A ROBUST CONCURRENT APPROACH FOR ROAD EXTRACTION AND URBANIZATION MONITORING BASED ON SUPERPIXELS ACQUIRED FROM SPECTRAL REMOTE SENSING IMAGES

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ABSTRACT

The extraction of road signatures from remote sensing images as a promising indicator for urbanization is a classical segmentation problem. However, some segmentation algorithms often lead to non-sufficient results. One way to overcome this problem is the usage of superpixels, that represent a locally coherent cluster of connected pixels. Superpixels allow flexible, highly adaptive segmentation approaches due to the possibility of merging as well as splitting and form new basic image entities. On the other hand, superpixels require an appropriate representation containing all relevant information about topology and geometry to maximize their advantages.

In this work, we present a combined geometric and topological representation based on a special graph representation, the so-called RS-graph. Moreover, we present the use of the RS-graph by means of a case study: the extraction of partially occluded road networks in rural areas from open source (spectral) remote sensing images by tracking. In addition, multiprocessing and GPU-based parallelization is used to speed up the construction of the representation and the application.

1. INTRODUCTION

The segmentation of remote sensing images of the visible spectral range into meaningful regions has a long tradition in the field of image processing, analysis and interpretation. It is the necessary first step to assign sets of pixels to certain imaged objects and is widely used in Earth observation tasks. However, in some cases it is hardly possible to apply this segmentation in one step as objects may possess a varying colour signature or too much prior knowledge is needed. Examples for such cases are rivers and especially roads, that can have different appearances and even vary significantly in terms of colour signature within few kilometres.

To overcome these problems for the task of road tracking, we propose a superpixel-based, parallel approach. The approach starts with an over segmented image. We refer to each over segmented region as a superpixel. Superpixels are generally defined as a local, and coherent set of pixels, “which preserves most of the structure necessary for segmentation at the scale of interest” [1]. Based on the initial segmentation, we track the road superpixel-wise. The proposed approach will be analysed with respect to other approaches in terms of completely visible and partially occluded roads. Since the development of a road network is a promising indicator for urbanization, we achieve urbanization monitoring using this approach, especially for rural areas. For a proper use of the superpixel images, we introduce a new representation of those images, that puts a special emphasis on the transitions between superpixels.

2. RELATED WORK

Both, the representation of image segmentations as well as the tracking of road networks from remote sensing images have a long tradition and are still under research. Thus, we will thus present the most common approaches for each aspect.

2.1. Geometric-Topologic Image Representations

After an image is segmented into different superpixels, the intuitive representation is another image, where the value of each pixel corresponds to a unique ID of the superpixel. This is often performed directly by means of the superpixel extraction algorithm or by labelling algorithms e.g. on thresholded images. However, this so-called label image cannot be considered as a valuable data structure when it comes to topological questions like, what are the neighboured superpixels of superpixel 132? To utilize such geometric-topologic information, different representations have been developed so far.

One of the first valuable representations is given by the region adjacency graph (RAG). The RAG is a very lightweight representation, since it stores each superpixel as a node and introduces edges for neighboured superpixels (cf. [2]). Due to its simplicity, the RAG is still in use by many other segmentation approaches (see [3,4]). As drawback and by design, a RAG can only answer simple (neighbourhood) questions efficiently.

To overcome the limitations of the RAG, Kropatsch corrected the RAG with respect to the segmentation and introduced based on that corrected RAG an edge graph. Combined, the two graphs form the dual image graph that explicitly captures both, superpixels and all edges in between them. (see [3]).

Another class of approaches is described by combinatorial maps, which use permutations and half edges (so-called "Darts") to describe the segmentation result (see [5, 6]).

Although both, the dual image graph as well as the combinatorial maps, are able to describe a geometric-topological correct representation, they do not provide enough explicit information. Moreover, they may also suffer from very complex structures and handling and may require the introduction of artificial elements.

2.2. Road Tracking from Spectral Images

The pixel-based automatic and semi-automatic extraction and tracking of roads based on their spectral signatures on remote sensing images has been a research area since many years. Comprehensive descriptions for the most common classes of algorithms as well as for the most commonly used algorithms may be found in [7] and [8].

As a proxy of the model based approaches, Geman and Jedynak describe a statistically motivated semi-automatic approach for road tracking in [9]. This approach is using probability density functions for the spectral intensities of road and non-road classes obtained from training images. Based on a seed location and an initial direction, this approach yields promising results, since the authors were able to track hundreds of km of highways without the need of intervening.

