Blog16: 'topomap' - a framework of R-scripts for the automated vectorization of buildings

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Abstract

The software tool 'topomap' enhances the classification results of remote sensing imagery by generalizing the content and vectorizing the irregular outlines of imaged objects. Vector data of urban environments are generated in an automated way and with high cartographic quality. The user may monitor the intermediate results which are displayed graphically together with the source data. The derived coordinates of the corner points may be stored together with a label in topographic databases and Geographic Information Systems (GIS). All scripts of 'topomap' are open-source and the package has the potential to contribute to national and private mapping projects and to crowdsourcing.

1. Motivation and significance

Topographic map data are lacking at many places in the world [1]. Imagery from satellites, airplanes and drones is taken in large numbers and used for mapping tasks. Besides governmental organizations many private organizations support these activities using expensive equipment and highly trained human operators. There are many efforts to automate mapping and production rates. Also, amateurs should be able to carry out mapping. Such activities are summarized with the term 'crowdsourcing'. Despite many efforts to automate topographic mapping a practical tool is still lacking [2].

The task of automated mapping of various landscape types is not trivial. Especially, mapping urban areas gives problems due to the variety of buildings and other man-made objects. The result must be vectors of high cartographic quality and geometric accuracy. The content of the map data should also be generalized. Many research projects have tried to use artificial intelligence (AI) and algorithms to automate topographic mapping. A solution of the author has been described in [3, 4, 23]. It is based on differential rectified images using a Digital Surface Model (DSM) derived from the same imagery. The developed software package 'topomap' achieved rectangularity and parallelism of the vectors forming the outline of buildings. The processing uses graphic displays of the intermediate results and various possibilities to edit. The geometric accuracy was tested by means of accurate reference data. From the gained experiences a new version of the software has been created. This new software package is named now 'topomap'. Its version 1.4.2 is subject of this article.

The user of the software must prepare the processing by choosing an ortho-image and proper methods and parameters to adapt to the particularities of the imaged objects. The selections concern the type of object, the mode of processing, the partition of object, and the methods for finding the sequence of lines. The selectable parameter concerns the smallest length of a line. The user may monitor the intermediate results which are displayed graphically together with the source data. The possibilities for editing are given by repeating the processing using another selection. Probable answers are suggested which are based on statistical methods. Furthermore, supporting scripts are given to generate a solution for very special objects. Numerous comments in the scripts help to understand the solution and make modifications easier for the user.

Automated generation of buildings and other man-made objects in vector format can be carried out by different methods. The software package 'topomap' uses classified ortho-images, from which buildings have been extracted, as input data. The generation of vector data from the derived raster image applies the Hough transform and least-squares adjustment for the detection and processing of lines. The sequence of the detected lines in the polygon is determined by selectable methods. Successive and adjusted lines are then intersected. The coordinates of the corners are improved using least-squares adjustment. The generated outline of the building will have orthogonal and parallel lines. Lines of other orientation may be added. Tools for interactive editing are integrated in the software.

Related work of other authors regarding cartographic enhancement and regularization of classification results is discussed in the following. The method applied in [5] derived several mask layer data from ortho-images and DSMs and processed the building outlines by means of various image processing and GIS tools. The extracted outlines were simplified using the Douglas-Peucker algorithm [6].

In [7], the outlines of the buildings have been extracted from a derived DSM using a minimum bounding rectangle. The approach in [8] used a dense point cloud derived by image matching. Buildings are extracted by thresholding the gradients of elevations. The edge pixels of the roof are then traced, and closed polygons are generated. By a split-and-merge process, line segments are obtained, and straight lines are fitted to them. Successive lines are intersected, and roof corners are obtained.

In [9], a building mask is derived from a DSM, and then further refined by classifying geometrical features of the images. By means of a tracing algorithm, boundary points are extracted, and a set of line segments is then fitted to the extracted points by least-squares adjustment. The obtained line segments are intersected and connected to building outlines.

