aerial images, even though various complicating factors concerning the image contents (see section 1.2.1) were considered during design of the concepts. Both the main contributions and shortcomings of the concepts to solve the problem of aerial image interpretation for updating of road maps will be reviewed. Compared to other work (see section 3.4) in the case study many tests were done on a separate learning and test set, which makes the conclusions more reliable.

7.1.1 MAIN CONTRIBUTIONS

An original contribution is that a road map is used to initiate the interpretation process. Outdated road maps are used to guide change detection, while incomplete road maps are used to find parts of objects which are defined as a whole in the map. The recognized objects, which have a relation with the map, are input for the process of contextual reasoning. As a result the designed interpretation strategy is also applicable for semi-automatic road extraction, because the map can be replaced by manual measurements.

Incorporation of the standards for road construction [Rijkswaterstaat, 1975] in the knowledge base has proven to contribute to the interpretation. Not only because specialized object classes can be recognized very well, but also because these classes help to improve the detection of spatially related objects. The search area, segmentation technique and its parameters can be tailored for the specialized object type, resulting in goal-directed segmentation. Especially errors due to the presence of other linear objects and other roads near the searched road are reduced, but cannot be prevented completely. No special attention was given to the design of low level image processing techniques. However, because in previous work hardly any techniques were used for grey-value based segmentation of junctions, it needed to be developed.

In contrast to other work the knowledge bases used in this thesis are part of a framework for a complete road network model, covering multiple scales of imagery. The connection between various scales reflexes the complex composition of parts of road networks. In order to handle a certain application, the knowledge base at a certain level of detail can be created by definition of specialized object classes and spatial relationships. This framework including the defined object classes and relationships can contribute to the design of a data model of an object-oriented road database, integrating multiple levels of detail.

7.1.2 MAIN SHORTCOMINGS

Whether interpretation is successful, heavily depends on the result of segmentation. Although goal-directed segmentation contributes to the improvement of the detection of roads, there are still roads which are not recognized, because they are not segmented. Segmentation remains the weakest part of the interpretation process. It is also the most time-consuming step in the interpretation strategy.

One of the reasons for omission errors is the limited part of the road network covered by the photograph. In case a junction lies near the image border, the position where to start the search for a new link road, will often not be optimal. This problem can be solved by using neighbouring photographs. If the road network is seen as completely covered by photographs, a new road element can be searched from two junctions, which increases the chance to find it. A shortcoming of the concept of object relations in the database is that only 1:1 relations are possible. Consequently, relations like the road between two junctions cannot be defined directly. Especially when neighbouring photographs are used, the need to define n:m relations will increase.

Inherent to the choice to use contextual relationships to search new objects is that a chain of successive search actions is formed. As a consequence omission errors also cause that other spatially related objects are not found. Therefore, one should carefully watch during the design of an interpretation strategy that there is more than one way to find every object and that re-segmentation is done. The interpretation strategy designed in the case study did not include enough alternatives for detection.

Summarizing, main contributions are the way in which outdated or incomplete maps are utilized in the interpretation strategy and the incorporation of standards for road construction in the knowledge base. Main shortcomings are that only 1:1 relations can be modelled in the knowledge base, the dependency between successive search actions and that segmentation remains the weakest part of the interpretation strategy.

7.2 EVALUATION OF THE DESIGNED INTERPRETATION STRATEGY FOR ROAD EXTRACTION AND CONTENTS OF THE KNOWLEDGE BASE

The design of an interpretation strategy is one of the main objectives of this thesis. Main contributions and shortcomings concerning the interpretation strategy were already mentioned in section 7.1. In this section the interpretation strategy will be reviewed in more detail. In the interpretation strategy low level processing (segmentation, classification) is integrated with high level reasoning (hypothesis generation, inconsistency detection). The concepts for design of each of these four stages will be evaluated next. The contents of the knowledge base plays an important role in the evaluation of the interpretation strategy.

7.2.1 HYPOTHESIS GENERATION

In the designed interpretation strategy for updating road maps, generation of hypotheses is initially guided by an outdated or incomplete map. The utilization of maps to initiate the interpretation process proved to be useful compared to previous work [e.g. Cleynenbreugel 1990, Hwang 1986], in which road extraction starts with initial segmentation of the whole image. Initial segmentation is often weak, while the objects and values of their derived attributes that maps provide are more accurate and reliable. This is important because omission and commission errors propagate during the interpretation process. The tests in the case study show that carriageways from the database can very well be classified into specialized object types. Consequently, the generated hypotheses about which specialized object types can be expected, have a better defined search area and more precise constraints for recognition than for generalized object types. As a result the number of omission and commission errors decreased in the case study.

Maps can also be useful when including radiometric models. In the case study the location of the carriageways from the map in the photograph was used to make a grey-value based profile model of the road. Because the aerial images in the case study originate from different flights and were taken at different times and seasons, the intensities of the various images differ considerably. However, the same values for the radiometric parameters give comparable results on training and test set, because the map was used to create the profile model.

Hypotheses concern changed or new roads, present in the context of changed roads. In order to generate hypotheses about changes, the assumption is made that there is only a limited number of changes which requires map updating. These hypotheses are defined in the knowledge base as an outdated object which changes into a new object. In reality changes are not always as simple as that. This makes the situation in the case study a little unrealistic. Often, it will be hard to indicate to which object the change is related and there will be more than one changes. Thus the relation will be n:m instead of 1:1. In the situation used for the case study for example, there usually is not only a part of the road which changes into a new junction, but also a part of the road which becomes wider because of the slip-road connected with the new link road. Because the low level image processing technique for change detection cannot discriminate both cases, often both parts of the road are merged, resulting in a non-optimal position to search the link road from.

The concepts are more suitable for definition of hypotheses about the context. There are often clear constraints about the location of one object in relation to the other, e.g. perpendicular, parallel, etc. These constraints make contextual reasoning into a powerful mechanism for hypothesis generation. Some of these constraints can be obtained from standards for road construction.

7.2.2 GOAL-DIRECTED SEGMENTATION

In general, segmentation is the weakest part of the interpretation strategy. The solution to use specific segmentation techniques, with parameters and a search area tailored for detection of specialized object types, improves the segmentation. These facts all contribute to the reduction of both the number of commission and omission errors.

A consequence of the use of a specific image processing technique for each object type is that for resembling object types the parameters should be tuned and the search area restricted such that the object type resembling the searched type is not detected instead. If matching is used for segmentation, this turned out to lead to inaccurate detection and misclassification. In the case study for example at high resolution most 1-lane link roads are detected and classified as 2-lane link roads, because these were searched first and the criterion for matching is not strict enough to make a distinction between both types. However, if the criterion had been stricter, there is more chance that the results become more dependent of the training set.

The use of knowledge from the standards for road construction [Rijkswaterstaat, 1975] to determine values for the parameters proved to be fruitful. Especially knowledge about the width of several road types reduces the search space and can directly be used as parameter for segmentation. Other knowledge, for example the maximal curvature of the road, can be used within the image processing routine in order to derive variables of the technique, like step size for road tracking. One should notice that tuning of parameters which are not based on the standards is not easy. It should be done by experiments on the training set. The problem is that parameters often depend on each other and results are difficult to judge. Even though it was tried to avoid dependency on resolution by using a scale factor for geometric attributes, still results were optimal for the resolution on which the parameters were tuned.

In the case study it was proved that restriction of the search area by introduction of knowledge from the standards for road construction [Rijkswaterstaat, 1975] reduced the number of commission errors. Because, in case of detection of the first part of a link road in a Y-junction, only one object is segmented within the search area, often also the number of omission errors reduces, because the object which causes the commission error is not detected, the real link road matches best. Obviously objects not fulfilling the standards and present outside the search area will never be found, so the number of omission errors can increase a little. The restriction of the search area is one of the main reasons why in the case study the complete interpretation process with use of the specialized road model was in total almost six times faster than in case the generalized model was used.

7.2.3 OBJECT RECOGNITION

A conclusion from the experiments in the case study at different resolution is that the choice of objects and their properties should correspond to the chosen image resolution. Further research should be done in order to determine the allowed range of resolutions for a certain object definition.

Three levels of detail are defined in the overall road network model, covering multiple scales: small, medium and large. Relations between objects at different levels can be used to represent knowledge corresponding to the problem of automating map generalisation. This is a complete area of research. In this thesis only relations between objects at one level are considered. At each level two kinds of objects are discriminated:

1) generalized objects, corresponding to parts of the road network in general terms;
2) specialized objects, corresponding to detailed real-world classifications of parts of the road network.

In the case study it was proved that definition of specialized object types not only has the advantage of more precise classification, but also of better performance than the generalized objects. The main reason is that more knowledge from the standards for road construction can be attached to specialized object classes.

In order to recognize the segmented objects, their attributes are compared with a range of allowed values attached in the knowledge base to each attribute of the searched object type. A conclusion from the case study is that in general the classification is good. It is possible to discriminate specialized object types. However, results are a little bit misleading, because a misclassification can cause that another object with essential relationships is not detected and consequently the misclassified object is rejected. In conclusion: a good classification can coincide with bad detection.

Ranges of attributes are fixed and if they are used to discriminate various specializations within one object class, like in the case study, they are mostly not allowed overlap, because only one feature is used. However, manual measurements for determination of these ranges show that some ranges overlap, because these objects resemble each other. One comment is that the set of attributes included in the road model should be extended with other features such that resembling objects can be discriminated. However, it will be very difficult to find such features. Another comment is that it would be better to use probability distributions of the attributes instead of ranges. Especially in case of objects which are hard to classify as a certain type, (for example, the link roads in fig. 5.5 which start as 1-lane link roads and ends as a 2-lane link roads) the uncertainty in the classification would then become more clear. Uncertainties larger than a predefined threshold could be handled as inconsistencies and lead to alternative hypotheses. Vosselman [1996] gives an overview of different ways of representing uncertainty in data and processing of uncertain data. However, the problem is that probabilities are needed to describe the uncertainty in the model, but these uncertainties and the way in which they propagate during processing are both unknown.

7.2.4 INCONSISTENCY DETECTION

As a matter of fact, inconsistency detection executes the bottom-up feedback and in this way realizes a hybrid control structure. This stage of processing contributes to a better performance of knowledge-based compared to traditional image processing. Not only inconsistencies between the same type of topographic objects can be detected, but also between different classes of topographic objects.

