Optimization methods
in remote sensing and geoinformatics

Theses of Ph.D. Dissertation

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1 Introduction

The dissertation presents three real world problems and their algorithmic solutions. The first problem is to classify pixels into specific categories in satellite images. The second one is to convert scanned raster maps to vectorized data. The third one is to plan the schedule of agents who visit customers in a city or in a larger region.

Beside these three problems, there is also a fourth topic, which is about the LEMON network optimization library. This library can be used as a basic starting point to implement optimization algorithms, therefore it was widely used for developing solutions for the previous three problems.

![Diagram showing relations between topics]

2 Classification of satellite images

The thematic classification, i.e. the categorization of the image pixels into given classes, is a fundamental step in remote sensing [10]. There is a set of satellite images from a given region, and a reference map of pixels with known categories. Based on this information and the spectral similarities, each pixel should be assigned to one of the given classes.

In the dissertation, the most important methods are presented for the classification problem. Traditionally, the pixel-wise methods were applied, like the well-known maximum likelihood or Bayes-decision. Both of these methods approximates the classes with multivariate normal distributions. In real-world problems, the classes can be more complex, e.g. a given thematic category can be characterized only as the union of multiple normal distributions. For the adequate handling of such classes, the clustering-based classification methods have been introduced.

\textsuperscript{1}In the figure, the arrow means “using the methods and results of” relation.
The pixel-wise classification algorithms assume that the pixels of the satellite image are independent, they do not consider the spatial structure of the image objects. In practice, the pixels form contiguous areas, so-called segments, which have uniform land cover and spectral properties.

In high resolution images, the segment-based classification can decrease the error of point-like misclassifications. The pixel-wise methods classify some of the uncertain pixels into wrong classes, which can be only partially corrected with the fine-tuning of the algorithm parameters. With segment-based methods, the surrounding environment can help to classify these pixels into the right categories.

In the dissertation, three methods are studied for assigning segments to classes. The maximum likelihood and the clustering-based methods are generalized to support the classification of the segments instead of the pixels. Furthermore, spectral similarity distance functions can be also used to assign the segments to categories.

The graph-based segmentation algorithms are studied in depth in the dissertation. In image processing algorithms, it is natural way to represent the image as a graph. An undirected graph can be assigned to an image, where nodes belong to pixels, and edges connect neighbouring pixels. A weight function is assigned to the edges, which is a measure of dissimilarity between the spectral properties of the pixels.

Four image segmentation algorithms are presented in the dissertation. The best merge segmentation is a bottom-up algorithm, i.e. at the beginning, each pixel is in a separate segment, and afterwards, the algorithm joins two adjacent segments in each step. The current implementation selects always those two neighbouring segments, which have the maximum average weight on the connecting edges.

The tree merge segmentation is similar to the best merge algorithm, but instead of looking for the most connected adjacent segments, the algorithm tries to join the segments in predefined order. First, the edges of the grid graph are sorted by the weight function into descending order, and the algorithm iterates over them and tries to merge the segments on the two endpoints. The adjacent segments are joined if adding the new edge do not increase significantly the variability of the segment. The variability of a segment is measured by the minimum edge weight in the maximum spanning tree of the corresponding subgraph.

The minimum mean cut segmentation is a top-down algorithm, i.e. the whole image is in the same segment at the beginning, and one segment can be split in each step. The algorithm calculates the minimum mean cut within a segment, and if the cut is smaller than a threshold, the segment is split.
The normalized cut segmentation [15] is similar to the previous algorithm, but it calculates a normalized cut to split the segments.

In the dissertation, the performance of the segmentation algorithms are compared in the classification problem. Classification accuracy assessment is the most important aspect of the comparison. We use the overall classification error, the error matrix and the error map to evaluate accuracy.

The result in this topic can be summarized as follows:

- A framework has been created for solving and evaluating classification problems in remote sensing, and several segmentation, clustering and classification algorithms have been implemented in this framework. The graph-based segmentation algorithms were investigated advantageously. Therefore, the best merge segmentation was interpreted as graph-based algorithm, and the normalized cut segmentation was simplified to use the power method.

- According to the research, the segment-based classification algorithms can outperform the pixel-wise methods both in accuracy and runtime efficiency.

- The experiments show that the top-down segmentation methods have better thematic accuracy than the bottom-up algorithms, since they are less affected by the differences in the spectral deviation of the classes.

- The segment-based classification methods with Bhattacharyya-distance decision rule are more robust against classification errors than with the maximum likelihood decision rule, since they handle more accurately the segments with large spectral extent.

- The minimum normalized cut image segmentation with Bhattacharyya-distance classification algorithm provides a robust and efficient method for thematic classification based on an exhaustive test.

3 Raster-vector conversion of maps

The raster-vector conversion of maps aims at creating digital maps which can be used in spatial databases and vector-based GIS systems. In the dissertation, the IRIS project and its optimization related tasks are presented [7, 6].

In the presented framework, the process of the map conversion is split into three distinct steps: preprocessing, vector retrieval and postprocessing. In the preprocessing step, the raster image is simplified in order to make
the maps more suitable for the vectorization algorithms. In the second step, the vector data are retrieved from the preprocessed raster. Finally, in the postprocessing step, the quality of the vector image is improved.

In the preprocessing, simple image manipulation algorithms are used, e.g. digital filters and color space transformations [14].