Other investigations start from Airborne Laser Scanning (ALS) and identify, trace, and regularize the outlines of buildings. In [10], e.g., a Delaunay triangulation is applied to an ALS point cloud. A boundary line consisting of small segments can then be identified. The line-segments are smoothed, and corners are derived. The use of two primary data sources (camera, ALS) requires simultaneous data acquisition and, therefore, more expensive equipment. The discussed work did not announce open-source software packages.

2. Software description

The R-package 'topomap' contains nine main programs, numerous functions and supporting scripts. Their names are 'line_detection', 'func_mean_line', and 'support_line_detection'. Data and parameters chosen by the author are also part of the package. Details of the used data are taken from [11, 12]. The applied parameters are adapted to these data. The diagram in Fig. 1 depicts the components of "topomap". For a few objects, the processing of examples required special solutions which are contained in additional scripts, e.g., 'spObj_line_detection'. Other open-source packages are "EBImage" and "spatstat". Details about these R-packages can be found in [13, 14]. Minor R packages are "tiff", "rpart", "RDP" and "nlme", which can be downloaded from [15].
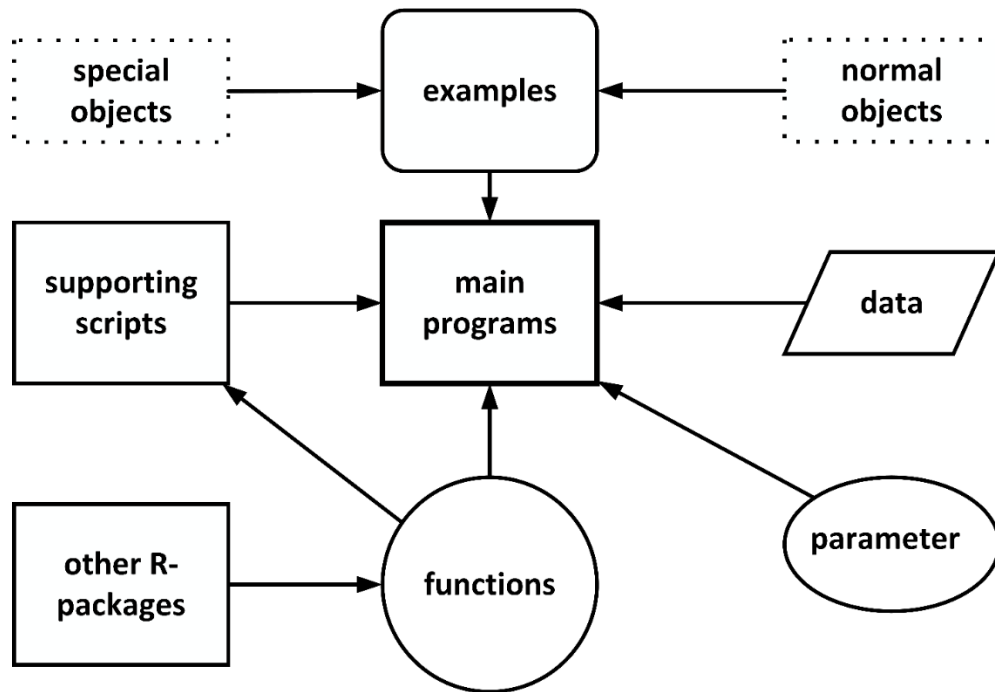
2.1 Software architecture

Fig. 1. Components of "topomap"

The package has nine main programs (*startup_topomap*, *enhance_image*, *extract_single_building*, *line_detection*, *sequence_of_lines*, *adjustment_of_line*, *intersect_corner_points*, *adjustment_of_corner_coordinates*, *plot_results_on_references*). Details of these programs are given in the following. The names of the main programs contain also the version number.

Each program starts with a short description of the task and instructions for the use. The required data are read and intermediate results which are required by the following programs are stored. Many parts of the programs are realized as functions. Graphic output can be used. Many tests check the plausibility of intermediate results. The main programs can be executed fully automatically one after the other. In case of problems an interaction may become necessary. Supplementing software will help in such situations.