In order to handle inconsistencies alternative definitions for object recognition as well as alternative techniques, parameter settings and search areas can be defined.
Alternative object definitions are useful to model exceptions to specialized object types. For example, the width of a 2-lane carriageway without hard shoulder in fig. 5.7 of the case study could be defined in an alternative object definition. These alternative definitions can always be replaced by separate object definitions. For this reason they were not used in the case study.

It is generally acknowledged that different segmentation techniques should be combined into effective image analysis processes. Different segmentation techniques which are combined by a logical "or" can be defined as alternative segmentation techniques. If the conditions for combination are more complicated, integration should take place within the technique itself or each technique should be attached to a different specialized object type and object relation.

In conclusion, both the utilization of maps for hypothesis generation and goal-directed segmentation reduce the number of omission and commission errors. A disadvantage of goal-directed segmentation is the danger of misclassification of resembling object types. Knowledge from the standards for road construction is useful for goal-directed segmentation in order to determine values of parameters and restrict the search area. It is also useful for recognition of specialized object types, which not only can be recognized very well, but also improve the performance. Object models have a range of resolutions on which they perform optimally. 1:1 relationships and fixed ranges of attributes in the knowledge base are not sufficient to model every situation. Inconsistency detection and handling contributes to a better performance. Explicit modelling by the use of alternative image processing techniques, parameter settings and search areas should be weighted against each other.

7.3 POTENTIAL FOR PUTTING THE CONCEPTS INTO PRACTICE

At this stage of development the concepts are not yet mature enough to be put in practice as a fully automatic process. In this section the potential of the concepts to be put into practice will be discussed for medium scale applications, like in the case study, other scales, semi-automatic processing and interpretation of other topographic objects than roads. Finally prospects for the future will be given.

7.3.1 POTENTIAL FOR GIS-GUIDED MEDIUM SCALE ROAD EXTRACTION

In this section the potential of putting the concepts into practice for the situation in the case study is discussed. This means the use of outdated road maps to guide the interpretation of medium scale scanned aerial photographs in order to detect medium scale road elements and junctions. The updating situation in the case study will not often happen in practice. Besides, it is a rather complex task, of which the subtasks depend on each other and the search space is large in both location and type of objects. Simpler tasks concerning the detection of well-defined changes with little impact on the rest of the road network have more potential to be successful in practice. An example is the detection of an extra lane on a stretch of road, which does not affect junctions. This means that these concepts can only be applied on a limited set of pre-selected photographs of a photo flight.
The idea to guide the interpretation process by an outdated or incomplete map and further by contextual relationships is essential to extract meaningful objects instead of geometric primitives. Classification of detected objects is very well possible. Besides, the use of maps limits the search space and consequently reduces the complexity of the task. As a result, the additional use of more information, like predicted locations of new roads obtained from road planning, will enlarge the potential to handle more complex updating situations.

7.3.2 POTENTIAL FOR OTHER SCALES

A conclusion from the case study is that the performance reduces if the same knowledge base is used at another scale. However, this does not mean that the concepts would not be applicable at another scale. But the contents of the knowledge base needs to be tuned for the other scale.

Preliminary experiments on SPOT-images (fig. 7.1 - 7.6) obtained by a little tuning of the values in the generalized road network model show reasonable results. The main difference is that at this scale a new road needs to be searched at both sides of the main road. The examples of detection of road markings on the road surface (section 4.8) already showed that the concepts are also suitable for large scale applications.

Because the generalized road network model contains general properties of roads, it can easier be adapted for another scale. The specialized road network model includes specific properties of specialized types of objects, while at another scale other objects need to be defined. In general, a specialized road network model should be designed for a specific range of resolutions. It should be examined for each knowledge base within which range it can be used.

Fig. 7.1 *Panchromatic SPOT image near Toulouse (Verfeil), France (320*320 pixels)*
© SPOT Image CNES

Fig. 7.2 *Result of detection of junctions and link roads in the SPOT image of fig. 7.1*

Fig. 7.3 *Panchromatic SPOT-image near Toulouse, France (320*320 pixels)*
© SPOT Image CNES

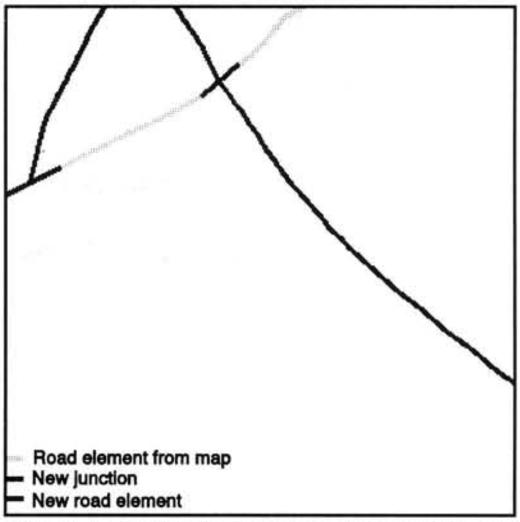

Fig. 7.4 *Result of detection of junctions and link roads in the SPOT image of fig. 7.3*

***Fig.* 7.5** *Panchromatic SPOT-image near Dubai, United Arabic Emirates (800*800 pixels) © SPOT Image CNES*

***Fig.* 7.6** *Result of detection of junctions and link roads in the SPOT image of fig. 7.5*

7.3.3 POTENTIAL FOR SEMI-AUTOMATIC PROCESSING

Because there are many exceptions to the standards and large variations within object classes, building a fully automatic system is not possible at this moment and it is doubtful if it ever will be. There will always remain work which has to be done manually by the human operator. Therefore, it is important to evaluate whether the concepts support inclusion of semi-automatic processing.

Various scenario can be considered:

1) Road tracker can be used as interactive tool
   The image processing technique developed for tracking the link roads can be used independently of the control mechanism and be driven by a human operator who indicates the points on the road where tracking starts. Results are given in [Gunst et al., 1991] and [Vosselman/Knecht, 1995]. This tool is most suitable for small scale and medium scale images. In order to detect the complete road network, a variant is thinkable in which the operator draws a rough sketch of the road network by indicating the junctions and which ones are interconnected.

2) The control mechanism can be used to guide the human operator to predicted positions of objects to be measured
   Instead of full-automatic image processing techniques defined within object relations, semi-automatic or even manual procedures are attached. The defined search area serves to zoom in

at a location in the image where the operator should measure. Constraints between related objects can be used to check whether everything is measured.

3) Measure a part of the objects manually and a part automatically
Just like the objects from the database of the old situation initiate searching new objects, also manually measured objects can be used for this purpose. One could measure objects which are difficult to detect automatically, like the road side. The road side is often hardly visible because it lies under the crash barrier, which cause aliasing effects during digitizing. The results of the case study showed that manually measured objects can be classified into more specialized classes automatically. These manually measured objects can be used to initiate searching automatically other objects. An example is detection of road markings from the road side, which have the potential for successful automatic detection, because they are clearly visible linear objects on a homogeneous background.

7.3.4 POTENTIAL FOR OTHER TOPOGRAPHIC OBJECTS

In this thesis interpretation of parts of the road network for updating of road maps is emphasized. Beside the detection of roads, it was shown that it is also possible to detect objects related to the layout of the road surface, like lanes. In the examples in section 4.8 it was already shown that the concepts are also applicable for detection of road markings. These road markings could be used to subdivide the road surface into lanes, hard shoulders and correction strips.

Related to road extraction is the detection of other linear topographic objects, like rivers, because similar image processing techniques can be used. Water surfaces, like rivers, channels and lakes are easier to segment than roads, especially in infrared images. However, fewer knowledge can be included because they are formed naturally and not according to standards.

Build-up areas are difficult to segment. There have been attempts to detect build-up areas at small scale by using texture [Baraldi/Parmiggiani, 1990] or to detect buildings at large scale by using shadows [Liow/Pavlidis, 1990]. Especially at large scale there are strong spatial relationships between buildings and roads, which could be used for detection.

7.3.5 FUTURE PROSPECTS ON AUTOMATIZED AERIAL IMAGE INTERPRETATION

Fully automatic interpretation of all topographic objects in aerial photographs in order to make maps will not be possible in the near future and it is doubtful if it ever will be. If a map of the old situation is used, possibly in case of small changes, and precisely described under which conditions, map updating can be done fully automatic in the near future.

At this moment we should concentrate on semi-automatic solutions. Especially detection should be done manually or for a limited task, because errors propagate quickly. Commission errors can be prevented by inclusion of many constraints which can be used for inconsistency detection.

Omission errors can be prevented by defining multiple relations to search objects. It is expected that techniques for detection become available object by object. In the near future some topographic objects can probably be measured automatically, but some still need to be measured manually. Looking at the amount of research on road extraction, roads will probably one of the first objects that can be extracted automatically.

7.4 RECOMMENDATIONS

Suggestions for further research are related to the main shortcomings discussed in section 7.1.2. Because segmentation remains the weakest part of the interpretation process, research in order to improve low level segmentation techniques is still necessary. Special attention should be paid on the development of integrated segmentation techniques for the detection of meaningful objects instead of lines. This kind of techniques are needed for goal-directed segmentation.

The concept of object relations should be changed such that it can also handle n:m relationships. This is not only needed to search objects spatially related to two objects, but also to detect inconsistencies concerning more than two classified objects. More attention should be paid to examine which inconsistencies can be defined during object modelling and within the road network model in particular.

The designed interpretation strategy seemed to be rather sensitive for the resolution of the images. It should be investigated in which range of resolutions objects defined at the three levels of detail can be used.

Just like a complete block of photographs is handled in the manual mapping process, also in the digital process neighbouring photographs should be used in the interpretation strategy. Especially because spatial relationships are used and related objects can be present on different images, this is essential in order to improve results.

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APPENDIX A

PHOTOGRAMMETRIC PROCESSING OF DIGITAL IMAGERY

This appendix aims to show how the subject of this thesis fits within the current automation of photogrammetric processing. Traditionally creation and updating of topographic information using aerial images as input was always the main task of photogrammetry. With the transition from analogue to analytical and now to digital photogrammetry the need of such information did not change. But the methods used to process the imagery changed considerably and need to change even more if photogrammetry wants to keep up with technological developments in other fields as discussed in section 1.1. Especially manual tasks will change drastically. The role of the human operator becomes more and more that of a supervisor who controls processing.