Another semi-automatic approach, especially for high-resolution remote sensing images, has been described by Shukla et al. in [10]. In contrast to Geman and Jedynak this approach works without prior probabilistic knowledge about the road pavement. Based on a cost function, which consists of different sub costs, a minimization problem is formulated with respect to the image. The road is then being tracked from a given starting point by means of the path with minimal costs throughout the pixels of the image. To compute the overall cost function, many pre-processing steps have to be carried out, like e.g. the detection of road boundaries using the Canny approach, and the initial estimation of the road's width. Eventually, crossings need a special post-processing.

Further approaches are using templates [11] or texture [12] to successfully track roads on images. Another popular class of algorithms is using Kalman filters [13, 14] based on a linear model over the position, the angle of the road, and the latest angle change as states and orthogonal profiles for detection of the road [15].

Instead of relying on the pixel level, it might be obvious to perform the road detection on a higher abstraction level – a representation with respect to superpixels. Many formerly needed properties may already be defined with respect to each superpixel, which makes them valuable as a model for a variety of algorithms and cost functions.

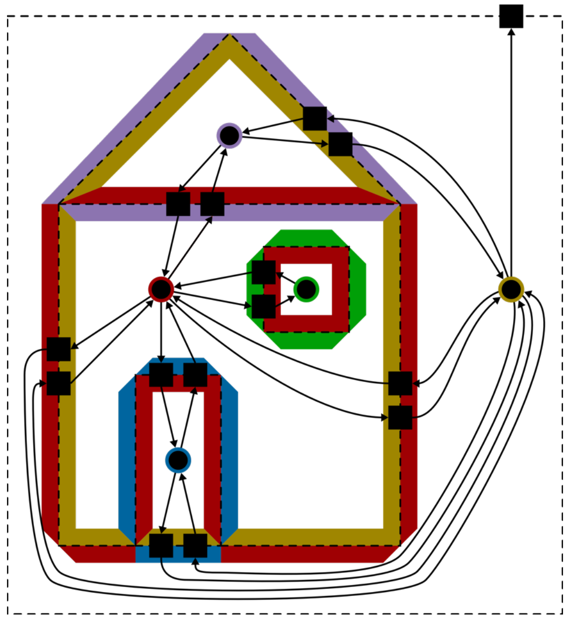

Figure 1. Example of an RS-graph representing the segmentation of a house with five superpixels (coloured dots). The borders (boxes) are marked with colours indicating the neighbouring superpixel.

3. THE RS-GRAPH FOR SUPERPIXEL IMAGE REPRESENTATION

To represent a superpixel image properly, a new graph-based representation, the region shell graph (RS-graph), has been introduced in [16]. In contrast to other representations mentioned in section 2.1, the RS-graph does not just represent the regions (superpixels) and their neighbourhoods. Additionally, it explicitly represents the borders (shells) of superpixels as nodes. Borders are thereby defined as pixels of a superpixel adjacent to a neighbouring superpixel, covering a crack edge (see Fig. 1). This explicit representation of the borders makes information about them easy and fast to access and thereby usable for any kind of application.

The above definitions result in a digraph with two different types of nodes, representing either borders or regions. To highlight the differences in Fig. 1, boxes and dots are used depending on the type. By the explicit representation of borders and the introduction of a border towards the outside of the image, it is possible to represent the topology of the superpixels without any artificial constructs, unlike [3] or [5]. Among other morphological operations a merging operation of superpixels has been implemented yielding a fully navigable irregular image pyramid of RS-graphs. The merging is based on vertex contraction and post-processing to improve an initial segmentation and work on different levels of the segmentation within one representation. A more detailed description of the construction of an RS-graph can be found in [16].

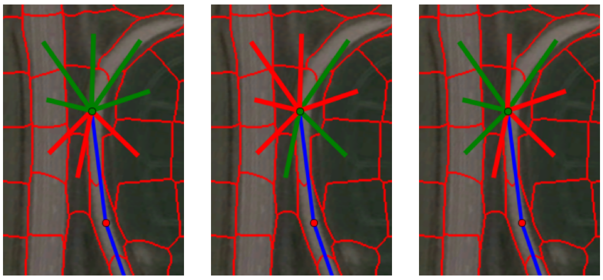

Figure 2. Results of the sub cost functions c_{angle}, c_{border}, c_{region} (l.t.r.) of the overall cost function c. Red: continuation not possible. Green: continuation possible. Image source: Google Earth, Copyright by Google Inc.

It should not be unmentioned, that the creation can be performed in parallel using multiple cores up to the number of superpixels. Some parts also use the GPU to further speed up the process.