2.1.1 startup_topomap

By means of this program the required software packages and functions are loaded. The project details (path- and file names) of examples are read.

2.1.2 enhance_image

The ortho-image of all extracted buildings is enhanced to prepare the vectorization. Several functions of the open-source package "EBImage" are applied. Morphological functions like 'dilation' and 'erosion' are used to make the outlines of the extracted objects smoother. The selectable parameters are the kernel size (2x2 pixels), and a deviation of the average intensity value (0.01). A shape (diamond) has been used in the function 'makeBrush'. Edges of objects (buildings) are generated using the function 'thresh'. All connected components (CC) are filled with pixels and labelled. Features like "area" and "maximum radius" of all objects are derived. Objects smaller than a threshold, e.g., 25 m^2 in nature at the used examples, are then removed by the following processing. Other scripts must be called to scale the image if required.

2.1.3 extract_single_building

The structure of the objects to be enhanced may be different. The CC may contain one, two or more buildings. The first step is the decision of the user whether a partition of the connected components is necessary. The processing is divided into three branches: no partition ("no-part"), two parts ("2parts_1" and "2parts_2"). The CC will be split into parts. Fig. 2 gives an example.
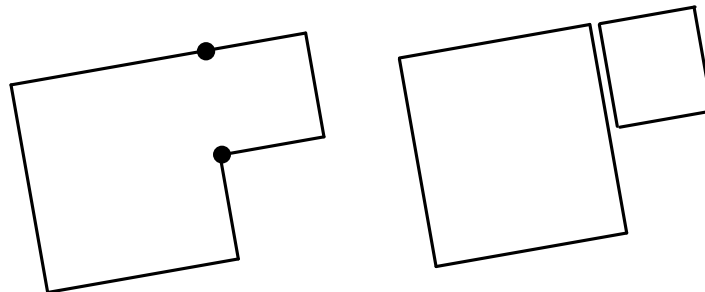

Fig. 2. Partition of a CC into 2 parts.

The points in the schematic drawing represent the places where the partition must take place. The coordinates are found by manual digitizing.

Features of an ellipse which is fitted to the CC of a single building (or part of it) are calculated. These features (centre coordinates, azimuth of the main axis) are used in the detection of line segments and of their sequence. Plots of the CC may be overlayed onto an enlarged section of the ortho-image. Errors in the classification may be detected. An image of the extracted single building with additional check marks for scaling is generated and stored using the R-package "tiff" [17].

2.1.4 line_detection

The detection of the line segments forming the outline of the buildings uses the Hough transform [16] where the line segments are displayed as points in the parameter space (H). Default values for the resolution of H are set to $\Delta\Theta$=5° and $\Delta\rho$=5 pixels. The array of H will then be manageable by smaller computers, and the line segments may safely be detected. The ρ-range should be as small as possible but contain all line segments of the object. Four possibilities for the calculation of the ρ-range are available. The default value covers the distance between the farthest object pixel and the origin. The results of the Hough transform are ordered by the lengths of the lines. The pixel clusters (PCs) of a selectable number of longest lines are displayed in a graph, and one PC is selected as reference. A plot of the line and of the ortho-image will inform whether the selection may serve as reference line for other parallel and rectangular lines. Further calculations are branched for the six object types. Fig. 3 depicts the four object types named 'extr_wd', '4_long', '100_all', '100_all+nonortho'. The calculation in the four branches is different. At the first two types, four lines are found by their length at extreme positions in both major directions. For the types 'multiple rectangular lines' and 'multiple rectangular and non-orthogonal lines', the solution is found by means of the functions *func_rectangular_lines* and *func_line_reduce*. The lines are analysed for their ρ- and length-values to find all line segments forming the outline of the building. A threshold (*thr*) for the minimum distance between two adjacent lines (*dρ*) avoids that lines are too close to each other. The selected default value is *thr* = 10 pixels.
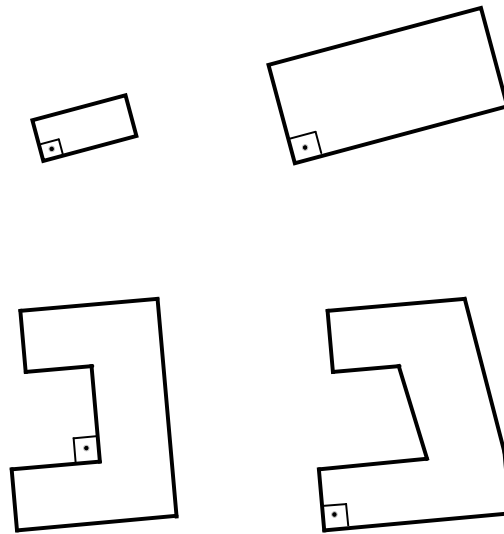
Fig. 3. Types of objects in "topomap". Upper row: 4-line rectangular (small and long), lower row: multiple rectangular lines and objects containing rectangular and non-orthogonal lines.