An essential change of digital photogrammetry compared to analytical photogrammetry is that input as well as output of processing are both in digital format. Output results are stored in topographic databases of GIS rather than on paper. Input for large-scale mapping are still analogue aerial photographs which need to be scanned before or during processing. An important difference is that the computer can directly access the image contents when using digital imagery. If we can develop computer programs to extract information from the image which is presently captured manually, this will yield benefits in time and money.

In this appendix the manual tasks in the analytical processing chain will be discussed followed by the state-of-the-art of methods for automation of these tasks in digital photogrammetry and bottlenecks for automation. We will only consider if the automation of tasks is scientifically solved and can be applied in practical work conditions, not if these algorithms are available on digital photogrammetric workstations. Also planning the photogrammetric process, taking photographs and terrestrial measurement of ground control points are outside the scope of this thesis.

A.1 MANUAL TASKS IN ANALYTICAL PHOTOGRAMMETRIC PROCESSES

For most applications the present photogrammetric process consists of three phases (fig. A.1):
1. pre-processing
2. information extraction
3. presentation

Manual tasks in an analytical processing chain will be described subsequently for each of these phases. Numerical calculations have long been carried out automatically and are not listed here. More details can be found in general text books about photogrammetry like [Wolf, 1983].

During the pre-processing phase orientation of the photographs and aerial triangulation are performed. The aim of orientation is to establish the relationship between local coordinate systems in the image and national coordinate systems in object-space, principally based on the mathematical description of the bundle of rays in the camera. Distinction can be made between interior, relative and absolute orientation. The next manual tasks are performed during orientation:

- measurement of image coordinates of the fiducial marks present in the camera in order to relate image coordinates to camera coordinates (interior orientation);
- selection and measurement of image coordinates of geometrically well distributed points on the overlap of two stereo images, called tie points, in order to relate two camera coordinate systems, which yields a stereoscopic model (relative orientation);
- selection and measurement of image coordinates of known terrestrial positions, called ground control points (GCPs), in order to relate this stereoscopic model to the coordinate system in object-space (absolute orientation).

The aim of aerial triangulation is simultaneous calculation and adjustment of relative and absolute orientation parameters of multiple images in order to reduce the number of GCPs, which need to be measured by ground survey. Besides manual tasks for relative and absolute orientation an additional manual task for aerial triangulation is:

- point transfer and marking of tie points on the photographic material.

Information extraction is done for a wide range of products, e.g. a topographic database or a digital terrain model (DTM). The manual task for all these products could be defined as:

- selection of object points that should be present in the map and measurement of image coordinates.

For presentation of topographic information in GIS these coordinates need to be converted to a topologically structured database during the last phase. Because of the suitability of orthoimages to serve as pictorial background information in GIS, their generation can be seen as a way of presentation as well. Orthoimages are rectified for the projective transformation in the camera and get the same orthogonal projection as a map. They are today the most successful product of digital photogrammetry and are increasingly becoming an additional layer in GIS. Since digital orthoprojection is available in commercial digital photogrammetric workstations, automation of manual tasks will not be discussed here. The reason why they are mentioned is because of their potential for GIS updating.

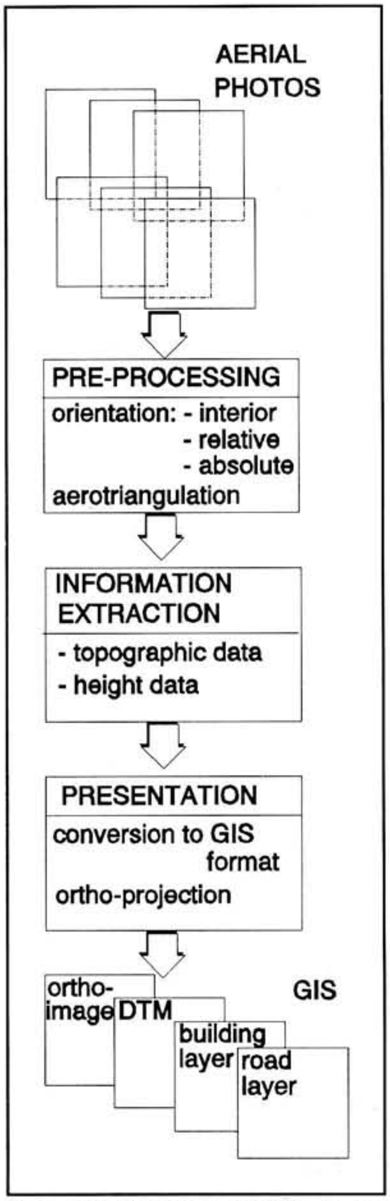

Fig. A.1 Phases and tasks in the manual photogrammetric process of GIS production

A.2 STATE-OF-THE ART OF AUTOMATIC PROCESSING

Nowadays automation in the digital domain is already possible for a substantial part of the list of manual tasks from analytical photogrammetry. However, the degree of automation differs from fully automatic solutions to semi-automatic interactive solutions.

Pre-processing tasks are mainly geometric tasks with the aim to establish the relation between aerial photograph and the terrain using camera models. In [Förstner, 1991] it is claimed that these tasks could at that time already be solved nearly automatically using available techniques of image analysis and could be expected to be nearly fully automated within the next years. Current solutions will be addressed briefly together with prospects for the near future.

Measurement of fiducial marks
Automatic interior orientation is fundamentally straightforward. Because there is only a limited set of different types of fiducial marks their shape is well-defined. Besides they have distinct radiometric properties, that is black colour, usually represented by very low grey values. There is only the problem of a varying background [Förstner, 1991]. Solutions for interior orientation by measuring fiducial marks are commercial available [Mayr, 1993].
In many digital cameras the sensor remains fixed. This means that interior orientation is not necessary. However, in the near future photogrammetry will still rely on scanned analogue photographs since digital cameras with a sufficient ground resolution are not yet available.

Measurement of tie points
Automatic relative orientation has been a popular topic of research for the last decades. A number of working solutions are available. An advantage of digital photogrammetry is that more than two overlapping images can be used simultaneously. The basic strategy behind fully automatic relative orientation [Schenk et al. 1991, Hellwich et al. 1994] is the use of a large number of less accurate points in stead of a few (usually 6 or 15 points per image) very accurate tie points in analytical photogrammetry. This has proven to lead to the same accuracy of the orientation, however to a much better confidence level. A large amount of automatically extracted point features are input for a hierarchical feature based matching approach. A preliminary list of candidate conjugate points is made using area-based correlation for detected feature pairs. Parameters of the relative orientation are iteratively calculated at each level of the image pyramid using robust least squares bundle adjustment. Instead of area-based matching Tsingas [1994] uses a graph-theoretical model for determination of corresponding point features. Digital image processing techniques like edge detection resulted in new viewpoint for relative orientation. Petsa and Patias [1994] formulate mathematically the use of straight linear features instead of tie-points, however, no results on real aerial images are given.
Systems in which measurement of tie point is carried out automatically under guidance of a human operator are commercially available [Han 1992, Heipke 1995].

Measurement of control points
Identification of GCPs is more difficult than identification of tie points, since they correspond to meaningful points measured in the terrain and cannot be chosen arbitrarily. Semi-automatic

measurement of GCPs [Heipke 1995, Lammi 1994] are feasible for commercial application. The first successful attempts for establishing automatically the correspondence between image and GCPs apply feature-based matching [Schickler, 1992] and relational matching [Haala/Vosselman, 1992]. A quite different approach by Ebner and Ohlhof [1994] skips identification of GCPs in the image, but measures three points near each GCP based on the assumption that these points lie on the same inclined plane as the GCP. This method can only be used in case of sufficient relief. Possibly, the GCP identification problem disappears when the camera orientation can be determined during the flight using GPS [Colomina 1988]. In this case the whole aerial triangulation, and with it the manual task of point transfer, becomes superfluous.

Point transfer
Marking of tie points can be skipped in digital photogrammetry. Points are transferred automatically at the time they are measured by matching techniques. Image matching improves the accuracy of point transfer [Jaakkoli/Sarjakoski, 1994].

Although the manual task during information extraction, measuring three dimensional coordinates for every object point present in the map, looks the same for every product, there is an important difference. One should discriminate extraction of two types of data: topographic information and height information.

Extraction of topographic information
Topographic information are objects like houses, roads, rivers, railways, etc.. During their manual extraction the operator also declares the type of object from which three dimensional coordinates are measured. This means that points to be measured are selected based on (unconscious) recognition and classification of topographic objects. Automation of this task is very hard.

Some semi-automatic solutions are promising to support the manual task of the operator, however, according to Heipke [1995], these algorithms are not yet mature enough to be used in commercial digital photogrammetric workstations. Many road following algorithms have been developed. Basically there are two approaches:

1. Extrapolation from a manually indicated road seed using e.g. homogeneity criterion along the road [Airault et al. 1994], edge detection and following [Heipke et al. 1994], a combination of dynamic programming and profile analysis [Gunst et al. 1991].
2. Interpolation between roughly manually indicated road points of the complete road by using e.g. dynamic programming [Grün/Li 1994] or snakes [Fua/Leclerc 1990].

Snakes are used for the extraction of house contours as well. In [Gülch, 1990] energy minimization techniques are used to determine automatically a more precise position of a roughly manually indicated contour. A drawback of this method is that the number of parameters to be set is very high and probably different for various photographs. McKeown [1991] and Garnesson et al. [1990] both combine edge-line intensity based techniques as well as shadow-analysis based techniques to detect buildings.

Full automatic extraction of topographic information is nowadays far beyond being applicable in photogrammetric practice. Early work of for example Bajcsy and Tavakoli [1976] and Fischler et al. [1981] is based on detection of lines, more then on recognition of roads and is therefore too unreliable. Cleynenbreugel et al. [1991] and McKeown [1990] use more specific properties of roads. However, the extracted network is still far from complete. More literature about extraction of roads will be reviewed in chapter 3. Although McKeown [1991] claims to detect almost all the buildings, the percentage of correctly identified pixels of buildings is 77.7%. This means that a lot of manual editing work should be done afterwards.