4. ROAD-TRACKING USING THE RS-GRAPH

Using the advantages of the proposed RS-graph, a semi-automatic, superpixel-based, parallel road tracking application has been developed to track a road from superpixel to superpixel. Given a starting point as seed on the road and therefore also the starting superpixel as well as the roads width by the user, the approach segments the image automatically into superpixels using the SLIC [17] algorithm and constructs an RS-graph.

The pixels around the seed are used as a colour sample of the road, which ensures paving invariance. Afterwards, the approach starts by searching for possible continuations of the road in a given direction. To find continuations, the superpixels neighboured to the current superpixel are evaluated according to a cost function c, which contains the parts seen in Fig. 2, where each ray marks the possibility of a continuation towards one of the neighbouring superpixels given a single sub cost function. The sub cost c_{angle} determines the angle of the change in direction from the last road segment to the proposed new road segment and rejects too tightly bended roads. c_{border} uses the borders of the RS-graph to determine, if the road continues in the direction of one of the neighbouring superpixels. It does so by searching for at least one pixel on the relevant border of the current superpixel that looks similar to the current colour signature of the road, accumulated during tracking. On the other hand, c_{region} compares the current colour signature of the road to the 20% of the pixels most similar to that signature on each of the neighbouring superpixels and thereby calculates the similarity of the possible road with the current. The results are accumulated for an overall result by allowing continuations of the current road to those superpixels with a positive result in all sub cost functions (green rays in Fig. 2). The most probable one, with the lowest cost, will be used as the next road superpixel, while all the others are later processed as junctions.

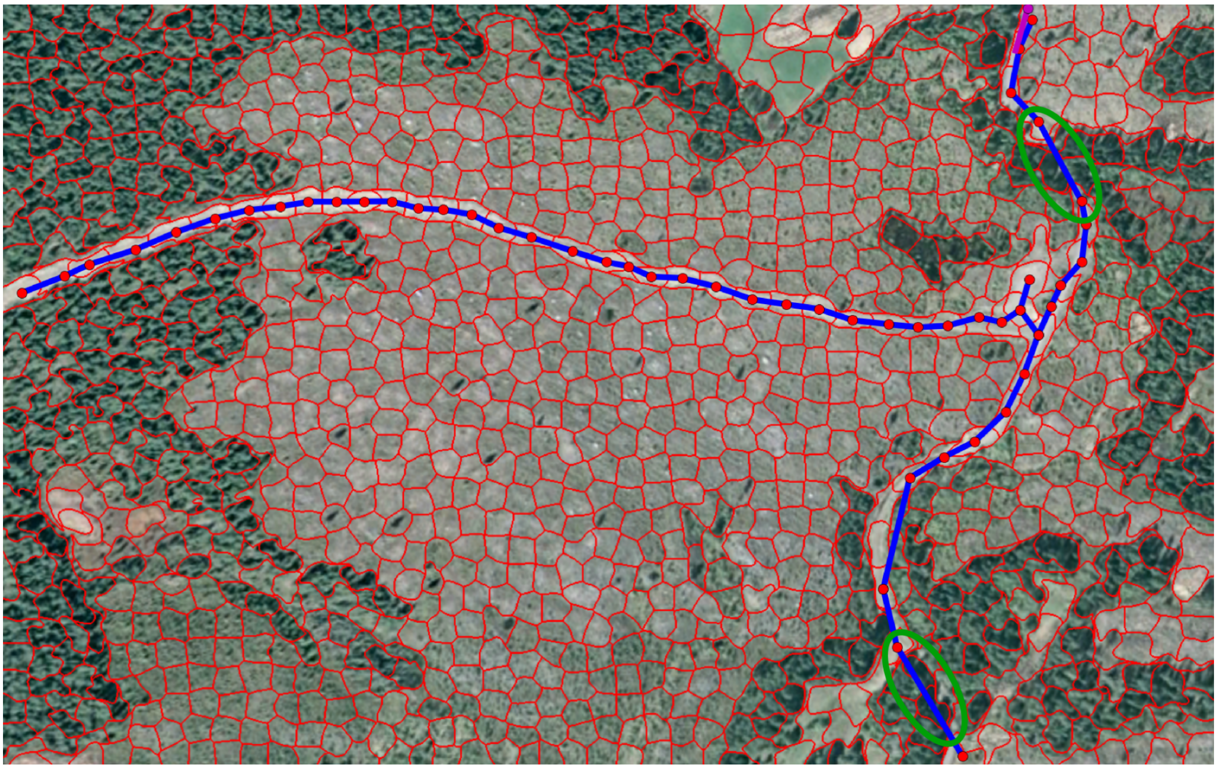

Figure 3. Result of the proposed road tracker. Seed is marked in pink (top right). Multiple occluded parts of the road (green) as well as a junction are correctly tracked. Image source: Google Earth, Copyright by Google Inc.