All points representing a detected line are extracted and the calculation of precise line parameters is carried out. The detected lines may contain points of another line. An analysis of the histogram of the point coordinates will detect gaps in the line segment. Points of other lines will then be removed. All detected lines and their centres are plotted on top of the ortho-image to discover whether the detected lines and their midpoints represent the imaged building correctly.

The fifth and sixth type are applied for buildings with non-orthogonal lines only. They are processed either automatically by an algorithm or manually. The fully automatic solution uses the Ramer-Douglas-Peucker (RDP) algorithm [22]. This algorithm reduces the number of vertices in the polygon by connecting the first and last vertices and calculating the distances of the intermediate vertices to the connected line. The vertex farthest from the line is retained as the new end-vertex, and all vertices smaller than a user-specified threshold are discarded. This process is repeated until a simplified polygon is achieved that meets the selected threshold. The manual approach starts with digitizing the estimated vertices. The xy-coordinates of two succeeding vertices are converted to coordinates of the $\Theta\rho$-system, and the labels of the corresponding line segment can be found in the modified and ordered Hough matrix (B4). The line segment labels of the building can then be entered individually or as a vector (mode 'single' or 'vector'). The following four main programs described in sections 2.1.5-2.1.8 are not used in these two building types.

2.1.5 sequence_of_lines

The sequence of lines may be determined by means of three methods, cf. Fig. 4. The first possibility uses the angle (α) between the centre of the CC and the midpoints of the PC representing a line segment. Ordering the angles according to their size will result in the sequence. In the second solution, a calculation of the minimum distance between the midpoints of line segments may be used for more complex building shapes. A third solution searches the midpoints of the line segments. The search is carried out in a 11x11 pixels large area around the midpoints. The used functions in this program are part of the open-source package "spatstat".
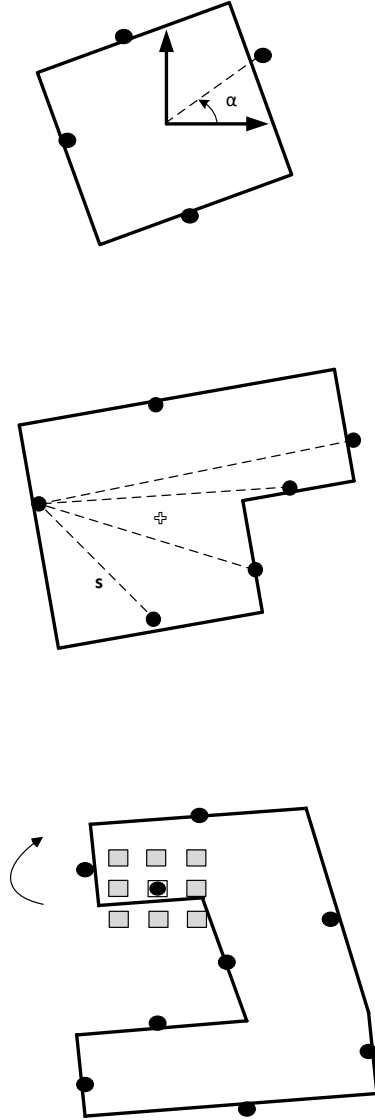
Fig. 4. Methods for finding the sequence of lines represented by their midpoints. Top: based on angle (α), middle: based on distance (s), bottom: based on scanning and line following.