Extraction of height information

Height information is usually represented as DTM or as a single height profile. Selection of points is mainly based on numerical grounds, e.g. at a certain distance from the last point. The height at this position is the desired information. The measurement of breaklines is an exception which needs selection of points. Breaklines are lines were the slope changes significantly. Just like for extraction of topographic information the meaning of the selected point is important.

Automation of generation of DTMs has been attempted for the last decades. The solution in [Hahn/Förstner, 1988] and [Krzystek, 1991] is based on a hierarchical matching approach. A DTM taken from each previous level of an image pyramid is used to predict approximate positions of corresponding points at the current level. Feature based matching, eventually followed by least square matching to improve the accuracy, results in a list of corresponding point pairs. These pairs are transformed to object space using robust estimation. In [Schewe/-Förstner, 1986] it is shown that this approach can also be used for measurement of height profiles. Grün and Baltsavias [1987] combined grey-level correlation with geometric conditions in a so-called adaptive least squares correlation. Furthermore Grün and Baltsavias [1988] showed that more than two images could be processed simultaneously. This work contributed to a new approach: DTM generation formulated in object space [Wrobel, 1987]. The strategy is to improve iteratively approximate height and orientation parameters by minimizing the differences of two orthoimages, calculated with approximate values [Heipke, 1993]. This is done at every level of an image pyramid. An advantage of this approach is that it is possible to process simultaneously more than images, which increases the robustness. Furthermore an orthoimage is produced at the same time, which can be used for presentation in GIS.
Operational solutions are nowadays available for medium and small scale imagery with rich texture. Large-scale imagery, especially of build-up areas, is still subject to blunders, but semi-automatic approaches give promising results for those images [Heipke, 1995].

A.3 BOTTLENECKS FOR AUTOMATIC PROCESSING

An aerial image is a two dimensional representation of the three dimensional world. Since satellite images and small scale photographs are taken high above the ground, the shapes of the objects change only little with the camera position. However, for large scale photographs the shape changes considerably. This is a complicating factor for interpretation, but also for DTM generation. Besides, in a single image the x,y-position of the objects is not correct. Using orthoimages as input can reduce this problem. Fundamentally it would be better to use stereo images just like in analytical photogrammetry, but that will bring associated complications. Two-dimensional flat objects do not have this problem.

Information extraction is the most time-consuming part of the analytical production process. Thousands of points often have to be measured, whereas orientation and aerial triangulation only need a few dozens of points per stereopair. Extraction of height information can be performed automatically with the current state-of-the-art of digital processing. However, extraction of topographic information remains very labour-intensive, also with the described semi-automatic tools.

Analysing the state-of-the-art of automation in digital photogrammetry, the conclusion can be drawn that tasks where interpretation capabilities are involved are bottlenecks for automation. Understanding the meaning of what is extracted from the image by the human operator is done unconsciously. However, the principle on which extraction of so-called semantic information is based is unknown. Therefore it is very difficult to formalize this ability, but this is required for automation.

APPENDIX B

GLOSSARY OF ROAD TERMS

All terms in this thesis which are related to road networks are explained in this appendix in alphabetical order. The terminologie of the Highway Code [Department of Transport, 1995] is adopted as much as possible. However, for some road terms related to the Dutch situation, like a "Haarlemmermeer solution", it is impossible to find an existing English road term. In these cases Dutch terms are translated as literally as possible. One should notice that some similar English terms have a specific meaning within this thesis. For example, "intersection" is used at small scale and "junction" is used at medium scale. This specific meaning is expressed in the explanation of the concerning road terms.

block line	specific type of road marking at large scale consisting of a row of square blocks which indicate the separation between a traffic lane and a slip-road
carriageway	specific type of road element at medium scale being the part of the motorway intended for through traffic
central reservation	area which separates two carriageways, usually covered with vegetation
cloverleaf	standard solution to construct a T-interchange, which enables traffic flow at a motorway intersecting at different levels, forming the pattern of a four-leaved clover
correction strip	specific type of traffic area at large scale being a narrow paved strip at the inner side of the carriageway which is present in case a hard shoulder is absent
crash barrier	protective metal obstruction in order to prevent cars go off the road
crossing	specific type of road junction at medium scale in which case traffic can flow at the same level from one road to another, usually guided by traffic lights
dual carriageway	physically separated carriageways of which each has one-way traffic in the opposite direction
edge line	specific type of road marking at large scale, being a unbroken white line, which separates the outermost traffic lanes from the hard shoulder or correction strip
fly-over	a specific type of road junction at medium scale in which case a bridge carries one road over another road at a different level

"Haarlemmermeer" solution	standard solution for construction of an interchange with four link roads, forming the pattern of a diamond, ending at two crossings which are connected by a fly-over, called after one of the places where it is applied
hard shoulder	a specific type of traffic area at large scale being a lane at the outer side of a carriageway on which only in exceptional circumstances traffic is allowed to drive or stop
interchange	specific type of intersection at small scale between a motorway and a main road at small scale, in which case both roads continue
intersection	whole of road elements and junctions at the point where a motorway intersects with another road at large scale
junction	collective term for the point where two road elements meet, unite or cross at medium scale
lane line	specific type of road marking at large scale, being a broken white line, which separates two traffic lanes and can be crossed
link road	specific type of road element at medium scale which enables traffic to flow from one carriageway to another
main road	specific type of road at small scale being an important (paved) road which connects cities and has motorway access
motorway	a specific type of road at small scale which is specially constructed for fast motor traffic and has a limited access from other roads by means of intersections
motorway intersection	specific type of intersection between two moterways at small scale in which case both motorways continue
overpass	place at small scale where a paved road passes over or under a motorway and looks like an intersection in 2D, but there is no motorway access
road element	collective term for stretches of road between two junctions at medium scale
road marking	collective term for lines or symbols with a specific meaning which are painted on the road surface in order to guide the traffic flow
roundabout	specific type of road junction at medium scale in which case traffic moves in one direction round a central island

service road	specific type of road element at medium scale which runs separated and parallel to motorway and is utilized to access service areas, houses, shops, etc.
single carriageway	carriageway with two-way traffic, which is not separated by a central reservation
slip-road	specific type of traffic area at large scale being an elongated taper lane utilized to join or leave a motorway at a Y-junction
T-interchange	specific type of intersection between a motorway and a main road at small scale in which case the main road ends at the motorway
T-intersection	specific type of intersection between two motorway at small scale in which case one moterway ends at the other
traffic area	collective term at large scale for all regions on the road surface with a specific function for traffic, like traffic lanes, hard shoulders and slip-roads
traffic lane	specific type of traffic area at large scale being a division of a carriageway for a stream of traffic
triangular mark	specific type of road marking at large scale being a white solid triangle which indicates that a at this point the slip-road leading to a link road leaves the main carriageway
Y-junction	a specific type of junction at medium scale at the point where traffic leaves a main carriageway by means of a link road

APPENDIX C

ADDITIONAL SUBJECTS ON DETERMINATION OF PARAMETER SETTING FOR IMAGE PROCESSING TECHNIQUES

C.1 INFLUENCE OF A CHANGE IN ROAD WIDTH ON THE CROSS-CORRELATION

In section 5.7.2 the setting of one of the parameters in the image processing technique for change detection, the threshold for the cross-correlation, is determined. This threshold needs to be chosen such that a significant change in width of the road due to the presence of a junction is detected. For this purpose the mathematical relation between the cross-correlation R_C and a change in width Δw between a road in the profile model and the extracted profile is derived in this appendix. Both a wider main road due to a slip-road and the presence of a link road close to the main carriageway are considered to indicate the presence of a junction.

The calculation is done for an ideal case in which the other road, with width Δw, has the same constant grey value (G+DG) as the main road, with width w, and the background has a constant grey value G. The profile for this ideal case is drawn in fig. C.1. In this figure the other road is merged with the main road, but the derivation of the threshold for the cross-correlation is also valid if both are apart. The total width of the profile is defined as a factor x times the width of the main road (w), thus xw.

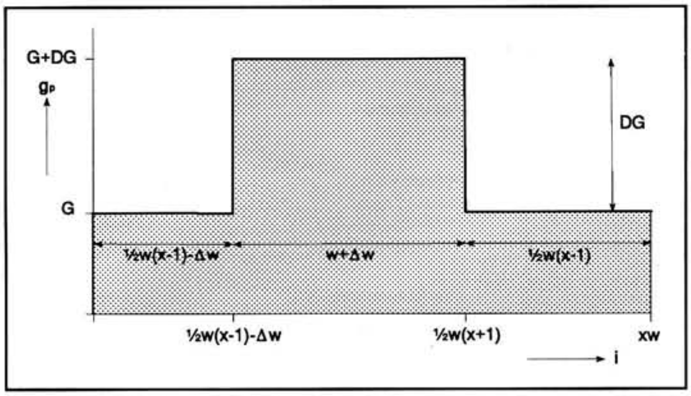

Fig. C.1 Artificial profile

The profile model is drawn in fig. C.2. Because the profile model is assumed to be correct for the considered profile, except for the presence of another road with width Δw, the road in the profile model has width w. Its grey value is g+dg. The background has grey value g. The width of the profile model is equal to the width of the extracted profile, xw.