For the vector retrieval, the map objects are classified by their properties into three categories, namely to fields, curves and symbols. Before the extraction of the field objects, the pixels of the map are classified into the eligible field colors. The vectorized data is stored as a planar graph together with the dual representation. The recognition of dotted areas was also studied in the dissertation as a special case of the field object extraction.

For recognizing the curves, a color decomposition method is used, which identifies each pixel as a mixture of a field and a curve or a symbol color. The curves can be extracted from the image after applying a thinning filter on the map.

For the symbol extraction, raster-based matching was used to find the symbol patterns in the map. In addition, an algorithm was developed for recognizing rectangular buildings with the minimum enclosing rectangle algorithm.

In the postprocessing step the recognized objects of different layers are used coherently to improve the overall quality of the map. Making corrections is part of this step. For example, when a symbol is recognized on a surface where it could not arise, it will be removed from the map.

We can summarize the results as follows:

- A software framework was developed for creating automatically suitable vector maps from raster images, and it was customized to a workflow to convert Hungarian topographic maps to vector data.

- Although the representation of spatial objects with planar graphs is a known technique, it is rarely used GIS-applications. The most of the commercial software and file formats do not support this kind of data representation. The presented conversion framework show that this data structure helps to maintain the consistency of the map objects but it also keeps the ability to easily modify the map.

- Algorithms were developed for recognizing dotted segments of maps using Delaunay-triangulation and rectangular shapes based on the minimum enclosing rectangle algorithm.
4 Optimization of work schedule of agents

There are some business agents, who have to visit certain customers at given times. Additionally, when the agents are not visiting customers, they have to do other jobs in their office. The task is to plan the work schedule of the agents for a single day. The presented solution is described in [4].

The workday regularly starts when the agent arrives at the office or at the place of the first meeting. Between the meetings or office shifts, they have to travel to the next location (or to the office) either by car or by public transport depending on the agents. The agents must also be allowed to have a lunch within a specified period.

For the task, a linear programming model was created in which a binary variable is assigned to each potential schedule of each agent. Because the model contains enormous number of variables, column generation method [13] was used to solve the linear program.

The column generation method needs a subroutine, which finds a dual constraint, which is not satisfied by the current dual solution. This problem was formalized as a resource constrained shortest path problem and dynamic programming method [9] was applied for finding the solution.

For getting integer solution, a greedy rounding method was used. It iteratively selects variables, and fixes them with the value 1. In each step, that variable is chosen from appropriate candidates which makes the smallest increase in the global cost function.

The planning of the routes of the agents between meetings and office shifts is an important subtask of the problem. However, a third party web-service product was used for this purpose; the dissertation also presents the most important methods for this sub-problem.

The main results in the topic of schedule planning are as follows:

- A complex optimization method for a work schedule planning problem has been developed.
- A heuristic rounding method for the column generation algorithm was evaluated.
- The experimental results show that the algorithm is a suitable and efficient solution for the agent scheduling problem.

5 LEMON optimization library

The LEMON library stands for Library for Efficient Modeling and Optimization in Networks. It is a highly efficient open source graph template
library that provides implementations of data structures and algorithms related to graph optimization [12, 5]. Note that the author has made significant contribution in the development of this library.

LEMON implements several data structures, which can be used in optimization algorithms. The most important types are the graph classes and the corresponding data types, like nodes, arcs and property maps. In addition, LEMON also provides several auxiliary data structures, like heaps, union-find structures.

LEMON provides highly efficient implementations of numerous algorithms related to graph theory and combinatorial optimization. These algorithms include fundamental methods, such as breadth-first search (BFS), depth-first search (DFS), Dijkstra algorithm, Bellman-Ford algorithm, Kruskal algorithm, and methods for discovering various graph properties (connectivity, bipartiteness, Eulerian property, etc.), as well as complex algorithms for finding maximum flows, minimum cuts, feasible circulations, maximum matchings, minimum mean cycles, minimum cost flows, and planar embedding of a graph.

Linear programming (LP) is probably the most fundamental general methods of operations research. Countless optimization problems can be formulated and solved using LP techniques. LEMON implements wrapper classes for several LP libraries providing a common high-level interface for them.

In the dissertation, some aspects of the implementation of the library are also presented. For example, using C++ vectors to represent the adjacency lists of the graph and Observer design pattern to signal graph alterations are the main key to the highly efficient and convenient property map types.

LEMON was compared in benchmark test with BGL [2] and LEDA [11], which are the main competitor libraries of LEMON. The results of these experiments imply the conclusion that the fundamental algorithms and data structures of LEMON turned out to be measurably faster than the corresponding implementations of the other two libraries.

The main results in the topic are the follows:

- The library provides a wide range of data structures, algorithms and other practical components, which can be combined easily for solving problems of various types related to graphs and networks.

- According to extensive benchmark tests, essential algorithms and data structures of LEMON typically turned out to be more efficient than the corresponding tools of widely used similar libraries, namely BGL and LEDA.

- The author has made many contributions to the library including the
development of several algorithms and data structures. Some significant design decisions can also be mentioned among his activities.

- The wide toolkit of the library makes it also available to use in several optimization algorithms related to geoinformatics and remote sensing.
- The LEMON graph data structures can naturally represent objects of real world geographic systems. Furthermore, due to the grid graph implementation, LEMON is easy to use in image processing algorithms.

6 Conclusion

When a complex real-world problem is to be solved, mathematics, computer science and software technology should be used in synthesis. First, the mathematical model should be established, then an adequate optimization method should be elaborated, and finally efficient algorithms should be implemented using appropriate software development environment. This approach has been successfully used to solve the above problems.

References