A decision tree (DT) is applied for the selection of the best suited method considering the characteristics of the object. The solution is carried out by the packages "rpart" [18] and "nlme" [19] and offered to the user as suggestion.

2.1.6 adjustment_of_line

A least-squares adjustment is carried out for all detected line segments. The adjusted lines may be plotted together with the PC. The least-squares adjustment of a single line (g) minimizes the orthogonal distances (r_i), cf. Fig. 5. The derivation of the formulae can be found in [20].

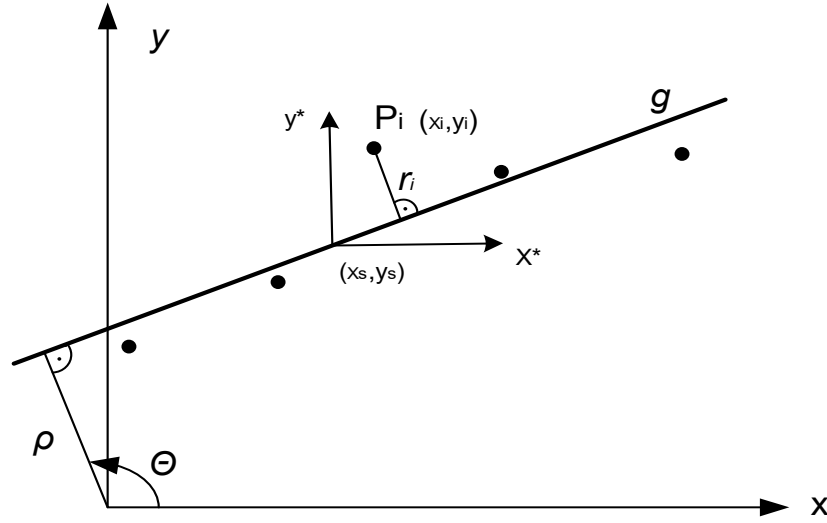Fig. 5. Orthogonal distance (r_i) from a point P_i (x_i, y_i) to a line segment (g). The black dots are pixels of the PC belonging to a detected line. Θ and ρ are the parameters of the adjusted line.

2.1.7 intersect_corner_points

The calculation of approximate corner points is carried out using the adjusted line parameters. As a test, the interior angles of the closed polygon are determined, and the deviations from rectangularity are compared with a threshold. If the test is successful, a weighted average for the major direction (Θ_{av}) is calculated. The approximate corner points and the connecting lines are plotted together with the CC.

2.1.8 adjustment_of_corner_coordinates

There are two cases to solve the adjustment of the corner coordinates. If only orthogonal lines exist, then the solution is derived from the condition that two successive vectors are perpendicular to each other. The derivation of the formulae can be found in [21].
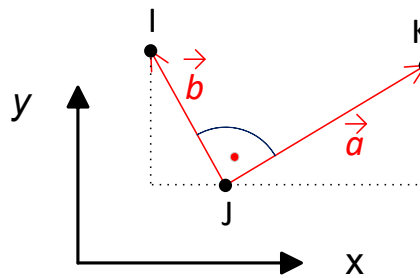

Fig. 6. Two orthogonal vectors.

The second case, where the object contains orthogonal and non-orthogonal lines, the averaged orientation angle (Θ_{av}) for each group of lines is used. The calculation of accurate corner coordinates uses the approximate coordinates and the Θ_{av} of each line group. The least-squares adjustment

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calculates new parameters (ρ_i) and the standard deviation of the residuals (r_x, r_y). A test checks whether the maximum residual is less than a threshold. In this case, the final coordinates of the building corners (vertices) are calculated and stored together with their labels.