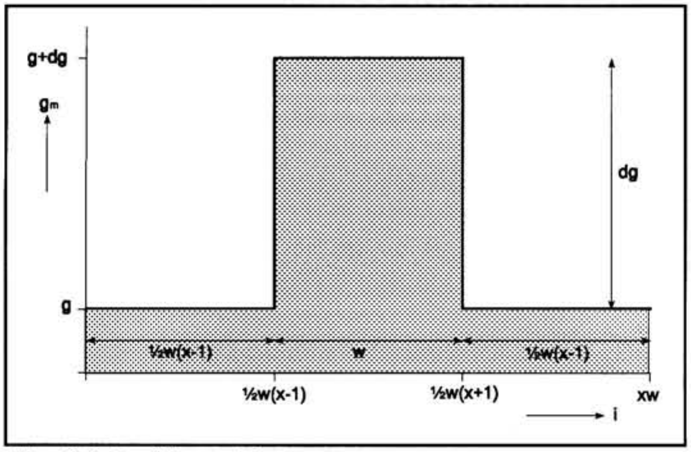

Fig. C.2 Profile model

In this case the cross-correlation R_C is given by:

$$R_C = \frac{\sum_{i=0}^{xw-1} (g^p(i) - \overline{g^p}) * (g^m(i) - \overline{g^m})}{\sqrt{\sum_{i=0}^{xw-1} [g^p(i) - \overline{g^p}]^2 * \sum_{i=0}^{xw-1} [g^m(i) - \overline{g^m}]^2}} \qquad -1 \leq R_C \leq 1 \qquad \textbf{(c.1)}$$

$g^p(i)$ grey value of pixel i in profile

$\overline{g^p}$ mean grey value of the profile

$g^m(i)$ grey value of pixel i in profile model

$\overline{g^m}$ mean grey value of the profile model

From fig. C.1 and C.2 it can be derived that the mean grey values of the artificial profile and the profile model can be calculated from:

$$\overline{g^p} = G + \frac{(w + \Delta w) * DG}{xw} \qquad \textbf{(c.2)}$$

$$\overline{g^m} = g + \frac{dg}{x} \qquad \textbf{(c.3)}$$

If the other road at the most fills the complete background at one side of the road, thus $\Delta w \leq \frac{1}{2} w * (x-1)$, for the grey values along the profile yields:

range i	$g^p(i) - \overline{g^p}$	$g^m(i) - \overline{g^m}$
for i = 0 to $\frac{1}{2}w*(x-1)-\Delta w$	$-\frac{(w+\Delta w)*DG}{xw}$	$-\frac{dg}{x}$
for i = $\frac{1}{2}w*(x-1)-\Delta w$ to $\frac{1}{2}w*(x-1)$	$\frac{((x-1)*w-\Delta w)*DG}{xw}$	$-\frac{dg}{x}$
for i = $\frac{1}{2}w*(x-1)$ to $\frac{1}{2}w*(x+1)$	$\frac{((x-1)*w-\Delta w)*DG}{xw}$	$\frac{(x-1)*dg}{x}$
for i = $\frac{1}{2}w*(x+1)$ to xw	$-\frac{(w+\Delta w)*DG}{xw}$	$-\frac{dg}{x}$

Table C.1 *Grey value minus average for various ranges of i along the profile(model).*

Substitution of these values into formula C.1 for cross-correlation yields:

$$R_C = \sqrt{\frac{(x-1)*w \ - \ \Delta w}{(x-1)*(w+\Delta w)}} \qquad if \ \Delta w \leq \tfrac{1}{2}w*(x-1) \tag{c.4}$$

If it is assumed that the profile should at least be so width that an extra lane to leave or enter the motorway completely falls within the profile at one side, thus $\Delta w \geq 3.5$ m., the multiplication factor x becomes larger than 1.6. The graph expressing the relation between the cross-correlation and Δw for a 2-lane single carriageway of a motorway (w = 11.55 m.) is draw in fig. C.3 for different values of x. It shows that the influence on the cross-correlation of another road in the profile with a certain width Δw reduces if x becomes larger. Therefore x=2 was chosen. In this case the number of road pixels is equal to the number of background pixels. Formula c.4 gets a simpler form for x=2:

$$R_C = \sqrt{\frac{w-\Delta w}{w+\Delta w}} \tag{c.5}$$

The graph in fig. C.4 expresses the relation between the cross-correlation coefficient R_C and Δw for 2-, 3- and 4-lane motorways and x=2.

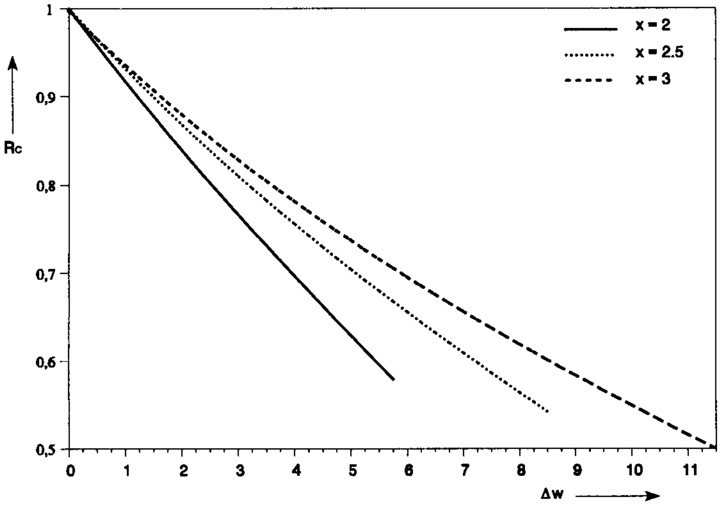

Fig. C.3 Relation between Rc and Δw for 2-lane motorway for different values of x

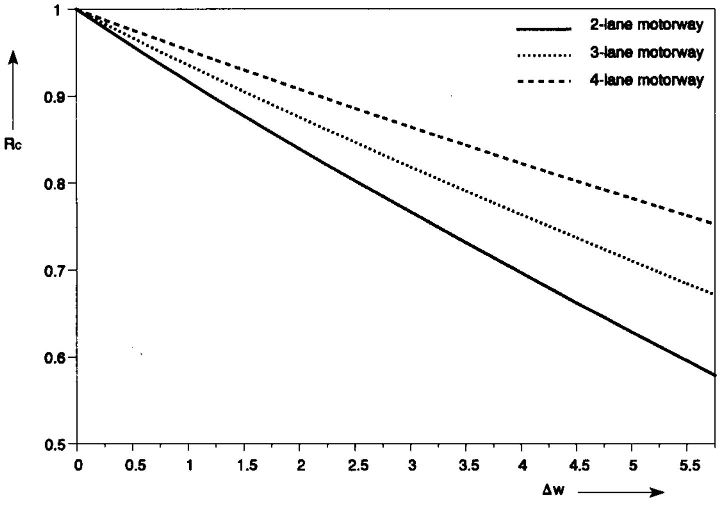

Fig. C.4 Relation between Rc and Δw for 2-, 3- and 4-lane motorways with x=2

C.2 SENSITIVITY OF PARAMETERS FOR DETECTION OF JUNCTIONS

The image processing techniques for detection of changes and junctions heavily depend on each other. Output of one procedure is input for the other. Consequently the parameter settings influence each other as well. The position on the axis from which a link road is searched and the distance to the search area depend on location and size of the changed part of the motorway. The aim of this appendix is to investigate how sensitive the parameters for detection of junctions are for variations in the detection of changed road parts.

One parameter for the detection of junctions is the distance to the search area D_i. It is varied between a minimum and maximum value. As can be expected the shape of a link road influences which value is optimal for D_i. The radius of the link road can vary from the smallest possible value according to the standards for road construction [Rijkswaterstaat, 1975] till infinity, corresponding to a straight road. In the Dutch road network three main types of link roads are often constructed:

- highly curved link roads (e.g. cloverleaf)
- lightly curved link roads (e.g. T-intersection)
- straight link roads (e.g. Haarlemmermeer solution)

The aim is to test for each of these configurations the ability to detect the link road in relation to the position on the axis, resulting from change detection. This ability is expressed by the value of the cross-correlation of the best match. In order to examine the influence on the parameter setting, various values for D_i within a large interval are tested.

One method (section 5.7.1) is to create artificial images of these situations. The right part of fig. C.5 - C.7 shows artificial images for the three configurations. For every position on the axis, and various distances to the search area, the procedure for detection of junctions is executed. The images on the left sides of fig. C.5 - C.7 express the results. If the cross-correlation is larger than 0.6, its value is plotted in the left image. The larger the value for the cross-correlation, the darker the colour. The position on the horizontal axis corresponds to the value of the distance. The vertical position corresponds to a position on the axis of the road in the artificial image at same vertical position. Note that the direction in which the link road is detected is not displayed.

The images with the cross-correlation of best matches can be seen as regions in which all solutions for detection of junction lie. They show the relation between a certain position on the axis of the road and the distance to the search area in an ideal situation.

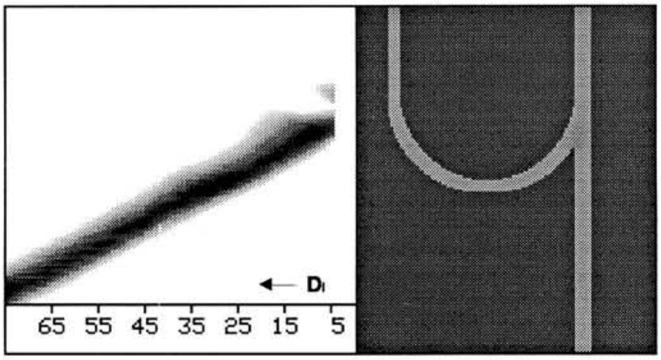

Fig. C.5 Region with cross-correlation of solutions for detection of a highly curved link road in artificial image

As can be seen, for each position on the axis there is only a limited range of values for the distance, which yields a successful match. But these regions with solutions not only show that the optimal setting of the parameters for the distance to the search area depends on the result of change detection, but that it also depends on the shape of the link road. The regions of the three different configurations each have a characteristic shape. The extent of the region with solutions depends on properties of the configuration. For example: if the radius of the link road in fig. C.6 is reduced until it is equal to the radius in fig. C.5, the extent of the region with solutions in fig. C.6 decreases until it is changed into the region in fig. C.5.

In addition, the setting of other parameters, like the length of the search area, influences the extent of the region with solutions. Fig. C.8 shows the region corresponding to the same configuration as fig. C.5, but detected with a shorter search area.