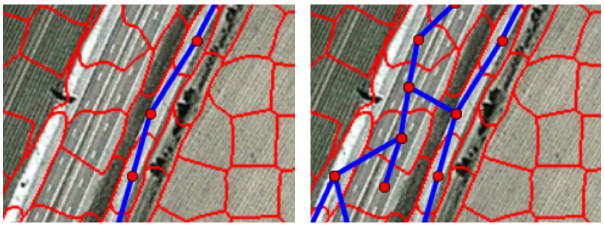

Figure 4. Effects of the use of the border (c_{border}) on the results of the proposed road tracking algorithm. Left: border is used. Right: border is not used. Image source: Google Earth, Copyright by Google Inc.

For a more robust tracking, it is also possible to not only use the directly neighboured superpixels in the cost function but, in case none of them is a possible continuation, to expand the search space to the neighbours of the neighbours. This enables skipping parts of the roads that are occluded by shadow or trees. To speed up the tracking all neighbours are processed in parallel using multi-core processing.

5. RESULTS

The results of the proposed approach on publicly available imagery of Google Earth show the robustness and the positive influence of the usage of the borders. Fig. 3 gives an example of a road partially occluded by shadow in the upper and bottom right parts (green). However, the road was tracked correctly from the seed (pink) to both ends, also recognising the junction correctly, due to the skipping of multiple superpixels described in the methodology.

For further results, which have been performed on different images of rural environments and road paving as well as an example of a street crossing water, see the appendix of this paper.

As displayed in Fig. 4, further results show the usefulness of introducing the borders of superpixels to the proposed cost function c. Without the use of the borders in c_{border}, a junction would have been introduced and the tracking would have continued on the highway, which is not actually connected to the original road.

6. EVALUATION

To quantify the results shown an evaluation against the approach of Shukla et al. [10], has been performed on two 3-element subset of the original test set. The images of the first subset all contain partially occluded roads like in Fig. 3 whereas the images of the second subset only include roads that are not occluded. We selected the approach Shukla et al., since it is typical for the class of pixel-based, geometric path following approaches.

The results of the evaluation are presented in Fig. 5. They reveal the unique robustness of the proposed approach compared to the approach of Shukla [10]. Whereas the difference on the subset of non-occluded roads is

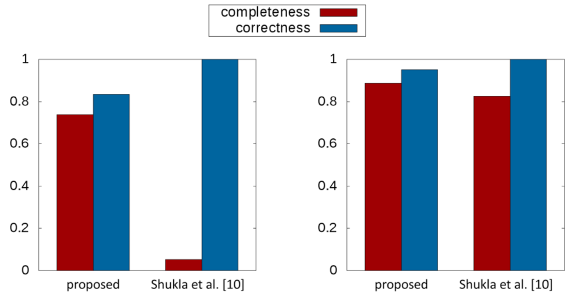

Figure 5. Results of the proposed method and the method of Shukla et al. [10] on a subset of three images containing partially occluded roads (left) and a subset of three images containing only non-occluded roads.

marginal, the proposed approach has a much higher completeness on the partially occluded roads. It can also be shown that this is mainly due to the road trackers ability to skip superpixels.

7. CONCLUSIONS

We presented a new superpixel-based, parallel approach for the problem of road tracking, that can be used for any kind of road network extraction e.g. in tasks like urbanization monitoring. As a preliminary for this approach, a new representation of superpixel images based on an RS-graph was introduced, which allows a direct access on the transitions of the superpixels without using any artificial constructs and thereby supports the road tracking.

The results of our approach are very promising even when applied on publicly available imagery. The robustness by invariance to occlusions of the roads is remarkable and one main advantage of the approach in contrast to other approaches. Therefore, this new tracking algorithm is particularly useful in rural areas or for areas with highly covered roads.

To further improve the results of the road tracking approach, additional data like the terrain slope calculated using digital elevation models might be helpful rejecting road candidates with unrealistic high terrain slopes. Also the addition of existing road maps of the area might be helpful, in case the approach loses track of the road.

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APPENDIX

More examples of the road tracking algorithm and the corresponding "Gold Standard" images may be found under:

http://lps16.esa.int/page_paper1900.php