2.1.9 plot_results_on_references
An overview of the quality of the result can be obtained by overlaying the final vectors of a single object (building) with the DSM-based ortho-image and, if available, with a topographic map. This may be done at large scale. In case of an unsatisfactory result, the calculations can be repeated using another object type and/or method for the determination of the line sequence.

Supplementing scripts are provided for some of the main programs. Examples are:
   -plot of numbers of buildings after applying a threshold for minimum size of area,
   -interactive determination of ortho-lines and non-ortho-lines by measuring one or two pixels in an
   ortho-image extract, and
   -plot of building outlines with corner- and line-numbers on an extract of the ortho-image.

In the given examples, a few special objects required corrections. For example, a calculated midpoint of the line segments could be well outside the line. The position of the midpoint must then be corrected using manual measurements. In the main program, the script *spObj_sequence_of_line* is then accessed, and the midpoint position of this line will be corrected. Another example for a special solution is the partition of objects where pixels must be measured at positions where the splitting should take place. The complete package "topomap", version 1.4.2, has 1805 files, 247 directories, and requires about 66 MB disk space.

2.2 Software functionalities

The classification results of DSM-based ortho-images are converted by "topomap" into accurate and georeferenced vector data of high cartographic quality. The raster data of buildings are first enhanced with image processing methods and then processed to vectors building by building. The processing is based on extraction of straight lines using the Hough transform and least-squares adjustment of the lines and coordinates of the building corners. Only few pixels of the line must be visible in the original images. This is an advantage of our approach because vegetation often hides parts of the building. The generated outline of the buildings will be a closed polygon with parallel, rectangular, and non-orthogonal vectors. Only buildings with specifiable area and side length are processed at the given examples. The results are checked by superimposition of the generated vectors onto the DSM-based ortho-image. Errors in the automated processing may be visually recognized and interactively corrected.

3. Illustrative examples

A topographical database must fully and accurately reflect the buildings of an urban environment. An automatically land cover map using remotely sensed imagery cannot fulfil this condition. Overlapping vegetation or other objects often hide parts of the building. This approach requires only few pixels of the imaged building edges to reconstruct a line. Furthermore, the least-squares adjustment for lines and vertex coordinates results in high geometric accuracy of the generated building representation.

Figure 7 depicts the result of the automated mapping using "topomap" together with the DSM-based ortho-image (source data) and the automatically derived CC of the building outline. The automated enhancement using "topomap" generated the building polygon completely and in its true position.

Fig. 7. Enhanced outline of building (blue polygon) together with an extract from the false-colour and DSM-based ortho-image and the connected components of the building outline (green dots) derived from a classification.

A result of the automated processing of several buildings is depicted in Fig. 8. The generated polygons reveal good agreement between the vectors and the imaged outline of the DSM-based ortho-image and high cartographic quality. Additional editing may improve the thematic as well as the geometric accuracy. The quality of the result depends very much on the quality of the source data and of the classification which are not discussed in this article.

Fig. 6. Generated vector data together with the source data (example in "topomap_v1.4.2")

4. Impact

There are many attempts to generate land cover data by classification of remote sensing images. To use these data in topographic databases and Geographic Information Systems a generalization and vectorization of the raster image is necessary. The software package "topomap" will fulfil this task. It has already been used in many tests which are published in international journals. In [3], the mathematic background of the applied methods is presented, and the geometric accuracy was evaluated in [4]. The latest version of the open-source software is available as repository at https://github.com/ObjEnh/topomap_v1.4.2. The use of the package is semi-automatic but checking and editing of intermediate results becomes always necessary at complex urban environments. Examples with other remote sensing imagery and elevation data should be carried out. Further attempts to speed-up the processing is of interest at large mapping tasks. More default values of parameters may be used to reduce the number of manual operations.

5. Conclusions

The software package "topomap" solves the vectorizing of imaged urban objects. Input are the classification results of DSM-base ortho-images. Output are vectors of high cartographic quality and geo-referenced coordinates of polygon vertices including a label. The package has the potential to contribute to national and private mapping projects.

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