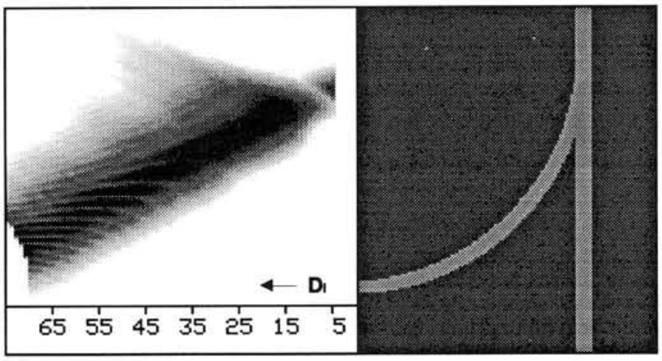

Fig. C.6 *Region with cross-correlation of solutions for detection of a lightly curved link road*

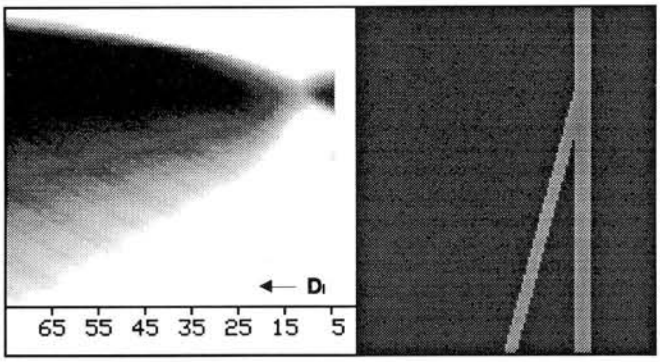

Fig. C.7 *Region with cross-correlation of solutions for detection of a straight link road*

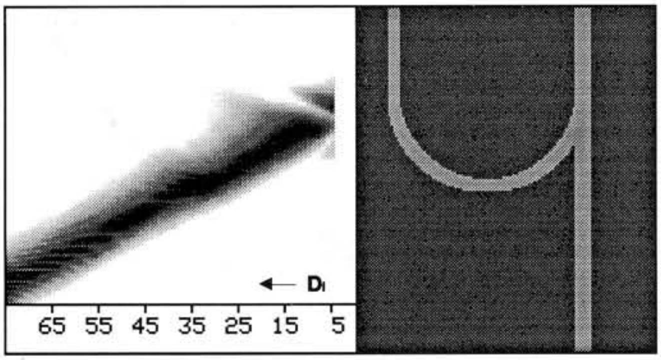

Fig. C.8 *Region with cross-correlation of solutions for detection of a highly curved link road and short search area*

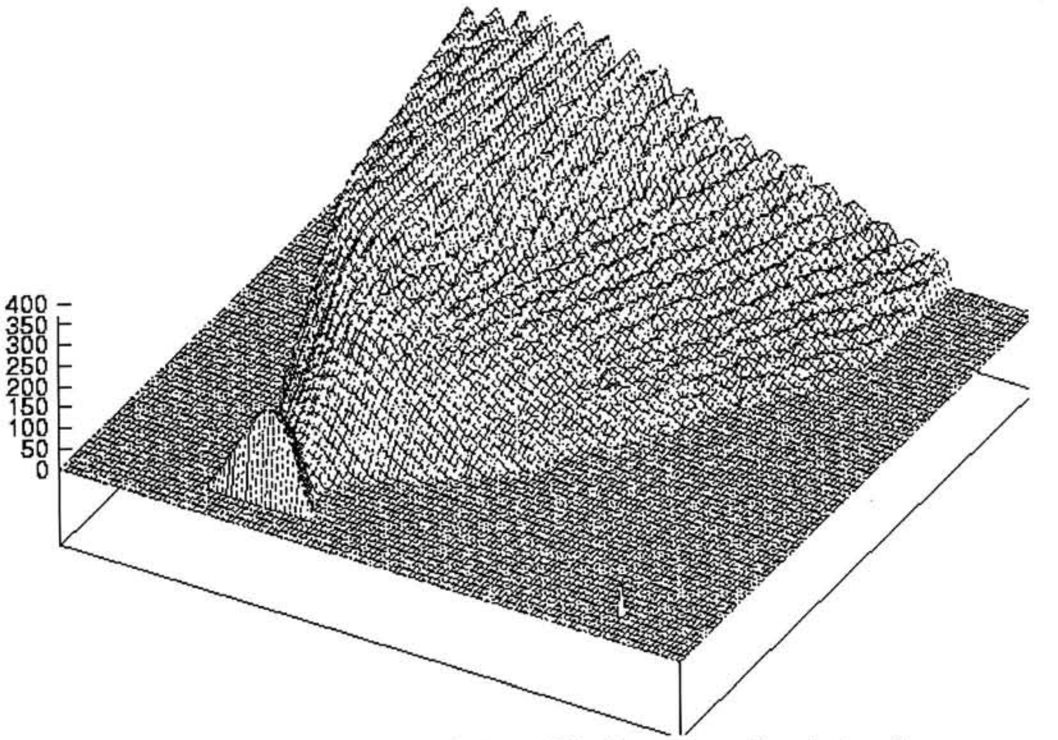

Fig. C.9 3D representation of the cross-correlation within the region with solutions for a straight link road and an angle difference of 1 degree.

The values of the cross-correlation within the region with solution can also be visualized as a 3D landscape. High peaks correspond to good matches. This representation clearly shows the influence of another parameter, the angle difference. Fig. C.9 shows in 3D the region with solutions for the straight link road of fig. C.7, calculated with an angle difference of 1 degree and fig. C.10 with an angle difference of 0.5 degrees. The ridges in fig. C.9 are due to a high correspondence between the direction of the link road and the search area. The valleys indicate that none of the tested directions of the search area coincide optimally with the link road. This setting of 1.0 degree of the parameter for the angle difference is not optimal, because the chance for successful detection of the link road, depends on the position on the axis from which it is searched. Fig. C.10 shows that if a smaller angle difference is used, the surface of the region with solutions becomes smoother. This means that detection of junctions is less sensitive for variations in the detection of changed parts. Therefore an angle difference of 0.5 pixels is used for Y-junctions in the experiments in the case study.

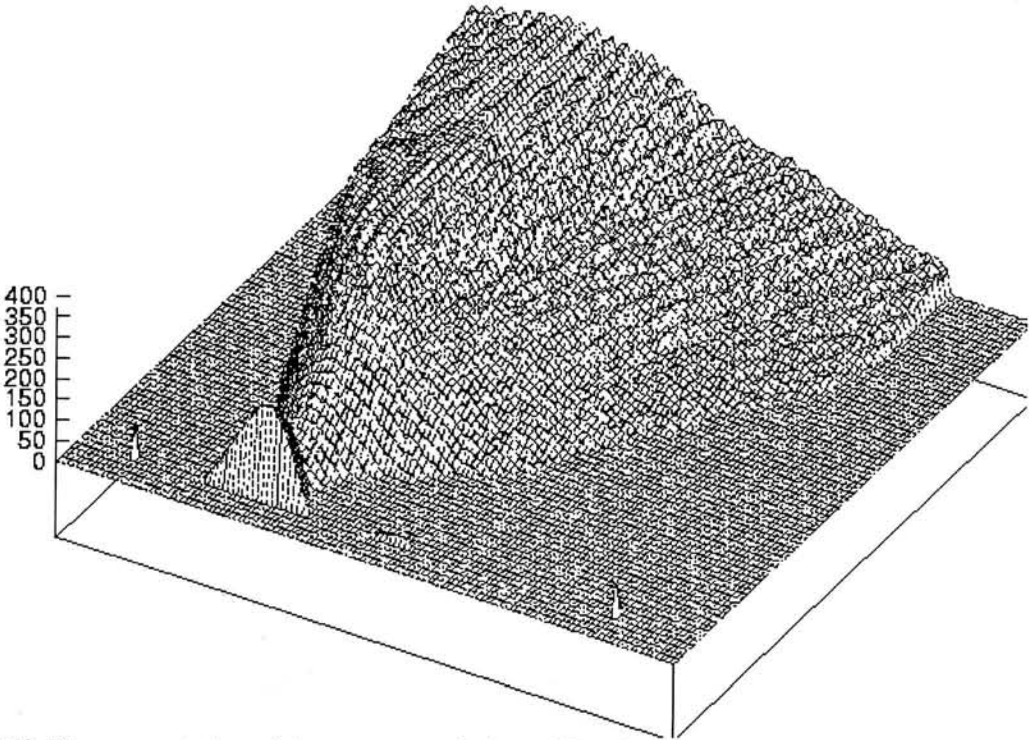

Fig. C.10 *3D representation of the cross-correlation within the region with solutions for a straight link road and an angle difference of 0.5 degrees.*

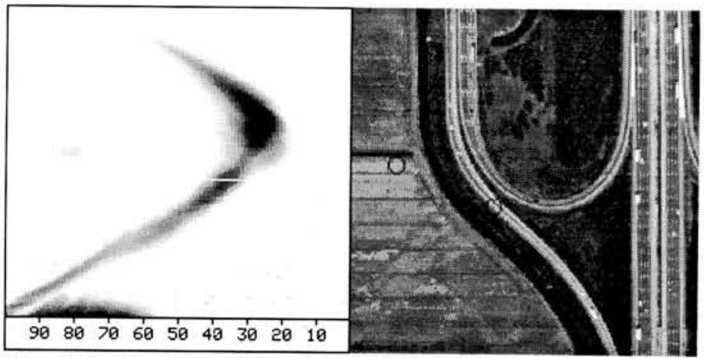

Fig. C.11 *Region with the cross-correlation of solutions for a highly curved link road in a real aerial image*

The same regions with solutions can be calculated for real aerial images. Fig. C.11 shows the region with solutions for a highly curved link road and fig. C.12 for a lightly curved link road in a part of the aerial image of fig. 5.4. The extra solutions in fig. C.11 compared to fig. C.5 are caused by the fact that the link road is a combination of a straight part with a sharp angle with the motorway, followed by a curve. The diagonal light coloured kind of shadow in fig. C.12 is caused by a truck on the link road.

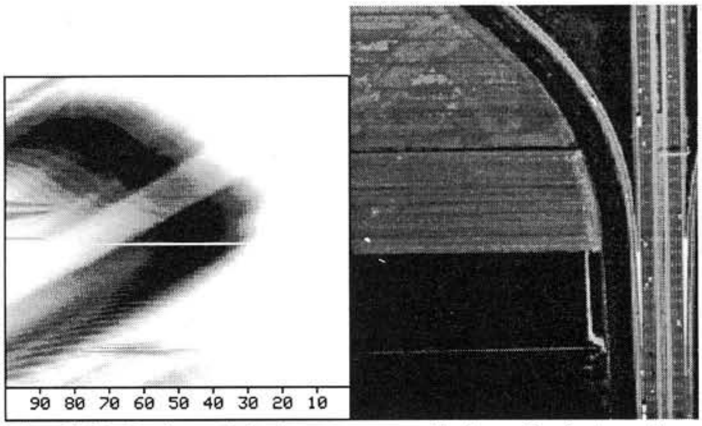

Fig. C.12 Region with the cross-correlation of solutions for a lightly curved link road in a real aerial image

From these graphs it can be concluded that in all these cases there are several positions on the axis from which a junction can be detected if the appropriate distance to the search area is used. For each type of configuration the value for this distance can be read from the graphs.

The conclusion can be drawn that variations in the result of change detection are allowed as long as the setting of parameters of the technique for the detection of junctions is such that it still yields a position within the region with solution.

In theory, these regions with solutions can be used to find an optimal parameter setting for a certain configuration. In this way the search space can be limited and the computation time will decrease. Determination of parameter settings tailored for the detection of specialized types of junctions fits well in the concept of goal-directed segmentation. In practice it seemed to be hard to realise for the following reasons:

- There are many parameters which influence the region with solutions. An optimal setting corresponds to solution in a multi-dimensional space;
- Experiments on real aerial images (fig. C.11 and C.12) show that a combination of the main types of link roads can be used;
- The regions with solutions correspond to an ideal case with high contrast, a homogeneous road and no disturbances in the background. Deviations from this ideal case can result in misdetection, even though the parameter setting is in theory optimal.

For these reasons these results are only used to determine the setting of the parameter for the angle difference.

APPENDIX D

NOTATIONS AND ABBREVIATIONS

B%	percentage of best matches with the artificial profile model, which are used to calculated the grey-value profile model
DG	grey value difference between road and background in an artificial profile
dg	grey value difference between road and background in a profile model
D_i	distance to the search area
$[D_{min}, D_{max}]$	range within which the distance from the starting point on the axis to the road element to the beginning of the search area is varied
G	grey value of the background in an artificial profile
g	grey value of the background in a profile model
$g^m(i)$	grey value of pixel i in profile model
$\overline{g^m}$	mean grey value of the profile model
$g^p(i)$	grey value of pixel i in profile
$\overline{g^p}$	mean grey value of the profile
L_R	length of changed part detected on road element from database
L_S	length of the search area in the direction of the line
$[M_{min}, M_{max}]$	range within which the width of the road in the model is varied
M_i	width of the road in a certain model within the defined range
M_W	width of the detected link road
N	number of pixels in a profile
Δp	maximum deviation between the predicted and real position during road tracking
R_C	threshold for cross-correlation
R_{min}	lowest possible value the radius of a link road with maximum curvature can have
s	distance to the predicted point during road tracking, called the step size
W_S	width of the search area or profile
W_{std}	width of the road according the standards for road construction
W_R	width of road element from database
(x,y)	the position on the axis of the changed road element in which the line starts
xw	width of a profile (model), defined as x times the width of the road w
$[\varphi_{min}, \varphi_{max}]$	range within which the direction is rotated
φ_i	certain direction within the range in which a new road element is searched
$\Delta\varphi$	angle difference between successive directions which are tested

SUMMARY

KNOWLEDGE-BASED INTERPRETATION OF AERIAL IMAGES FOR UPDATING OP ROAD MAPS

In modern map production a shift took place from analogue maps to maps in digital format, stored in Geographic Information Systems (GIS). Because of the advantages of GIS, this development caused a wider use of topographic data and therefore a larger demand. To be effective, GIS depends on accurate and up-to-date input data. The major part of this data is acquired from aerial photographs and satellite images. However, the photogrammetric processing of the data forms the bottleneck in the geo-information supply. Its present form, outlining manually every object in the photograph, is labour-intensive and time-consuming. Therefore, automation of the acquisition of topographic information from aerial images is highly desirable.

Considering the current state-of-the-art of automation of photogrammetric processing, the conclusion can be drawn that tasks involving interpretation capabilities of human operators are very difficult to solve by computer. A large number of publications deals with the problem of interpretation of aerial images in general and extraction of roads in particular, but results are not suitable for application in practice. An important reason for disappointing results is the complex contents of aerial images. It has been shown that none of the image processing operators are perfect and that we have to select useful image processing operators and combine them into effective image analysis processes. Even though maps are recognized to be a quite valuable knowledge source for interpretation, they are hardly used in previous work.

The science of computer vision is confronted with similar problems when trying to automate interpretation tasks. Knowledge-based concepts have shown to be most promising for these tasks. The design philosophy is to make the involved object properties more clear by organizing a priori knowledge into models or knowledge bases for each object class and to separate this knowledge from general problem-solving computation. This thesis focuses on the potential of knowledge-based concepts for updating road maps by interpretation of aerial images. The aim is to design and evaluate an interpretation strategy based on a knowledge base, which reflects the complex contents of aerial images.

In the designed interpretation strategy bottom-up processing (segmentation, object recognition) is integrated with top-down reasoning (hypothesis generation, inconsistency detection). Outdated or incomplete road maps are utilized to initiate the search for new parts of the road network in up-to-date aerial images. Hypotheses are generated for detection of changes a road network may undergo and for the presence of new roads that appear in the context of the changed parts. Recognized related parts on their turn generate hypotheses for further search based upon spatially related objects. Thus a chain of successive search actions is formed. This process is called contextual reasoning. Each search action activates its own image processing technique and values for its parameters, especially suitable for change detection or segmentation of a specific type of road.

They operate on a restricted region of interest in the grey-value domain. This strategy is called goal-directed segmentation. By generation of hypotheses, the combination of several image processing techniques is realized. A priori defined properties of the searched type of road in the knowledge base are used for testing hypotheses and result in object recognition. Since errors are inevitable in image analysis, inconsistencies need to be detected and solved. For this purpose constraints in the knowledge base are defined for the presence of objects in relation to the presence of other objects. If the object is not found, alternative hypotheses are generated, resulting in resegmentation.

The contents of the knowledge base plays an important role in the performance of the interpretation strategy. Objects and their relationships are the basic primitives, represented in the knowledge base by frames. Object definitions are used for the task of object recognition in the interpretation strategy. Object relationships are used for hypotheses generation, goal-directed segmentation and inconsistency detection. The question is, which parts of the road network should be defined as objects and which properties should be used to build a road model. The complex contents of aerial images requires recognition of meaningful parts of the road network instead of linear structures. The standards for road construction can be used to define properties of specialized road types.

By means of a case study the concepts are concretized for a certain updating situation and it is tested if our research objectives are met. The case is considered in which the outdated map only contains a motorway and that connected link roads present in aerial photographs are newly constructed. For this case experiments on nine different scanned aerial photographs are done. This imagery originates from the photogrammetric practice of the Survey Department of Rijkswaterstaat. They were divided into a learning and a test set. Experiments on images at a resolution of 0.4 and 1.6 m. are done in order to investigate the influence of resolution. The effect of incorporation of knowledge from the standards for road construction is tested by using two different road models in the knowledge base. One defines general parts of the road network as objects, e.g. road elements and junction, and includes their general properties. The other defines specific objects like 2-, 3- or 4-lane carriageways and fly-overs with properties based on the standards for road construction. The knowledge base contains temporal and spatial relationships, which activate segmentation techniques. No special attention is given in the scope of this thesis to development of image processing techniques. The used segmentation techniques are based on evaluation of the grey-value profile perpendicular to the road. The procedure for detection of junctions yields an original contribution. Standards for road construction are also used to set parameters and their values are represented explicitly in the knowledge base.

The results of the case study show, that for rather simple configurations, detection and classification are good for both used road network models, but for more complex configurations or worse road appearance, the specialized model gives better results than the generalized model. The reason is that restriction of the search space and of constraints for recognition realised by incorporation of the standards for road construction reduce both the number of omission and commission errors in detection. Besides, it is very well possible to recognize meaningful objects like main carriageways with various number of lanes and discriminate Y-junction from fly-overs.

Thus, addition of knowledge from the standards and definition of specialized road types contribute to the improvement of the interpretation. Results using images at a resolution of 0.4 m. are worse than at a resolution of 1.6 m. The reason is that object properties and segmentation routines developed at low resolution can only be applied at a limited range of image resolutions, which was exceeded at high resolution.

Main contributions are the way in which outdated or incomplete maps are utilized in the interpretation strategy and the incorporation of standards for road construction in the knowledge base. Although goal-directed segmentation improves results on interpretation, segmentation remains the weakest and most time-consuming part of the interpretation strategy. Special attention should be paid on the development of techniques for goal-directed segmentation. One of the reasons for omission errors is the limited part of the road network covered by the aerial photograph. This problem can be solved by using neighbouring photographs. Inherent to the use of spatial relationships to search new roads is the dependency between successive search actions. Therefore inconsistency detection and alternative hypotheses generation play an important role in the interpretation strategy, but are hard to define. It should be examined which constraints can be defined within models of topographic objects en their relationships.

In conclusion, the designed interpretation strategy and knowledge-based concepts are suitable for extraction of topographic objects, in particular road networks, from aerial images. The concepts are applicable on various resolutions, for example on satellite images, but the knowledge base needs to be tuned carefully for objects at those scales. At this stage of development the concepts are not yet mature enough to be put in practice as a fully automatic process and it is doubtful if this will ever be achieved. At this time we should concentrate on semi-automatic solutions for the photogrammetric practice. The concepts support inclusion of semi-automatic image processing techniques.

KENNISGESTUURDE INTERPRETATIE VAN LUCHTFOTO'S VOOR HET BIJWERKEN VAN WEGENKAARTEN

In het moderne kaartvervaardigingsproces heeft een verschuiving plaatsgevonden van analoge kaarten naar kaarten in digitaal formaat, die kunnen worden gebruikt in Geografische Informatie Systemen (GIS). Door de extra mogelijkheden die GIS biedt, is het gebruik van topografische informatie toegenomen en daarmee ook de vraag ernaar. Om de effectiviteit te kunnen waarborgen, is GIS afhankelijk van nauwkeurige en actuele data als invoer. Het grootste gedeelte van deze data wordt ingewonnen uit luchtfoto's en satellietbeelden. Echter, het fotogrammetrische verwerkingsproces van deze data is het knelpunt in de geografische informatievoorziening. In zijn huidige vorm, waarbij elk topografisch object handmatig wordt aangemeten in de luchtfoto, is dit een arbeidsintensief en tijdrovend proces.

Als we kijken naar de huidige stand van de automatisering van het fotogrammetrische proces, kan de conclusie worden getrokken dat taken, waarbij de operateur de foto moet interpreteren om te kunnen karteren, moeilijk op te lossen zijn met behulp van de computer. Een groot aantal publikaties is gewijd aan interpretatie van luchtfoto's in het algemeen en aan het detecteren van wegen in het bijzonder. Echter, de resultaten zijn nog niet geschikt om in de praktijk te worden toegepast. Een belangrijke oorzaak van de tegenvallende resultaten is de complexe inhoud van luchtfoto's. Een conclusie, die uit de literatuur kan worden getrokken, is dat geschikte beeldverwerkingstechnieken moeten worden geselecteerd en gecombineerd in procedures, omdat geen van de beeldverwerkingstechnieken op zich perfect geschikt is voor het detecteren van topografische objecten. Hoewel kaarten worden beschouwd als een waardevolle kennisbron voor interpretatie, is nauwelijks literatuur beschikbaar waarin ze ook daadwerkelijk worden gebruikt ter ondersteuning van de interpretatie.

Binnen het vakgebied van de "computer vision" wordt men geconfronteerd met soortgelijke problemen bij het automatiseren van interpretatie taken. Kennisgestuurde concepten worden beschouwd als meest belovende oplossing voor het automatisch uitvoeren van deze taken. De filosofie voor het ontwerp van systemen is om de gebruikte eigenschappen van objecten zo duidelijk mogelijk te maken door a priori kennis hierover te verzamelen in modellen of kennisdatabases voor elk object type en om bovendien deze kennis te scheiden van algemene oplossingsgerichte procedures. Het onderzoeken van de mogelijkheden van kennisgestuurde concepten voor de interpretatie van luchtfoto's is het onderwerp van dit proefschrift. Het doel is om een interpretatiestrategie te ontwikkelen en te evalueren, die gebaseerd is op een kennis-database die geschikt is om de complexe inhoud van luchtfoto's te representeren.

In de ontworpen interpretatiestrategie worden "bottom-up" processen (segmentatie, objectherkenning) gecombineerd met "top-down" redeneermechanismen (genereren van hypotheses, detecteren van inconsistenties). Verouderde of incomplete wegenkaarten worden gebruikt om het zoekproces naar nieuwe delen van het wegennetwerk te starten. Hypotheses worden gegenereerd over mogelijke veranderingen die het wegennetwerk kan ondergaan en over de aanwezigheid van nieuwe wegen die een contextuele relatie hebben met de gedetecteerde verandering. Gedetecteerde nieuwe wegen op hun beurt genereren hypotheses om verder te zoeken naar andere wegen in de omgeving. Zo ontstaat een keten van opeenvolgende zoekacties. Dit proces wordt contextueel redeneren genoemd. Elke zoekactie activeert zijn eigen beeldverwerkingstechniek met bijbehorende waarden van parameters, die speciaal geschikt zijn om een specifiek type object te segmenteren. Deze strategie wordt doelgericht segmenteren genoemd. Met het genereren van hypotheses wordt voldaan aan de eis dat verschillende beeldverwerkingstechnieken moeten worden gecombineerd. A priori gedefinieerde eigenschappen van het gezochte type weg in de kennis-database worden gebruikt om hypotheses te testen en leiden tot het herkennen van objecten. Omdat fouten in segmentatie onvermijdelijk zijn, dienen inconsistenties te worden gedetecteerd en te worden opgelost. Voor dit doel worden voorwaarden in de kennis-database gedefinieerd om de aanwezigheid van objecten in relatie tot andere objecten te testen. Als een vereist object niet wordt gevonden, worden alternatieve hypotheses gegenereerd die leiden tot opnieuw segmenteren.

De inhoud van de database speelt een belangrijke rol in het wel of niet slagen van de interpretatie. Objecten en hun relaties zijn de basis primitieven en worden in de kennis-database gerepresenteerd door middel van "frames". Object definities worden gebruikt in de interpretatiestrategie voor objectherkenning en object-relaties voor het genereren van hypotheses, doelgericht segmenteren en het detecteren van inconsistenties. De vraag is welke delen van het wegennetwerk moeten worden gedefinieerd als objecten en welke eigenschappen zouden moeten worden gebruikt om een wegenmodel te bouwen. De complexe inhoud van luchtfoto's vereist het definiëren van betekenisvolle delen van het wegennetwerk in plaats van lijnvormige structuren. De richtlijnen voor het ontwerp van autosnelwegen kunnen worden gebruikt om eigenschappen te definiëren van specialistische typen wegen.

Door middel van een casestudie worden de concepten concreet gemaakt aan de hand van een bepaalde situatie en wordt getest of de onderzoeksdoelen worden gehaald. De situatie wordt onderzocht waarin de verouderde kaart alleen een autosnelweg bevat en dat de verbindingswegen, die aanwezig zijn in de luchtfoto, nieuw geconstrueerd zijn. Voor deze situatie worden experimenten gedaan op negen gescande luchtfoto's. Deze beelden komen uit de fotogrammetrische praktijk van de Meetkundige Dienst van Rijkswaterstaat. Ze werden verdeeld in een leer set en een test set. Experimenten worden gedaan op foto's met een resolutie van 0.4 en 1.6 meter om de invloed van de resolutie te testen. Het effect van het gebruik van richtlijnen voor het ontwerp van autosnelwegen wordt getest door twee verschillen wegenmodellen te definiëren in de kennis-database. Het ene model definieert algemene delen van het wegennetwerk als object, zoals onvertakte stukken weg en knooppunten, en bevat algemene eigenschappen van wegen. Het andere model definieert specifieke objecten, zoals 2-, 3- en 4-baans snelwegen en viaducten als objecten en gebruikt eigenschappen uit de richtlijnen voor het ontwerp van wegen. De kennis-database bevat relaties in ruimte en tijd, gerelateerd aan een specifieke segmentatietechniek. Binnen dit proefschrift wordt geen speciale aandacht geschonken aan het ontwikkelen van beeldverwerkingstechnieken. De gebruikte segmentatietechnieken zijn gebaseerd op evaluatie van het grijswaarden profiel loodrecht op de weg. De procedure voor het detecteren van knooppunten is origineel. De richtlijnen voor het ontwerp van wegen worden ook gebruikt om de waarden van parameters te bepalen. Deze waarden worden expliciet gerepresenteerd in de kennis-database.

De resultaten van de casestudie laten zien dat voor redelijk eenvoudige configuraties van wegen deze goed kunnen worden gedetecteerd en geclassificeerd met behulp van beide wegenmodellen. In geval van meer complexe configuraties, of slechtere zichtbaarheid van wegen, geeft het specialistische wegenmodel betere resultaten dan het algemene model. De reden is dat de beperking van de zoekruimte en van het bereik van gedefinieerde eigenschappen voor herkenning, die mogelijk zijn door gebruik van de richtlijnen voor het ontwerp, het aantal omissie en commissie fouten in de detectie vermindert. Daarnaast is het goed mogelijk om de betekenisvolle typen wegen in het gespecialiseerde model, zoals rijbanen met een verschillend aantal rijstroken, te herkennen en onderscheid te maken tussen viaducten en op/afritten. Kortom, het toevoegen van kennis over de constructie van wegen en het definiëren van betekenisvolle typen wegen draagt bij aan de verbetering van het interpretatie resultaat. Resultaten gebaseerd op beelden met een resolutie van 0.40 m. zijn slechter dan die op een resolutie van 1.6 m. De reden is dat eigenschappen van objecten en segmentatie routines, ontwikkeld op de lage resolutie, slechts een beperkte geldigheid hebben voor andere resoluties, die in geval van de hoge resolutie wordt overschreden.

Originele bijdragen zijn de manier waarop verouderde en incomplete kaarten worden gebruikt binnen de interpretatiestrategie en het gebruik van richtlijnen voor het ontwerp van autosnelwegen in de kennis-database. Hoewel doelgericht segmenteren de resultaten verbetert, blijft segmentatie de zwakste en meest tijdrovende schakel in de interpretatiestrategie. Speciale aandacht zou moeten worden gegeven aan de ontwikkeling van technieken voor doelgericht segmenteren. Eén van de redenen voor omissie fouten is het beperkte deel van het wegennetwerk dat binnen het bereik van één luchtfoto valt. Dit probleem kan worden opgelost door aangrenzende foto's uit de fotovlucht te gebruiken. Inherent aan het gebruik van ruimtelijke relaties om nieuwe wegen te zoeken, is de afhankelijkheid tussen opeenvolgende zoekacties. Daarom spelen detectie van inconsistenties en het genereren van alternatieve hypotheses een belangrijke rol in de interpretatiestrategie, maar deze zijn moeilijk te definiëren. Het is daarom gewenst te analyseren welke voorwaarden gebruikt kunnen worden om topografische objecten en hun relaties te modelleren.

De algemene conclusie kan worden getrokken dat de ontworpen interpretatiestrategie en de kennisgestuurde concepten geschikt zijn om topografische objecten, in het bijzonder wegennetwerken, te detecteren in luchtfoto's en correct te classificeren. De concepten zijn toepasbaar op meerdere resoluties, bijvoorbeeld op satellietbeelden, maar de definities van objecten en beeldverwerkingsroutines dienen te worden aangepast voor deze resolutie. In dit stadium van de ontwikkeling zijn de concepten nog niet volwassen genoeg om volledig automatisch te kunnen worden ingezet in een produktieproces en het is twijfelachtig of dit ooit zal gebeuren. Op dit moment moeten we ons voor de praktijk concentreren op semi-automatische oplossingen. De concepten bieden de mogelijkheid om semi-automatische beeldverwerkingsroutines aan te sturen.

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CURRICULUM VITAE

Surname: de Gunst
First names: Maria Elisabeth (Marlies)

1967	July 12th, born in Delft
1979 - 1985	St. Laurenscollege, Rotterdam: VWO
1985 - 1990	Delft University of Technology, Faculty of Geodetic Engineering: doctoral-engineer Graduation thesis: "Automatic extraction of roads from SPOT images"
1991 - 1996	Delft University of Technology, Faculty of Geodetic Engineering: doctorate (PhD) PhD thesis: "Knowledge-based interpretation of aerial images for updating of road maps"
1996	Dutch Cadastre: information manager